UNIVERSITY OF BIRMINGHAM

School of Engineering

PhD Civil Engineering

The Development of a Risk-Informed Framework for the Appraisal of Drainage Maintenance of Ballasted Railway Track

by

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ABSTRACT

Poor drainage of ballasted railway track can lead to a variety of issues, including flooding, accelerated track degradation and substructure failure. These issues in turn can result in unplanned track maintenance, imposition of speed restrictions, delay, safety issues and damage to third party property. However, despite the potential costly impacts of poor drainage, managing the maintenance of drainage assets is challenging because it involves the consideration of large interconnected networks of assets and maintenance budgets are often limited.

To address these issues, this doctoral research develops a risk-informed tool that can be used by railway asset managers to facilitate the management of railway drainage assets. The tool incorporates an engineering model to help identify drainage associated risks and assign probabilities of occurrence to the risks, a cost model to determine the risk impacts, and an integrated model to determine risk values.

The tool is demonstrated using data obtained from three sites on the UK railway network, namely, Ardsley Tunnel, Clay Cross Tunnel and Draycott. The analysis shows that the Clay Cross Tunnel had the highest failure risk and should be prioritised for maintenance over the other two sites. It was found that the required maintenance needs to focus on the risks associated with blocked of drainage assets due to vegetation overgrowth or lack of debris clean out. The tool offers ranges of risk values associated with inadequate drainage assets which are also affected by the occurrence of causal events. These events can be categorized into a variety of contributing factors including environment, design, component (material) deterioration, installation, maintenance, traffic, and land use.

The research shows that the developed risk-informed approach is suitable for identifying and quantifying the risks associated with the drainage of ballasted railway track, even when there is a paucity of data. The approach therefore provides the railway drainage engineer with a means for arguing for funds and rational and transparent tool for prioritising the preventive maintenance of drainage assets at greatest failure risk.

DEDICATION

For my parents

Drs. Usman Sofyan (Alm) and Mutmainah Usman

For my children:

Nabiel Razzan Rivaldo and Scarlett Nafisa Miura who always be my healing power.

For Firdasari:

Wife and mother of my children

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ABBREVIATIONS

AT	Austria (Vienna)
BCR	Benefit Cost Ratio
BE	Belgium (Brussels)
BG	Bulgaria (Sofia)
BN	Bayesian network
BSI	British Standards Institute
CBA	Cost Benefit Analysis
CFD	Contributing Factor Diagram
CH	Confoederatio Helvetica/ Switzerland (Bern)
CP	Control Period
CZ	Czech Republic (Prague)
DE	Deutschland/ Germany (Berlin)
DfT	Department for Transport
DK	Denmark (Copenhagen)
EE	Estonia (Tallin)
EL	Ελλάδα (*)/ Greece (Athens)
ES	España/ Spain (Madrid)
ETA	Event Tree Analysis
FGD	Focus Group Discussion
FAHP	Fuzzy Analytic Hierarchy Process
FMEA	Failure mode and effect analysis
FMECA	Failure Mode, Effect and Criticality Analysis
FI	Finland (Helsinki)
FR	France (Paris)
FT	Fault Tree
FTA	Fault Tree Analysis
HCCP	Hazard Analysis and Critical Control Point
HAZOP	Hazard and Operability Studies
HR	Hrvatska/ Croatia (Zagreb)

HRA	Human Reliability Analysis
HU	Hungary (Budapest)
I	Impact
IE	Ireland (Dublin)
IoT	Internet of Things
IT	Italy (Rome)
LA	Local Authority
LOPA	Layers of Protection Analysis
LV	Latvia (Riga)
LU	London Underground
MCM	Multi Coloured Manual
MCS	Monte Carlo Simulation
NL	Netherlands (Amsterdam)
NO	Norway (Oslo)
NPV	Net Present Value
NR	Network Rail
ORR	Office of Rail and Road
OS	Ordinance Survey
P	Probability
PL	Poland (Warsaw)
P90	90th Percentile Valuet
PT	Portugal (Lisbon)
R	Risk Value
RCA	Root Cause Analysis
SE	Sweden (Stockholm)
SK	Slovakia (Bratislava)
SWIFT	Structured What If Technique
UK	United Kingdom (London)
TfL	Transport for London
VOT	Value of Time
WAAD	Weighted Annual Average Damages

NOMENCLATURE

f	Frequency of occurrence
λ	Failure rate
IØ(Xi)	The relative importance of basic event Xi
Lh	Length of the occurrence of basic event
Ls	Length of the section exposed to failure
r	Discount rate
x	Occurrence time(s)
t	time period (e.g. per year)
Xi	Basic event i

1 INTRODUCTION

1.1 Background

Proper drainage is critical to the performance of any ballasted railway since it impacts directly on the railway track structure (Li *et al*., 2016). Inadequate track drainage can lead to a variety of issues including flooding of the track and adjacent land, accelerated track degradation, progressive or sudden railway track, slope, and embankment failure. These issues in turn can result in unplanned track maintenance, the imposition of speed restrictions and delay times, additional time spent travelling, flooding damage to adjacent property, and train derailment (Penning-Rowsell, 2013; Spink *et al.*, 2014; Jaroszweski *et al*., 2015; Kellermann *et al*., 2015; Sihota, 2016; Usman *et al.*, 2017). Travel delay costs in the UK due to poor railway drainage alone amounted to £119 million during the period 2000 – 2017 (Network Rail, 2017a). However, despite the potential costly impacts of inadequate railway drainage, managing the maintenance of drainage assets is still often undervalued, in part because it is not considered to be important or is difficult to achieve.

The above issues are exacerbated in many countries which have mature railway networks where the track and its drainage assets can be 150 years old and are nearing the end of their useful life, necessitating increased rates of expenditure (DfT, 2014). In the UK for example, it is estimated that the cost of drainage renewals doubled from £184 m in 2014 to £368 m in 2016 (Sihota, 2016).

Under a legal obligation, the railway track drainage systems in the UK are maintained by Network Rail (NR) to ensure they function appropriate and that they are kept well maintained. However, much of the UK's railway is aged, has received underinvestment in maintenance, and the capacity of its drainage infrastructure is unknown (Burrow *et al*., 2013; DfT, 2014;

Glendinning *et al.*, 2014). These complications pose challenges to a railway track drainage asset manager who has to make the best use of scarce resources to assess track drainage integrtity and to plan and prioritise remedial actions.

Due to the importance of track drainage to ensure the integrity of the railway track, NR has planned an investment of £328 million in drainage maintenance and improvements in Control Period Five (CP5) from 2014 to 2019. This investment represents a significant increase compared to the £201 million spent on track drainage in CP4 (2009-2014). To allocate this investment effectively and allow for preventative maintenance, a systematic identification of the drainage assets' failure risk is required (DfT, 2014).

A risk-informed framework for railway drainage asset management is therefore required, as it allows the uncertainties associated with the extent and performance of assets to be considered when selecting and prioritising assets for maintenance. Such a framework also provides a rational means of arguing for funds for renewal and maintenance.

1.2 Problem Statement

Adequate railway track drainage is required to ensure the proper functioning of ballasted railway track infrastructure, and thereby, the operational performance of the overall railway system. This requires:

1. The drainage system to be designed and built appropriately to operate under a current or future environment (i.e. train load and speed, extreme weather, subgrade condition).
2. Effective track drainage maintenance.

However, railway drainage asset management is challenging because it involves the consideration of large interconnected networks of assets, significant parts of which are buried and therefore difficult to assess. These assets are made from a variety of materials which deteriorate at different rates, are of varying ages and have unknown maintenance history. In addition, the railway operational environment constrains maintenance activities spatially and temporarily, and maintenance budgets are often limited.

In order to facilitate drainage asset managers under these challenging conditions, there is a need to develop a decision support tool. This tool should take into account uncertainties associated with the current and future condition of assets, non-homogeneous deterioration rates, and insufficient maintenance budget. Such a risk informed tool will help track drainage managers to plan appropriate drainage intervention, by facilitating the prioritisation of preventive maintenance of those areas of the track at greatest failure risk. The requirements for such a system is the subject of this thesis.

1.3 Aim and Objectives

The aim of this research is to develop a risk-informed framework which can be used by railway track asset managers to plan appropriate railway track drainage interventions, by facilitating the prioritisation of preventive maintenance of those areas of the track at greatest failure risk.

To achieve this, the research has the following objectives:

1. Explore the literature to understand the potential risks associated with poor subsurface and surface drainage of railway ballasted track.
2. Explore the literature to identify risk assessment concepts and techniques which could be utilised within a risk-informed drainage asset management model.

3. To develop an engineering model to identify the factors which contribute towards drainage component failure and to quantify the probabilities of their occurrence.
4. To explore the use of a cost model to appraise the socio-economic impacts associated with poor track drainage.
5. To develop an integrated model to quantify the risk probabilities and impacts associated with the risk-informed engineering and costs' models (objectives 3 and 4) for the appraisal of drainage maintenance.
6. Demonstrate the applicability of the developed model using a number of case studies.

1.4 Benefits of Research

The research has developed a risk-informed framework which can be used to assist asset managers to plan the maintenance of drainage components of ballasted railway track. This framework can be used to identify the parts of a railway network at the greatest drainage failure risk. The framework helps to:

1. Identify the causal events and failure modes.
2. Quantify the probability of occurrence of the causal events.
3. Assign the identified risk with its contributing factors (i.e. environment, components, traffic, design, installation and maintenance).
4. Quantify the cost of social and economic impacts as adverse outcomes of poor drainage.
5. Provide a decision support tool which can prioritize maintenance and remediation interventions for drainage assets.

The approach has been presented to Network Rail's drainage team who have provided funding to incorporate the approach within their own decision support.

1.5 Gap in Knowledge and Novelty of Research

Currently, there is no robust framework which can be used to identify and quantify risk associated with inadequate railway drainage. Such a framework would provide drainage asset managers with a tool for managing and prioritising the maintenance of railway drainage assets at greatest failure risk. This research addresses this gap by developing risk informed approach.

Accordingly, the novelty of the research concerns the development of fault charts to identify and quantify the likelihood of railway drainage failure. The novelty of the research is associated with the development of fault charts, a social-economic impact model, and an integrated model to quantify railway drainage failure risk. The fault charts are developed to identify the causal events associated with drainage failure and quantify the probability of occurrence of the risks. The cost-model has been formulated to appraise the socio-economic impacts associated with poor track drainage risk. Thereafter, both risk parameters (i.e. probability and impacts) are used within an integrated model to provide risk values for the appraisal of drainage maintenance, so that appropriate maintenance action may be undertaken or planned. . Furthermore, as far as the researcher is aware, this is also the first time in the railway drainage domain that an engineering model in the form of a fault chart has been combined with a cost-model

1.6 Thesis Structure

This thesis is structured as ten chapters as follows:

Chapter 1 (this chapter) provides an introduction to the research subject. This comprises the background, defines a problem statement, and presents the aims and objectives of the research, along with the benefits and novelty of the research.

Chapter 2 summarises the findings from the review of the literature on the drainage of ballasted railway tracks.

Chapter 3 summarises findings from the literature review of risk assessment approaches. It includes a section justifying the selection of risk assessment techniques used to develop the risk-informed framework.

Chapter 4 describes the key components of the research methodology; namely a literature review and building the risk-informed framework based on a theoretical concept, model development, and case studies. Moreover, this chaper presents the development of the engineering and cost models. The engineering model is developed to identify the causal factors of drainage failure and to quantify the probabilities of the occurrence of this drainage failure. The cost-risk model is developed to quantify the impact of drainage failure. Thereafter, the engineering and cost models are merged into an integrated model to quantify risk values. This chapter also describes a cost benefit analysis (CBA) approach for the appraisal of drainage maintenance of ballasted railway track.

Chapter 5 presents the data for case studies which consists detail information of the selected sites, availability of drainage risks based on expert elicitation, and range of frequency occurrence of the identified risks.

Chapter 6 examines the developed engineering model which relates causal (risk) events and failure modes with poor drainage of railway ballasted track; and furthermore, demonstrates the applicability of the model through three case studies taken from the UK's railway network.

Chapter 7 quantifies the potential social-economic impacts (cost) model of the case studies using data obtained from the selected sites. The impacts comprise: cost components such as unplanned maintenance, time delays, additional travel spending for the passengers, alternative travel mode (usually bus) transfer, property (other than farming) damage, farming land damage.

Chapter 8 brings the case studies together and analyses the results of the two models which are integrated into one engineering–cost model.

Chapter 9 presents a discussion of the research.

Chapter 10 draws conclusions from the research and suggests recommendations for further research.

2 DRAINAGE OF BALLASTED RAILWAY TRACK

2.1 Introduction

The integrity and performance of a ballasted railway track substructure relies upon its drainage systems to remove water adequately (Selig and Waters, 2004; Tzanakakis, 2013; Li *et al.*, 2015; Usman *et al*., 2015). Properly functioning railway track drainage systems should intersect, divert and remove water from the track substructure. The railway track drainage is typically comprised of subsurface and surface drainage features. Subsurface drainage consists of components such as pipes, catchpits and manholes, whereas surface drainage includes channel drains and ditches, outfalls and culverts (Li *et al*., 2015; Tzanakakis, 2013). According to Li *et al*. (2015), water may infiltrate into the railway track from three main sources i.e. directly from rainfall or snow melt, runoff from surrounding land and ground water which flows through the adjacent land to the track (see Figure 2.1)

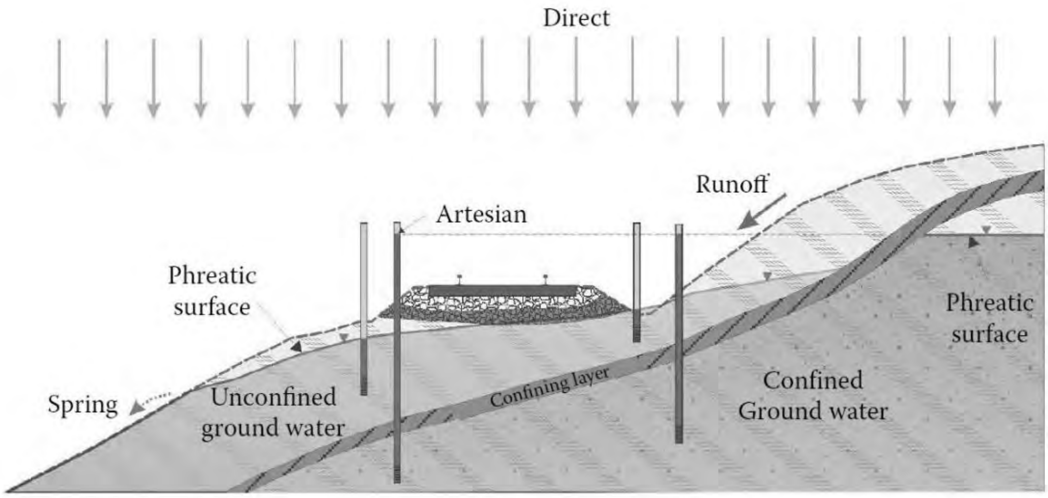

Figure 2.1 Sources of water in ballasted railway track (Li *et al*., 2015)

A variety of types of track failure in a variety of forms (e.g. wet bed, ballast pocket, cess heave) may occur as a result of poor drainage. These failures are generally caused by blocked or collapsed drains, issues with the filter media within drains and drainage capacity problems

(Network Rail, 2010; Tzanakakis, 2013; Li *et al*., 2015). The resulting track failures may result in unplanned railway track maintenance and the costly imposition of train speed restrictions and delays (DfT, 2014; Usman *et al*., 2015;).

In order to provide an insight into how such poor railway track drainage can occur and its direct and indirect impacts, this chapter presents a review of the literature on the typical ballasted railway track subsurface and surface drainage components and the causes and consequences of inadequate track drainage. Section 2.1 introduces the role of components of railway track drainage in removing water adequately. Section 2.2 drainage asset management. Section 2.3 and 2.4 describe the function of subsurface (i.e. pipe, catch pits and manholes) and surface drainage (i.e. channel drains and ditches, outfalls, culverts) and describe issues associated with the failure of these components. Section 2.5 examines the causes of failure of track drainage components associated with blocked drains, collapse drains, drainage filter media failure and capacity problems. Section 2.6 explores the potential impacts of drainage failure. Section 2.7 addresses the uncertainty of drainage performance (and therefore track performance). Section 2.8 provides a summary of the chapter.

2.2 Drainage Asset Management

2.2.1 Introduction

In many countries with mature railway drainage assets, which are ageing or deteriorating at unexpected rates, the ongoing demand and efforts to maintain these assets are challenging due to the paucity of funding and the availability of natural resources. Consequently, there is a trade-off between maintenance expenditure and asset condition, and the limited resources available need to be prioritised to carry out suitable interventions. Hence, some issues need to be considered, such as types, locations, and conditions of drainage assets; potential interventions (i.e. repairing, renewal); and consequences of defective or failed assets (Network Rail, 2010; DfT, 2014; Spink *et al.*, 2014; Usman *et al.*, 2017).

In order to address the above issues, asset management, which is seen as a structured, long-term approach to deal with the above issues, can be used to optimise assets' performance and investment. According to BSI (2008), asset management has been defined as the systematic, co-ordinated activities and practices which involve a sustainable effort of management to ensure the optimal performance of assets, risks and expenditures to be considered for achieving its organisational strategic plan.

2.2.2 Asset management hierarchy

In general, there are three levels in asset management, as shown in Figure 2.2; these consist of operational planning, tactical planning, and strategic planning levels. The lowest level, operational planning, is devoted to operational plans that generally comprise detailed implementation and information over a short-term period (1-3 years); these include the organisational direction plans which are provided as practical guidance rather than visionary elements. The mid-level, tactical planning, concerns the application of the detailed asset management process, procedures, and standards; in respect to resource (e.g. natural, physical, financial) allocation planning to meet the defined levels of service and achieve the intended strategic goals (Kirtsis *et al.*, 2009; Spink *et al.*, 2014). The highest level, strategic planning, involves adopted asset management which provides a framework to integrate with organisational strategic plans to perform the asset management strategy and achieve specific asset management objectives, targets, and plans (Spink *et al*, 2014; IPWEA, 2018).

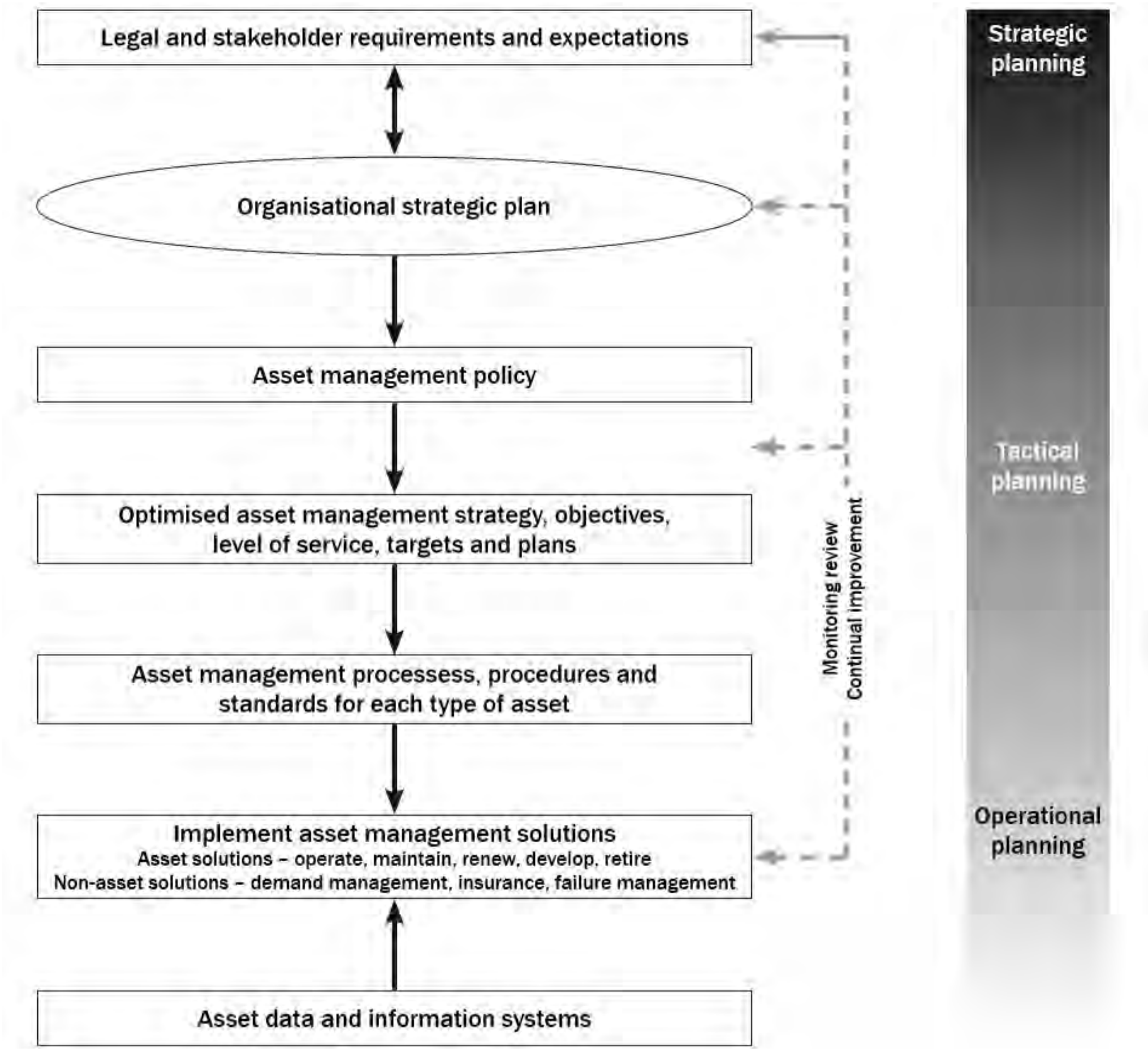

Figure 2.2 The hierarchy of asset management (Spink *et al*., 2014)

2.2.3 Asset knowledge

Asset knowledge is essential in the decision-making process of drainage assets, to provide reliable information for maintaining the drainage assets appropriately. Current estimates of the quantities of the various types of drainage assets of major infrastructure owners in the UK are presented in Table 2.1 and Table 2.2. Despite growing attention and effort to improve the knowledge of drainage assets, especially railway drainage, there are some issues with these records and the gathering of the data which need to be considered; they are as follows (Network Rail, 2010; 2018; Spink *et al.,* 2014):

- Monitoring the condition using CCTV (closed circuit television) is often costly; there is an insufficient database for digital data.
- Much of the survey data is not designated geographically and may not be centrally compiled.
- The data concerning the assets' condition is time limited. For example, condition information from surveys conducted five years ago might not suitable to represent the current condition of the assets. In the case of structural defects, if not immediately addressed, the asset may have excessively deteriorated or collapsed.
- There is a lack of relevant national standards (mainly originating from the water and waste water industry), particularly for assessing drainage asset information, thus specific standards are still being developed. For example, the draft document of the drainage inspections (NR/L2/CIV/005 Module 4) as part of the standard for railway drainage in the UK, - Network Rail (2018) Draft: Drainage Inspections, was released by Network Rail in 2018; whereas most parts of the standards are still based on the NR/L3/CIV/005: Railway Drainage Systems Manual (2010).

Table 2.1 Estimated quantities of drainage assets by major UK infrastructure owner (Spink *et al.*, 2014)

Asset group	Highways Agency*	Network Rail	LU	TfL
Chambers	350 000	155 000	11 000	9 500
Gullies	300 000	N/A	N/A	45 000
Inlets and outlets	100 000	21 000	Unknown	> 1000
Pipes and culverts	16 000 km	3800 km	320 km	750 km
Filter drains	11 000 km	30 km	Unknown	< 50 km
Ditches and channels	7500 km	3200 km	250 km	< 50 km
Informal drainage	Unknown	Unknown	Unknown	Unknown
Ponds	1000	350	4	20
Miscellaneous including pumps	2500	Unknown	>1000	Unknown

Table 2.2 UK infrastructure asset owner's estimate of drainage knowledge (%) (Spink *et al.*, 2014)

Organisation	Approximate network coverage of drainage asset knowledge in 2013			
	Inventory		Condition	
	Historic records	*Field surveys*	*Asset level*	*Defect level*
Highways Agency*	95	85	15	15
Network Rail	30	100	60	15
LU	15	85	80	80
TfL Streets	10	3	3	2

Note

- *the Highways Agency network represents only about two per cent of the national road network, the remainder being local authority (LA) maintained; however, collective statistics for LA roads are not currently available.
- LU : London Underground
- TfL : Transport for London

2.2.3.1 Condition appraisal

In order to determine the physical condition of drainage assets, historical data which was obtained from inspection and monitoring, can be used to provide an appraisal of residual life. The output of the condition appraisal can be used as an input of a risk-informed approach, to facilitate an assessment of potential risks and allocate the scarce maintenance resources properly.

2.2.4 Asset performance

To meet a required performance, railway drainage assets are designed and constructed based on a modern standard; whereas older drainage assets may not have been formally designed. The required performance may periodically need to be reassessed to deal with physical or operational changes such as changes in catchment size or use, higher volumes of traffic or extreme weather. However, the performance gap, which is defined as the difference between the required and the actual performance, may occur due to some of the following causes (Spink *et al.*, 2014):

- Component (material) deterioration
- Physical damage, e.g. root damage
- Changing design standards

2.2.4.1 Intervention criteria

As mentioned above, a performance gap caused by various uncertainties may lead to defective or failed drainage assets, and to various adverse impacts such as rail disruption or speed restrictions. It is therefore a risk-informed approach which may be suitable to determine the intervention criteria, as it would take into consideration the impact of potential failures of drainage asset

2.2.4.2 Maintenance, refurbishment, and renewal

Maintenance, refurbishment, and renewal may be required to improve the performance of drainage assets. Maintenance involves simple techniques to be conducted when a problem occurs, e.g. blockages that inhibit water from draining properly. The types of maintenance are as follows (Spink *et al*., 2014):

- Routine (cyclical) maintenance: scheduled work, such as cleaning catchpits, required on regular basis.
- Preventive (non-cyclical or planned) maintenance: small-scale targeted work that does not require a change in the material of drainage assets, e.g. debris clean out, vegetation overgrowth. It is scheduled following an inspection or condition assessment and can be periodically required
- Emergency (unplanned) maintenance: this is reactive work conducted to deal with incidents associated with flooding or pollution. Repairs must be carried out rapidly while still considering safety and operational matters.

When the drainage assets collapse or are defective due to heavy sedimentation, refurbishment or renewal is likely to be carried out. These are as follows:

- Refurbishment (also termed repair, remediation, rehabilitation, or heavy maintenance): non-routine work to address significant defects in the drainage asset to restore, as far as possible, the as-built performance, e.g. pipe relining, ditch re-profiling, catchpit re-pointing (Spink *et al*., 2014, p 23).

- Renewal (also termed replacement): where the asset is beyond its useful life or alterations to other infrastructure assets change to the boundary conditions, e.g. increased runoff, the asset may be replaced entirely either like for like or with a newly designed system (Spink *et al*., 2014, p 23).

2.3 Drainage of Ballasted Railway Track

Drainage of railway ballasted track consists two main types namely subsurface and surface track drainage (Network Rail, 2010; Tzanakakis, 2013) Figure 2.3 shows the components of subsurface and surface drainage and their position in ballasted railway track.

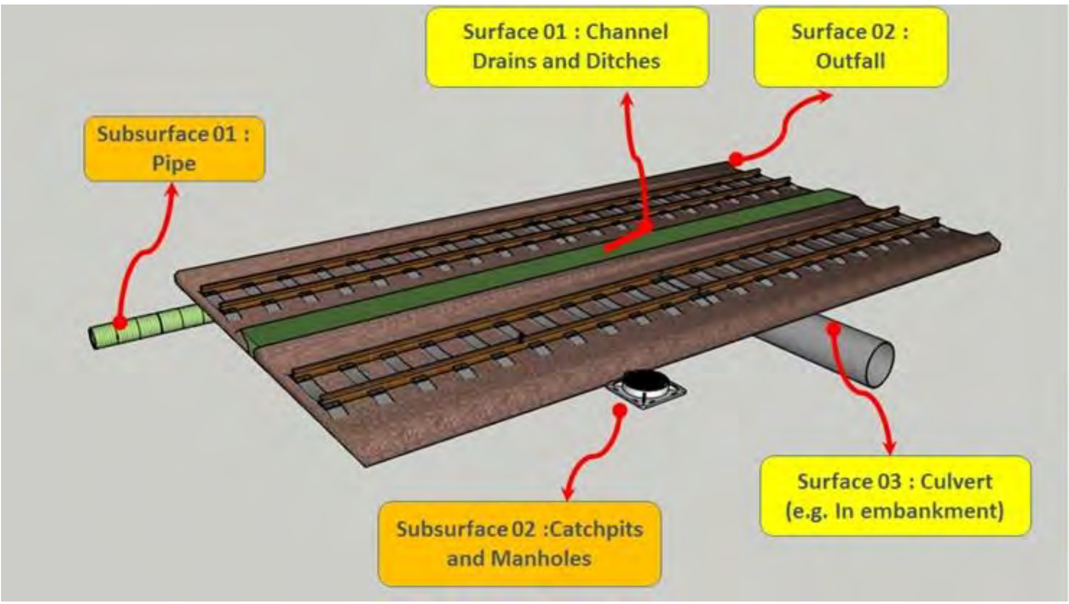

Figure 2.3 Illustration of track drainage components (i.e. subsurface, surface) in a railway track support system (Usman *et. al*., 2017)

2.4 Subsurface Track Drainage

Subsurface drainage is used to drain water from the railway track where adequate surface drainage cannot be provided due to space or outlet restrictions (e.g. cutting slope) (Li *et al*., 2015; Tzanakakis, 2013). Subsurface drainage is intended to:

- Dissipate water from the railway track bed (see Figure 2.3)
- Lower the water table (see Figure 2.5);
- Drain water from cuttings (see Figure 2.6).

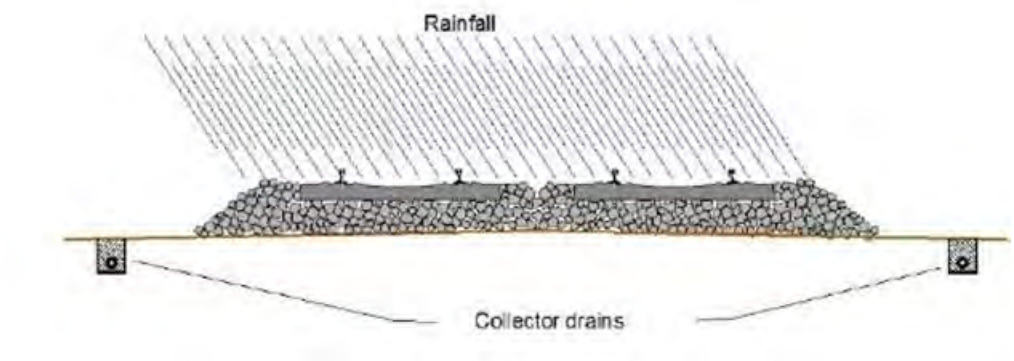

Figure 2.4 Collection of water seeping into the ballast structure (Tzanakakis, 2013

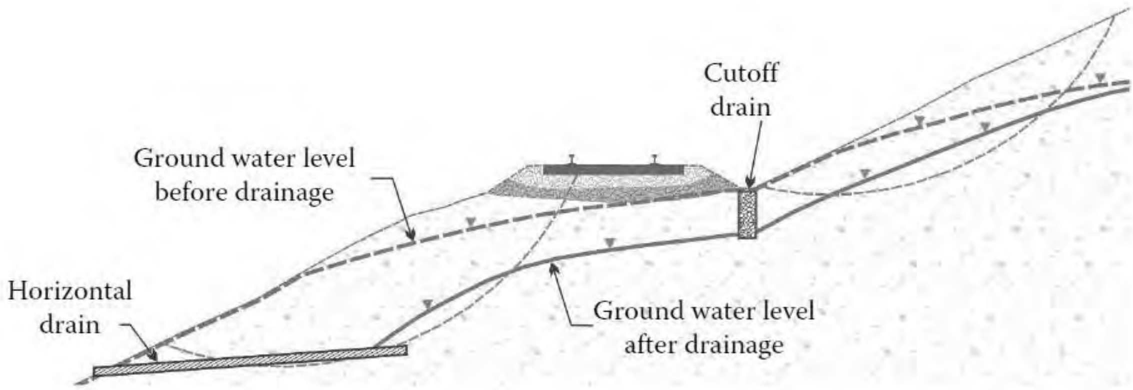

Figure 2.5 Example of track drainage lowering the existing water table, source Li *et al*. (2015)

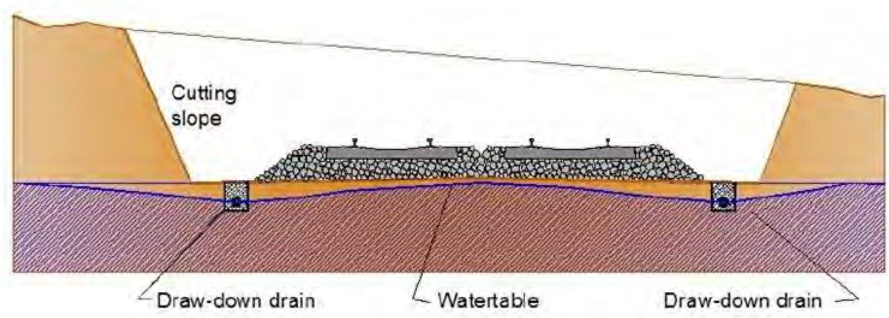

Figure 2.6 Pipe as a collector drain at cutting slope in a railway track section, source Tzanakakis (2013)

Subsurface track drainage has two components (Network Rail, 2010; Tzanakakis, 2013):

- Pipes;
- Catch pits and manholes.

2.4.1 Pipes as collector or carrier drains

As a collector drain, pipes are designed with open joints and / or perforations and are positioned longitudinally along to the track to collect water from the surrounding land (see Figure 2.7 and Figure 2.8). Pipes also can be act as a carrier or cross drain, in which water drains from a collector drain to another in a horizontal direction through these pipes (see Figure 2.9). Pipes are usually installed below the surface of the ground and should be laid at an adequate uniform gradient to ensure uniform fall and appropriate discharge. The suitable depth for installing pipes is 500 mm or more. In the UK pipes usually contain granular filter material and an associated permeable geotextile (Network Rail, 2010). This standard composition is designed to reduce silting while still allowing water to infiltrate into the filter layers. Figure 2.7, Figure 2.8, and Figure 2.9 show the typical forms of pipes drains (Network Rail, 2010)

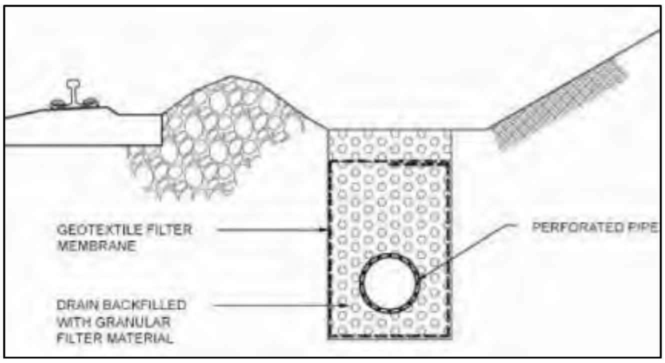

Figure 2.7 Typical piped cess collector drain, source Network Rail (2010)

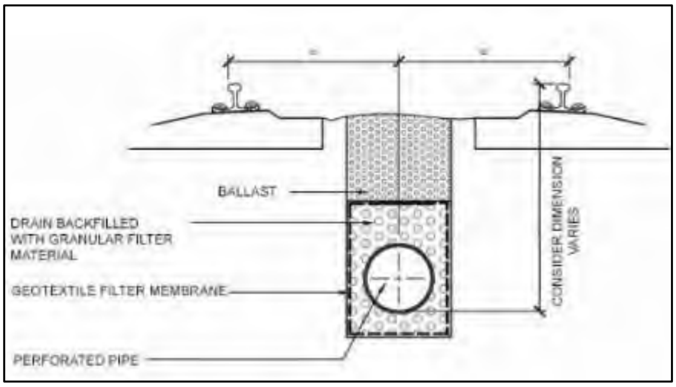

Figure 2.8 Typical piped drain (Network Rail, 2010)

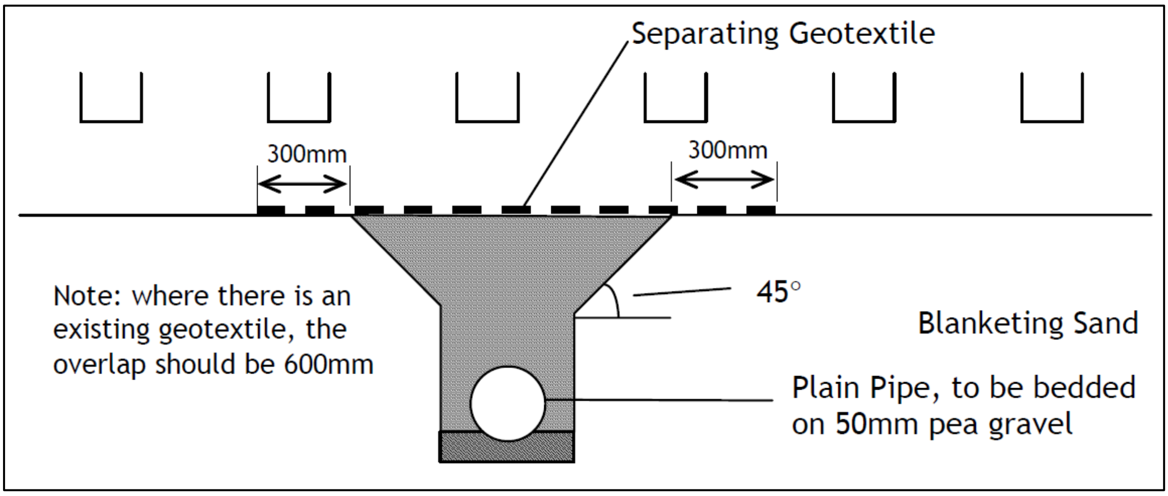

Figure 2.9 Typical piped cross drain (Network Rail, 2010)

2.4.1.1 Technical parameters for pipe drains

In the UK the discharge capacity, Q, of a pipe , is determined using the Darcy- Weisbach and Colebrook and White equation as follows (Network Rail, 2010):

$$Q = \frac{\pi D^2}{4}[-2\sqrt{2gDS}\,log\left(\frac{k}{3.7D} + \frac{2.51v}{D\sqrt{2gDS}}\right)] \qquad \text{Eq. 2.1}$$

Where D is the internal diameter of pipe in metres, S the hydraulic gradient, K the hydraulic roughness (mm), g is the acceleration due to gravity (g = 9.81 m/s^2), and v is the kinematic viscosity of water (v=1.14x10-^{6} m^2/s at 15◦C).

Equation 2.1 shows that the hydraulic roughness associated with pipe material and gradient are important in providing an adequate velocity for self-cleansing (see Appendix 5.1). i.e. an adequate velocity is required to mitigate a silting risk in the pipe. Network Rail (2010) suggests that the ideal gradient should be equal to or greater than 0.0033 (1 in 300) whereas the minimum is 1 in 500. In terms of maintenance, a gradient of 0.067 (1 in 150) can be performed as self-cleansing pipe (Network Rail, 2010).

Equation 2.1 is used to determine the flow in the pipe with the assumption of full discharge. Otherwise, for the case of partially full pipes, the flows can be calculated by multiplying the Q value by the coefficient of proportional pipe depth (see Appendix 5.2).

In terms of pipe drain installation below switches and crossings (S&C), the particular requirements recommended in the UK are as follows (Network Rail, 2010):

- A minimum 150 mm cover is required to cover pipes or the collars of pipe sockets where installed;
- A desirable depth for the invert is 150 mm under the bottom of ballast or sand blanket, if applied;
- The maximum depth of the invert is 1050 mm below ground level. The depth can be deeper in certain cases, such as in long cuttings with shallow gradients where the pipe can function as a carrier drain;

- The diameter of the collector drain should be adequate to allow water to flow along the track length, whereas the diameter of the carrier drain is designed to carry water from the surrounding catchment area;
- A minimum depth of 1,000 mm from the rail level to the top of a pipe collar or surround pipe surface (e.g. concrete) is required for drains under the track.

2.4.1.2 Geotextiles layer as filter for pipes

A geotextile layer can be installed around a pipe to prevent fines' infiltration and to maintain water flow through the pipe. The geotextile should be tied into the track support system (see Figure 2.6). However, in such occasions, water cannot enter the geotextile layer due to clogged with fines which then resulting hydraulic surcharging. This can be indicated when pipe condition is clean, but water is inhibited from passing into the geotextiles layer (Network Rail, 2010). Considering all of the above parameters, it seems that the diameter, depth, gradient, geotextile filter material and water discharge condition (i.e. full, part) of a pipe drain governs its ability to function properly.

The literature describes a number of causes of the improper functioning of pipes. These are as follows (Network Rail, 2010; Tzanakakis, 2013):

- Siltation in pipes;
- Accumulation of debris in pipes;
- Filter media clogged;
- Uneven pipe gradient due to a disturbance of the formation (i.e. subgrade);
- Inadequate capacity of catchment runoff;
- Capacity reduced by ingress of ballast or silt, crushed pipes, poor pipe alignment;
- Root intrusion;
- Pipe structural defects;

- Poor gradient or pipe alignment;
- Inadequate pipe capacity;
- Pipe deterioration;
- Ponding at inlet
- Scour and erosion around or behind inlet and outlet.

2.4.2 Catchpits and manholes

A catchpit is an empty chamber built into a drainage system to trap silt and other debris carried along the drainage pipe by water (see Figure 2.9). Catchpits play a crucial role in preventing the build-up of material that can cause pipe blockages, resulting in backing up of water in the drainage system, which can result in localised flooding. For maintenance activities a chatchpit chamber can be accessed for water jetting or debris removal. This chamber should be maintained on a regular basis to ensure it is kept clear and works properly. It is also substantial to maintain its cover. The uncovered or damaged catchpit can be infiltrated by the ingress of ballast or debris that may lead it to function inadequately (Defence Estate, 1997; Network Rail, 2010;).

A manhole is an access point to subsurface railway drainage. The presence of manhole allows the subsurface pipes to be inspected, surveyed, unblocked, cleaned, or repaired. (Network Rail 2010; Spink *et al.,* 2014; UKDN, 2018), Figure 2.11 shows typical precast concrete manhole.

The following guidelines are used to determine when a catchpit is required (Network Rail, 2010) :

- For manual maintenance activities, when the chamber is likely to be maintained manually, a 30 m interval is likely to conduct;

- To allow for jetting and other mechanical maintenance activities, a 60 m interval is recommended. The interval can be extended up to 100 m under special permission from the railway route asset manager;
- Where the change of direction of the track is greater than 15°;
- When there is a stepped change of the invert level;
- At all pipe junctions including the junction of pipe drains and channel drains;
- At a connection to or from other drains (e.g. earthwork drain).

The literature suggests the following common problems may contribute to the performance of catch pits and manholes (Network Rail, 2010):

- Silting;
- Damaged or missing covers;
- Poor ballasting practices;
- Damage by ground movement
- Damage by on track plant;
- Debris infiltration;
- Structural defects of catchpits and manholes;
- Insufficient depth;
- Water level above invert;
- Inadequate depth level;
- Inappropriate porous material for backfilling and prevent the silting process;
- Damaged cover;
- Lack of silt trap.
- Spoil tipping

Figure 2.10 shows a newly installed catch pit and Figure 2.11 shows a typical catchpits in the track structure.

Figure 2.10 Typical catchpits (Network Rail, 2010)

Figure 2.11 Typical precast concrete manholes (Precon, 2017)

2.5 Surface Track Drainage

Surface track drainage is used to collect surface water from the surrounding railway track and to remove water seeping out of the track structure (Tzanakakis, 2013). Surface track drainage comprises of channel drains and ditches, outfalls and culverts

2.5.1 Channel drains and ditches

Channel drains are installed at a specific location. Channel drains are usually lined with grass, a geotextile membrane, stone or with pre-cast concrete slabs (Tzanakakis, 2013). Unlike a channel drain, a ditch is constructed in a relatively simple form, usually without a lining. The ditches are typically trapezoidal in cross-section with a variety of angle of side slopes from a shallow "v" to vertical (Network Rail, 2010).Figure 2.12 shows typical channel drains in the cess. These drains are located at subgrade (formation) level at both sides of the track and are designed to capture water that dissipates from the ballast layers along the railway track (Tzanakakis, 2013).

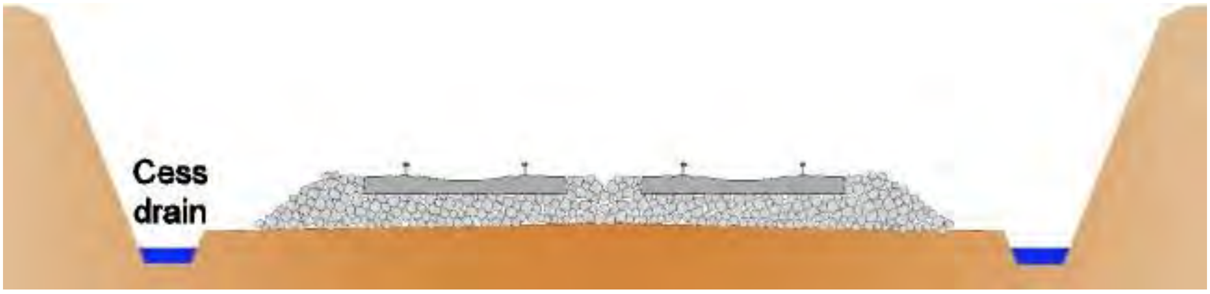

Figure 2.12 Cess drains typical location (Tzanakakis, 2013)

Figure 2.13 shows a typical channel drains as a catch or top drains. These drains are located at the top of a cutting slope or at the bottom of an embankment and function to intercept water from the surrounding land before it reaches the track (Tzanakakis, 2013). Figure 2.14 shows a typical ditch surrounding railway track.

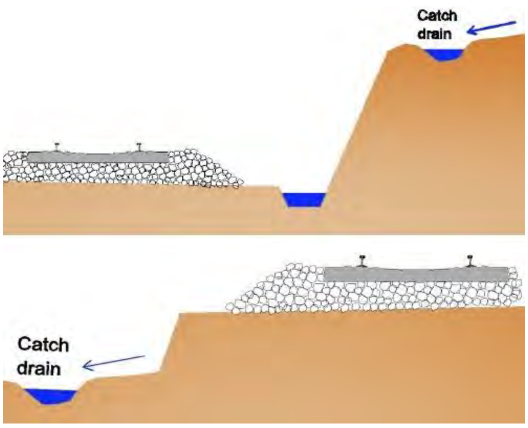

Figure 2.13 Typical catch drains (Tzanakakis, 2013)

Figure 2.14 Typical ditch as a toe drain (Network Rail, 2010)

As illustrated above, proper channel drains and ditches are used to collect water from the surrounding area and carry it to the watercourse. However, their performance may be negatively affected by vegetation overgrowth, debris, spoil tipping, frequent siltation, bank instability, scour, changes in gradient, ponding, burrowing animals and the deterioration of their constituent materials (Tzanakakis, 2013; Network Rail, 2010).

2.5.2 Outfall

An outfall is as an outlet point for the discharge of water from the drainage system. Often the outfall drains into an adjacent watercourse or a river. The construction of an outfall incorporates the following (Network Rail, 2010) :

- Bed and or bank protection including a cascade, apron, headwall or training wall to absorb or reduce the kinetic energy of water discharge;
- Flow vortex device for controlling the water flow;
- A flap valve which is used as a non-return valve to control water flow from flooding or flood surcharge.

A typical construction of an outfall is illustrated in Figure 2.15 and a flap valve is shown in Figure 2.16.

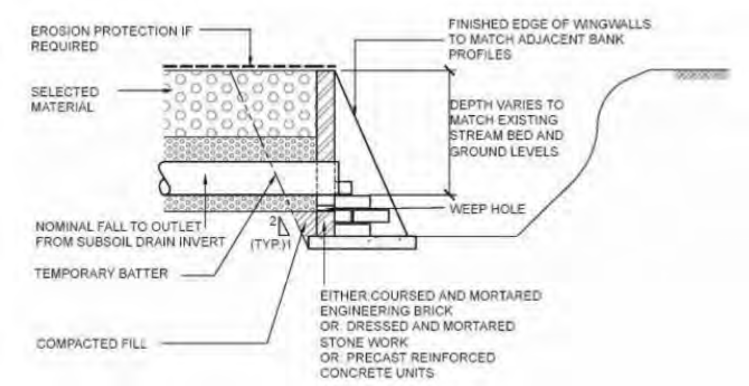

Figure 2.15 Masonry headwall to outfall (Network Rail, 2010)


Figure 2.16 Flap valve (Network Rail, 2010)

According to Network Rail (2010), an outfall may be prone to the following problems :

- Scour below the bed;
- Structural damage on its bed or bank protection parts (i.e. cascade, apron, headwall);
- Seized flap valve;
- Blockage;
- General deterioration.

2.5.3 Culvert

A culvert consists of three main parts – an inlet, a conduit and an outlet. The culvert can be formed as single or multiple barrels with various shapes (i.e. circular, rectangular, arched or ovoid in section) and they can be constructed from brick, stone masonry, concrete or steel (NR, 2010). Figure 2.17 shows an example of a culvert which has been installed over awatercourse.

Figure 2.17 Watercourse passing under a track through a culvert (Network Rail, 2010)

As illustrated in Figure 2.17, the culvert is often used to bridge a watercourse. The adjacent area may therefore have potential subgrade or earthworks softening issues due to the prevailing topography, geology and geological history, poor original embankment construction practices, and because water can be diverted toward the culverts (Tzanakakis, 2013).

The literature suggests that the performance of the culvert can be affected by (Network Rail, 2010):

- A defective trash screen;
- General deterioration;
- Scour;
- Structural defects;
- Change in upstream catchments (leading to changes in water flow through the culvert);
- A smaller outlet than inlet.

2.6 Failure Modes of Railway Ballasted Track Drainage

Based on the above overview of railway track subsurface and surface drainage failures have been categorised into: blocked drainage (2.6.1), collapsed drainage structure (2.6.2), clogged filter media associated (2.6.3) and inadequate capacity associated (2.6.4). These may incorporate various potential problems of drainage of railway ballasted track as causal events (see Sections -2.5).

2.6.1 Blocked drainage

For sub-surface drainage, blocked pipes, catchpits and manholes may be considered to have failed when their capacity is reduced below a specified level.

Pipes tend to become blocked due to the accumulation of silt (silting pipe), poor pipe alignment or by vegetation / root intrusion. According to Network Rail standards, a pipe is considered to be partially blocked when its capacity reduction is less than 50 % but more than 25%, and fully blocked when its capacity is reduced to zero (Network Rail, 2010). Blockages tend to occur when catch pits and manholes become blocked due to missing or ineffective covers or lack of a silt trap. These circumstances allow surrounding debris to accumulate within the structure to a variety of depths e.g. below the level of the bottom encompassed drainage. In terms of railway track surface drainage, blockages occur in channel drains and ditches, culverts and outfalls.

According to Network Rail standards, channel drains and ditches are considered to be partially blocked when their capacity is less than 50 % of their designed maximum but more than 25%, and fully blocked when their capacity is reduced to zero (Network Rail, 2010). A number of processes can contribute to drains and ditches becoming blocked including, bank erosion and collapse, overgrown vegetation, frequent siltation, a change in gradient and pondi (Network Rail, 2010; Tzanakakis, 2013). Network Rail standards separate culvert failure into two categories associated with partial blockage when the capacity reduction is less 50% or less and, fully when a culvert's capacity is reduced to zero. For the the outfalls, blockage is typically associated with a seized flap valve (Network Rail, 2010).

2.6.2 Collapsed drainage structure

The collapse of railway track subsurface drainage is associated with pipes, catch-pits and manholes (Network Rail, 2010). A pipe is considered to have partially collapsed according to Network Rail standards when a major part of the pipe has cracked or deformed but the collapse is less than one pipe length. A pipe is considered to be completely collapsed when a structural failure occurs on more than one pipe length (Network-Rail 2010). The collapse of subsurface drainage infrastructure can be caused by a number of factors including material corrosion over time, damage by ground movement or by track plant (i.e. track vehicles). It can often be exacerbated by train induced dynamic loads, particularly where the infrastructure is in close proximity to the rail.

For surface drainage the collapse of channel drains and ditches can be caused by bank instability, the removal of vegetation, scour or burrowing animals. The collapse of culverts can be due to general deterioration, scour, or overloading which causes overstressing (Tzanakakis, 2013). The collapse of outfalls can be associated with general deterioration over time or scour (Network Rail, 2010).

2.6.3 Clogged filter media

In the construction of the railway trackbed a filter layer is often placed as a separator between the sub-ballast and subgrade or granular layers to both filter water sideways and to prevent the upward migration of fines. However, the layer can be become clogged through the accumulation of fines on the surface of the geotextile. This in turn may inhibit water flow into the filter layer. Although the pipes and catch-pits may be clear, a clogged filter layer will cause water to remain on the track surface or to saturate the ground (Network-Rail 2010).

2.6.4 Inadequate capacity (hydraulic surcharging)

The problem of capacity failure, in terms of sub-surface drainage components is associated with the components being overwhelmed by the flow of water, even though they are in good working order (Network Rail, 2010). This issue can be caused by a change of gradient (poor fall or gradient) due to subgrade settlement or the disturbance of the formation, inadequate pipe capacity for the size of catchment runoff and insufficient depth of the catch-pits and manholes.

For surface drainage components the capacity problem is similar to that of subsurface drainage (Network Rail, 2010). However, in some cases the causes may be different. The capacity problem in channel drains, ditches and culverts are most often related to an inadequate gradient, inadequate pipe capacity for the catchment, accelerated runoff due to land use change within the catchment area, changes to upstream drainage conditions and extreme climate events. Incapacity issues associated with the outfall are as those above, albeit an inadequate gradient is less of an issue. Issues of capacity may increase with time as the effects of climate change are increasing the duration and intensity of rain storms and the frequency of extreme weather events.

2.7 Cost Impacts of Failure Modes Associated with Poor Drainage of Railway Ballasted Track

This section presents the potential cost impacts of failure modes associated with poor drainage of railway ballasted track. The potential cost impacts can be regarded as being associated with unplanned maintenance (2.7.1), delay time (2.7.2), bus transfer (2.7.3), additional daily travel times for passengers (2.7.4), property (other than farming) damage (2.7.5), farming land damage (2.7.6).

2.7.1 Unplanned maintenance cost

The direct physical impacts of poor drainage are (Li *et al.*, 2015; Network Rail, 2010; Tzanakakis. 2013):

- Wet bed occurrence (see Figure 2.18);
- Mud pumping (see Figure 2.19);
- Ponded water adjacent to the railway track (see Figure 2.20);
- Track geometry faults (see Figure 2.21);
- Infiltration and embankment failure (see Figure 2.22).

Figure 2.18 Wet beds (Network Rail, 2010)

Figure 2.19 Mud pumping (Network Rail, 2010

Figure 2.20 Water ponded in ditch and wetland plants (Tzanakakis, 2013)

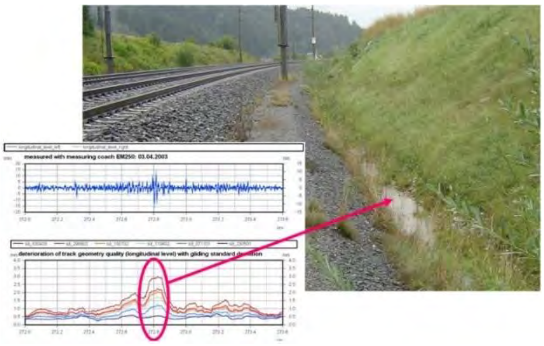

Figure 2.21 Track geometry faults due to poor drainage (Tzanakakis, 2013)

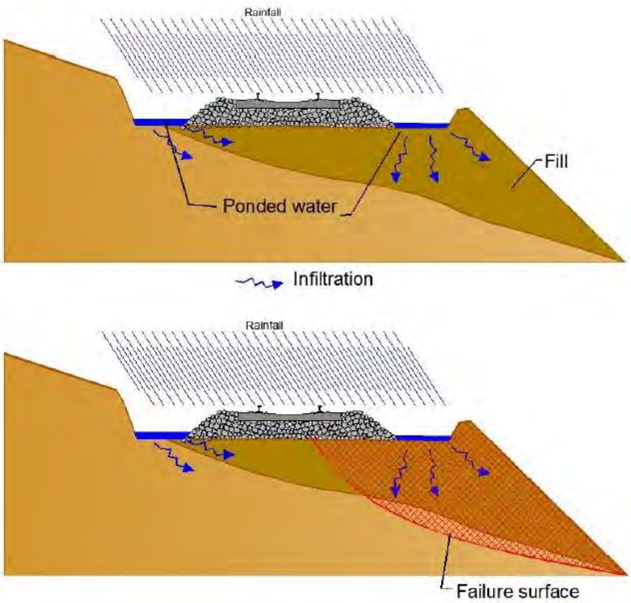

Figure 2.22 Infiltration and embankment failure resulting from poor drainage (Tzanakakis, 2013)

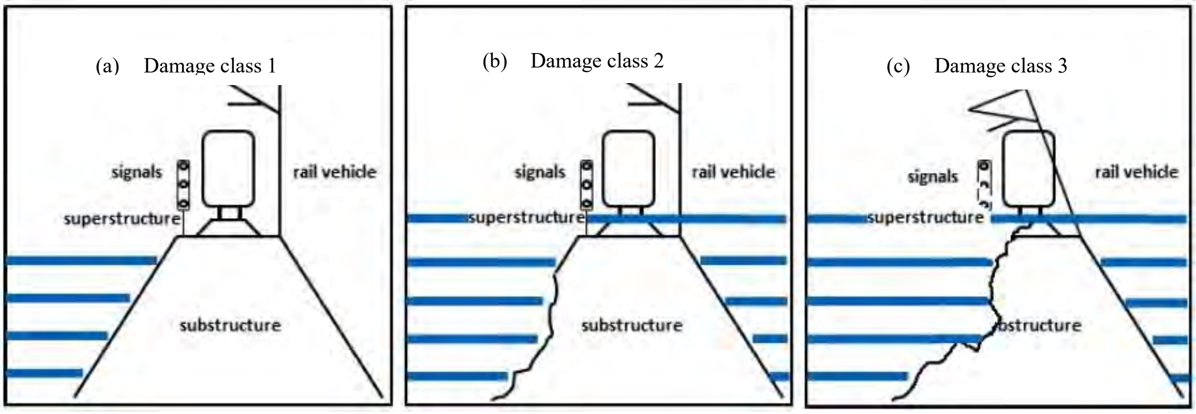

Figure 2.23 Damage classification scheme (Kellermann, 2015

The above issues may lead to costly unplanned maintenance of the railway track substructure The cost of three types of embankment damages due to flooding events in some parts of the Austrian Northern Railway has been examined by Kellerman *et al.* (2015). Figure 2.23 shows their damage classification scheme. The related costs are given in Table 2.3.

As indicated previously in Table 2.3, the embankment damage class 3 is estimated as the costliest type in the Austrian railway.

Table 2.3 Standard repair costs per 100m segment of a double tracked railway standard cross-section (after Kellermann, 2015)

	Damage class 1	Damage class 2	Damage class 3
Cost per 100 m segment	EUR 11700	EUR 135550	EUR 702200

2.7.2 Delay time costs

A Travel delay costs may occur as direct or indirect results of drainage failure. For example, poor drainage may lead to localised flooding and the imposition of speed restrictions, whereas poor drainage which leads to softening of the subgrade can eventually lead to a similar outcome if it causes the track quality to fall below safety standards. Excessive water laying on the surface of railway track infrastructure can cause severe disruption to railway operation. In the UK, the impact of a storm event on 28 June 2012 has been examined by Jaroszweski *et al*. (2015). The event was mostly associated with heavy rainfall and flooding in some parts of the country, resulting in 10,000 delay minutes and speed reductions across the UK railway network. Moreover, using the assumption £76.06 per delayed minute of a train, the cost of delay minutes in the incident date was estimated as £760,600 (Jaroszweski *et al*., 2015)

2.7.3 Bus transfer costs

An incident on the part of a railway network due to track problems may lead to the closure of the railway line for a period of time whilst safety checks, emergency repairs or non-emergency scheduled maintenance repairs are carried out. (e.g. poor drainage -. Softening of subgrade -> poor track geometry -> ballast realignment (tamping)). In many cases, passengers of the affected train services are transferred to buses to continue their journey (Jaroszweski *et al*., 2015). In the UK, the operating cost of a bus in the metropolitan and country areas for 2004/2005 until 2015/2016 periods are given in Table 2.4 (DfT, 2017).

Table 2.4 Operating cost per vehicle kilometre (2004 - 2017) on local bus services by metropolitan area status and country: Great Britain outside London, annual from 2004/05 (DfT, 2017)

								Pence
Year		London[3]	English metropolitan areas	English non-metropolitan areas	**England outside London**	**Scotland**	**Wales**	**Great Britain outside London**
2004/05	r	:	137	124	**129**	**114**	**99**	**125**
2005/06	r	:	140	130	**134**	**111**	**115**	**129**
2006/07	r	:	155	146	**150**	**125**	**130**	**144**
2007/08	r	:	171	151	**158**	**127**	**135**	**151**
2008/09	r	:	179	158	**166**	**145**	**147**	**161**
2009/10	r	:	189	166	**175**	**150**	**140**	**169**
2010/11	r	:	194	166	**176**	**158**	**136**	**171**
2011/12	r	:	194	177	**183**	**178**	**158**	**181**
2012/13	r	:	198	180	**187**	**181**	**170**	**185**
2013/14	r	:	202	186	**192**	**181**	**174**	**189**
2014/15	r	:	211	189	**197**	**183**	**175**	**194**
2015/16	r	:	210	197	**202**	**179**	**179**	**197**
2016/17		:	216	196	**204**	**184**	**190**	**200**

[1] Not adjusted for inflation.
[2] Operating cost includes administration and depreciation.
[3] Buses in London operate under a different regulatory model to the rest of the country, and comparisons on an operating costs basis between London and the rest of the country would have little meaning. London figures are therefore excluded from this table.
[r] Minor revisions have been made to earlier years data.

2.7.4 Additional daily travel cost for passengers

A drainage related incident that leads to track closure may have an additional cost impact on the daily travel costs of passengers. For suburban fares (single) the cost for the European countries and UK is presented in Figure 2.25. Abbreviations in Figure 2.24 represent the name of a country, e.g. AT for Austria and its capital city, Vienna. (see Abbreviations). These show the cost benchmark in countries across Europe in 2016 subject to interurban trips under and above 300 kilometres respectively (European Commission, 2016) Both of these figures use the similar abbreviations as informed in Figure 2.26

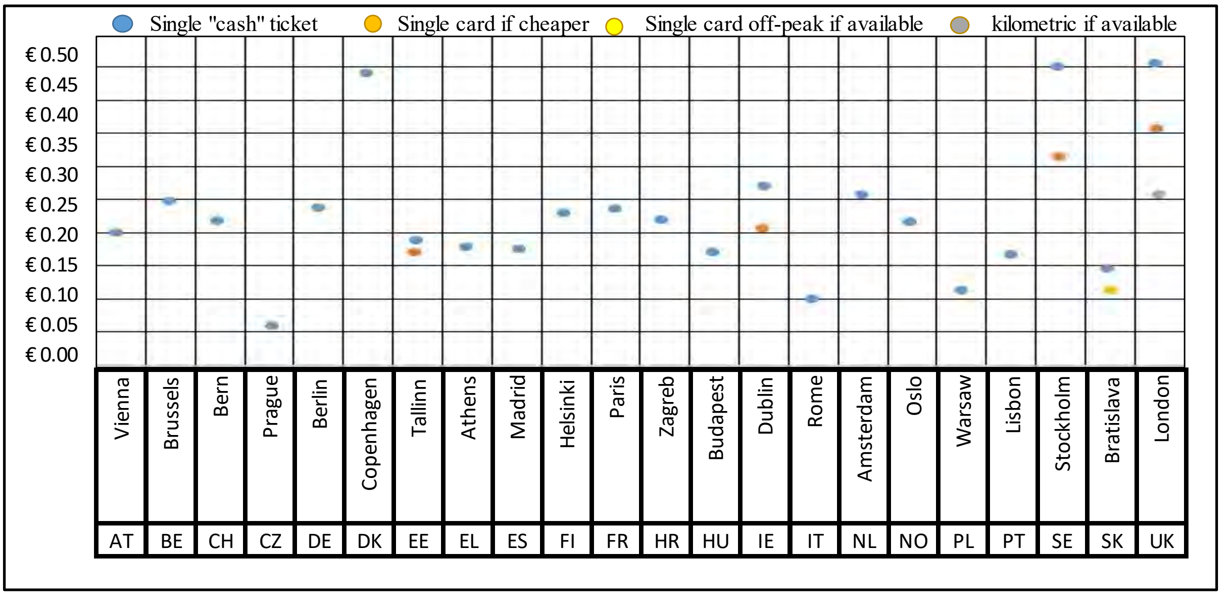

Figure 2.24 Suburban fares (single) in European countries and UK (after European Commission, 2016)

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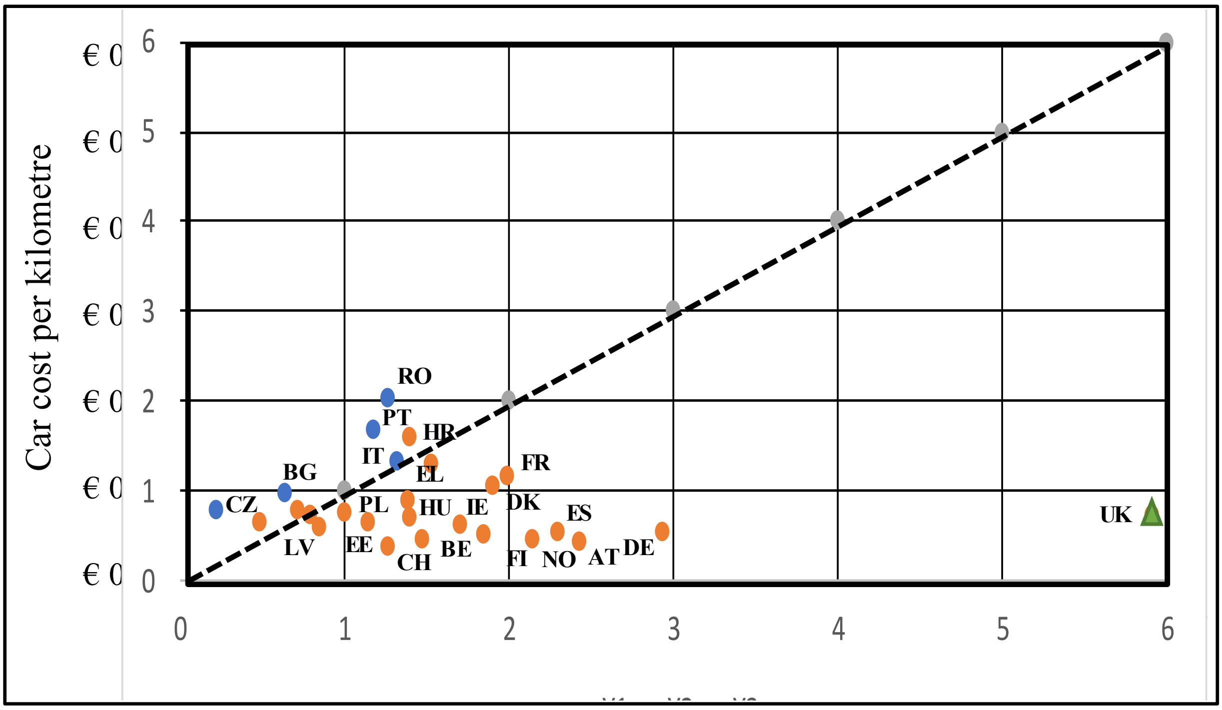


Figure 2.25 Rail and car costs: interurban trips under 300 kilometres (after European Commission, 2016)

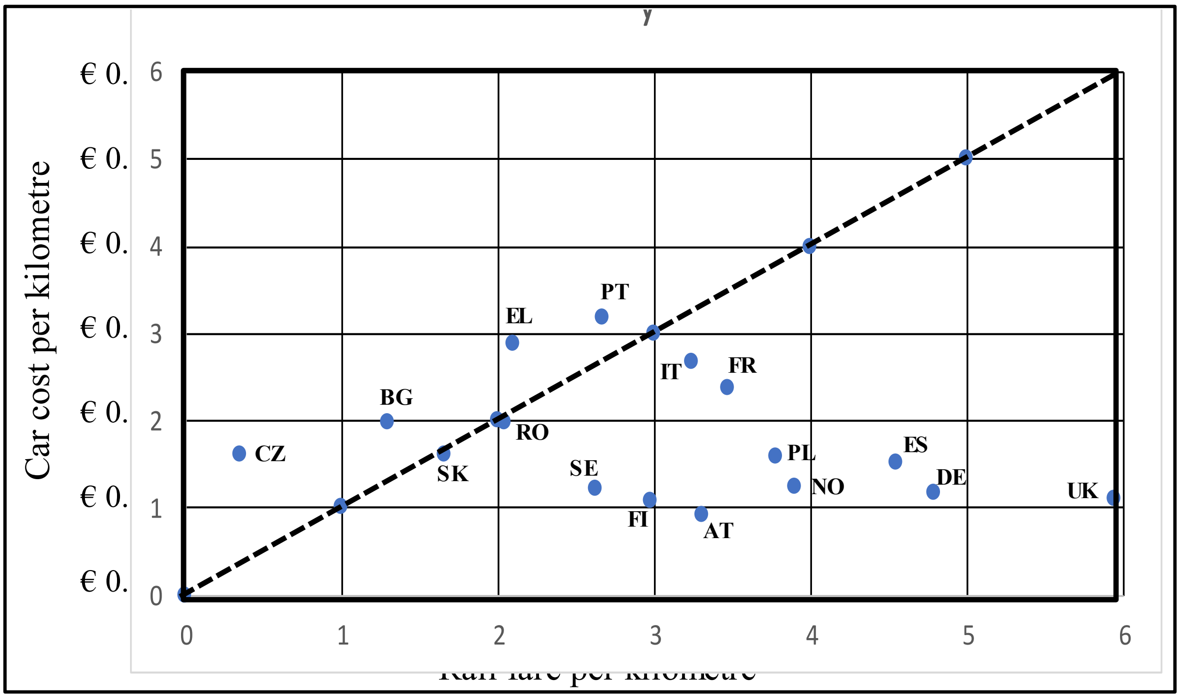


Figure 2.26 Rail and car costs: Rail and car costs: interurban trips over 300 kilometres (after European Commission, 2016)

2.7.5 Property (other than farming) damage costs

Penning-Rowsell *et al.* *(*2013) reported that the 2007 floods event across the UK caused losses of approximately £ 36 billion to the rail sector. The losses they estimated were comprised of £10.5 billion associated with the direct damage to the railway track, whereas the remaining £ 25.6 billion was associated with the disruption costs. The costs are quantified in two ways:

1. First, Network Rail's compensation payment to Train Operating Companies (TOCs) which is estimated following a delay in service or performance as a result of severe weather
2. Second, Value of Time (VOT) approach which quantifies the value of a delay as consequences of the incidents

Table 2.5 shows the weighted annual average damage (WAAD) with specific standards of protection (SoP) whereas Table 2.6 shows the estimated number of properties affected by different floods. Both estimations are for residential property.

Table 2.5 Weighted Annual Average Damages (WAAD) (2013/14 prices) assuming variable threshold Standards of Protection (SoP) (Penning-Rowsell et al., 2013)

Existing SoP	No warning (£)	<8 hour warning (£)	>8 hour warning (£)
No protection	4,728	4,559	4,513
2 years	4,728	4,559	4,513
5 years	2,828	2,727	2,700
10 years	1,400	1,350	1,336
25 years	612	590	584
50 years	261	252	249
100 years	65	63	62
200 years	33	32	32

Table 2.6 Estimate of the number of properties affected by different floods (Penning-Rowsell *et al*., 2013)

Return Period	No. Of properties as % of 200 year No.
100	93
50	80
25	25
10	10
5	5

In addition to the impact of flooding to the surrounding track, flooding may also affect non-residential buildings. According to Penning *et al.* (2013) the property type and its affected floor area are given in Table 2.7 , whereas Table 2.8 shows the estimation of the weighted annual average damage (WAAD) for these non-residential properties due to flooding.

Table 2.7 Indicative floor sizes for Non-Residential Properties (Penning-Rowsell et al., 2013))

Property Type	Floor Area (m²)
Retail	340
Offices	360
Warehouses	3,270
Leisure and sports	NA
Leisure	1,020
Sports	NA
Playing Fields	21,850
Sports Center	5,400
Marina	1,860
Sport Stadium	25,600
Public Buildings	1,300
Industry	2,480
Miscellaneous	NA
Car Park	3,500
Multi-Storey Car Park	2,700
Electricity SubStation	48

Table 2.8 Non-Residential Price Base (2013-2014) Weighted Annual Average Damages (Penning-Rowsell et al., 2013)

		Standard Of Protection						
New MCM Code	Sector Type	None	5	10	25	50	100	200
2	Retail	69.87	34.47	25.10	12.92	5.77	1.44	0.72
3	Offices	66.43	31.11	23.31	11.77	5.19	1.30	0.65
4	Warehouses	81.72	43.33	31.32	15.89	7.20	1.80	0.90
5	Leisure and sports	NOT APPLICABLE - CONSTITUENT CATEGORIES TOO DIVERSE						
51	Leisure	127.38	44.82	35.50	16.30	7.00	1.75	0.88
52	Sports	NOT APPLICABLE - CONSTITUENT CATEGORIES TOO DIVERSE						
521	Playing Field	0.89	0.40	0.30	0.15	0.07	0.02	0.01
523	Sports Centre	24.88	11.40	8.56	4.22	1.87	0.47	0.23
526	Marina	9.08	4.40	3.18	1.65	0.73	0.18	0.09
525	Sports Stadium	9.44	4.24	3.18	1.60	0.70	0.18	0.09
6	Public Buildings	32.92	15.85	11.78	5.95	2.64	0.66	0.33
8	Industry	13.24	6.75	4.91	2.52	1.13	0.28	0.14
9	Miscellaneous	NOT APPLICABLE - CONSTITUENT CATEGORIES TOO DIVERSE						
910	Car park	2.19	1.16	0.82	0.44	0.20	0.05	0.02
960	SubStation	181.24	112.05	79.95	43.91	19.90	4.97	2.49
NRP sector average		65.26	34.52	25.25	13.41	6.14	1.63	0.81

2.7.6 Farming land damage cost

Flooding of the railway track may also lead to flooding of adjacent farming land. Table 2.9 provides an indication of the costs per hectare which may accrue in the UK. The values in Table 2.9 are based on the summer 2007 flood events.

Table 2.9 Estimated damage costs to farming land of the summer 2007 flood events (ADAS, 2008)

	Area flooded, ha *	Loss, £ million**	Average loss £/ha flooded**
Arable	26,500	34.3 (±9.2)	1,293(±347)
Grassland and livestock	15,600	10.1 (±6.5)	647(±416)
Other costs	42,100	4.2 (±2.0)	100(±48)
Total	**42,100**	**48.5(±17.7)***	**1,153 (±422)**

* based on ADAS, 2008 using Environment Agency sources,

** 95% confidence intervals shown in brackets

2.8 Physical and Operational Uncertainties of Drainage System

Railway drainage asset management is challenging because it involves the consideration of large interconnected networks of assets, significant parts of which are buried and therefore their condition is difficult to assess. As mentioned above, drainage assets are made from a variety of materials which deteriorate at different rates, are of varying ages and often of unknown maintenance history. This is exacerbated in many countries which have mature railway networks where the track and its drainage assets can be 150 years old and are nearing the end of their useful life. As a consequence, the performance of individual drainage assets and therefore any drainage network is uncertain. Uncertainty in performance is further aggravated by the effects of climate change which is increasing the number and ferocity of extreme weather events (i.e. storms) in many parts of the world, including the UK.

BSI (2010) defines uncertainty as, “the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood”. Whilst in reliability based-civil engineering, the above definition can be further refined based on the sources of uncertainty or contributing factors (Ayyub, 2014). A number of texts describe the sources of uncertainty in various engineering fields (e.g .McKOne and Bogen, 1991; Cox, 2009; Ayyub, 2014). A physical uncertainty of an engineering system (i.e. railway track drainage) can be defined as a random process of the system and its given environment beyond the planned assumptions, e.g. higher load and speed, prolong service life (Wirsching, 2006). This uncertainty may lead to the operational uncertainty of a system with the potential for costly impacts of an undesired event. (Cox, 2009).

The contributing factors to do with the uncertainty of the performance of drainage (leading to poor drainage) can be regarded as being associated with the environmental, the subgrade, the design of drainage assets, the condition of the constituent components, installation of drainage components, maintenance, traffic loading, and land use.

Section 2.4 described how the potential problems associated with track drainage described in section 2.3 can be classified according to the above categories.

Often in practice poor drainage occurs due to a number of factors as follows:

1. **Environmental**: In terms of environmental aspect, xtreme weather events (i.e. heavy rainfall, flooding, prolonged hot weather) may frequently occurr and affect the built draiange assets. These events reflect a tcondition “wetter winter and hotter summer” (Baker *et al*., 2010).
2. **Subgrade**: Drainage components are installed on or within the subgrade which can be softened due excessive water infiltration event (e.g. heavy rainfall, river flooding); this may lead to change of a gradient or position of the components, which can contribute to various types of drainage failure. Moreover, if the ground movement is excessive it can cause various types of drainage failure (see Table 2.10). Another problem is clogged of geotextile filter; this is caused by the silting or clogging of the filter and inhibits water to drain into the pipe. (Selig and Waters, 1994; Network Rail, 2010; Ghataora and Rushton, 2012;

Glendinning et al 2014; Rushton and Ghataora, 2014, Burrow *et al*.,2013; Usman *et al.*, 2017).

3. **Design**: The original design may be inadequate to cope with the current given environment (i.e. higher load and speed, extreme weather). Inadequate drainage can be caused by poor design of the drainage infrastructure including inadequate size of the assets, a flatter than appropriate gradient. For example, capacity issues associated with an almost flat gradient of the track drainage system in Bletchingley tunnel, on the South East line in the UK was reported as contributing to the resulting flood (Sihota, 2016). In Wessex-Knockmore, the failure of the culvert system to withstand heavy rainfall in the catchment area was attributed to a lack of adequate capacity of the culvert. The flood caused track washout an incident whereby a train ran onto the unsupported section of track (Network Rail, 2010; Sihota, 2016).
4. **Component**: This may involve unexpected rates of deterioration of the material (excessive wear) used to construct the drainage component. This may be due to aging, weathering or fatigue. Drainage assets, which are buried beneath the track as subsurface drainage (i.e. pipe, catchpits and manholes) or installed as surface drainage (i.e. channel drains and ditches, outfall, culvert), can potentially fail through the aging of their constituent materials (Selig and Waters, 1994; Network Rail, 2010; Rogers *et a*l., 2012; Usman *et al*., 2017). This is made worse by a lack of maintenance. Fatigue damage can occur if the drainage asset is not of sufficient strength to withstand the cumulative passages of railway vehicles.
5. **Installation**: Poor installation or construction can lead to the improper functioning of drainage components and may therefore affect their serviceability. Inadequate installation is associated with the incorrect construction of drainage assets so that they do not perform as designed (cf. Section 2.6.1.2) (Network Rail, 2017). An example is the need to install the

cover of catch pits above ballast level in the cess drain. This prevents ballast or debris accumulation in buried catch pits (Network Rail, 2010; Sihota, 2016).

6. **Maintenance**: The inadequate or neglected maintenance of drainage assets can occur due to a lack of resources to carry out maintenance, or because the locations of subsurface drainage assets are unknown. (Selig and Waters, 1994; Network Rail, 2010; 2018; Franklin, 2015; Li *et al*, 2015; Sihota, 2016).
7. **Traffic**: Heavier and faster trains than originally designed for may accelerate component deterioration or cause sudden failure. The current load or speed may be higher than designed for traffic loads. This may be exacerbated by a poor railway track functional condition or train wheels, which can lead to higher train dynamic loads or an inadequate structural design of the railway track. Furthermore, this condition will cause higher cyclic stresses which then could lead to increased fatigue loading of track and drainage components (Burrow *et al.,* 2013; 2017; Powrie, 2014; Li *et al*, 2015).
8. **Land use**: a change of land use may lead to some adverse outcomes to track drainage components. For example, deforestation in the vicinity of the railway track can lead to faster and greater amounts of runoff and could lead to flooding as well as the damage to drainage components (Sihota, 2016; Usman *et al.,* 2017).

The above factors may contribute towards, or cause directly, drainage system failure and thereby lead to a variety of socio-economic impacts as mentioned previously.

Table 2.10 Track subgrade problems associated with inadequate drainage (Li et.al, 2015; Rushton and Ghataora, 2014; Burrow, et al., 2007; Selig and Waters, 1994)

No	Failure Type	Cause	Factors	Features
1	Subgrade attrition	Traffic-induced deterioration (live load)	-Hard subgrade is loaded repeatedly by ballast -Contact between ballast and subgrade, and the subgrade is penetrated and wore by the ballast -Associated with the upper most part of the subgrade where cyclic shear stresses are likely to be at their highest fine-grained soils such as clays	-Muddy ballast -Inadequate subballast
2	Progressive shear failure (cess heave		-Repeated overstressing -Fine-grained soils -High water content	- The soil is sheared and remoulded due to sufficiently high cyclic stresses - Squeezing near subgrade surface -Heaves in crib and/or shoulder -Depression under ties
3	Excessive settlement		-Repeated loading -Soft or loose soils	-Differential subgrade settlement -Ballast pocket -Water retained in ballast pocket lead to subgrade weakening and possibly resulting in mud pumping
4	Cyclic mobility/Liquefaction		-Repeated loading -Saturated silt and fine sand	-Large displacement -More severe with vibration -Can happen in subballast
5	Massive shear failure	Dead Load	-Weight of train, track and subgrade	-High embankment and cut slope

2.9 Summary

The chapter found that the factors which contribute to poor drainage can be categorized in terms of the environment, the design, the condition and construction of components, the subgrade, land use, installation, maintenance and traffic loading.

The chapter found that the literature on railway track drainage uncertainty is scant and that previous studies of poor subsurface and surface drainage of ballasted railway track have not distinguished relationships between failure modes, do not deal with uncertainty of performance and their causal events and impacts.

Taking all of these in combinations as outlined in the methodology (Chapter 4) it is possible to provide an assessment framework for poor drainage of railway ballasted track. In order to achieve this, the focus of this research has been on developing a risk-based methodology for addressing uncertainty for the appraisal of the maintenance of railway ballasted track drainage. To this end, Chapter 3 discusses the concept of risk in relation to railway drainage failure and reviews the risk management literature with a focus on linear asset system

3 RISK ASSESSMENT FOR DRAINAGE OF BALLASTED RAILWAY TRACK

3.1 Introduction

This chapter provides a review of the literature on risk assessment with a focus on drainage of railway ballasted track and related infrastructure. The review is divided into the following sections: risk assessment concepts (3.2); modelling tools or techniques for quantitative analysis (3.3); Risk semi-quantification (3.4), risk quantification (3.5), cost benefit analysis (3.6), risk assessment in practice (3.7); risk assessment in the railway industry (3.8); drainage risk assessment approaches (3.9), and; summary (3.10). The review identifies appropriate risk-based assessment techniques to enable a risk-based assessment framework to be built for the assessment of drainage of railway ballasted track. The selected techniques allow for uncertainty in the performance of drainage assets, the nature of data used to make decisions and, in the occurrence, and impact of risks. These uncertainties have been discussed in Chapter 2.

3.2 Risk Assessment Concepts

Vose (2008) points out that an understanding of uncertainty can assist decision makers to provide improved decisions. An appropriate means of understanding and addressing uncertainty is a structured risk assessment process (Bedford and Cooke, 2001; Vose, 2008; Ayyub, 2014). Consequently, such a process was adopted in this research to establish a risk-informed framework for rack drainage asset. A risk assessment procedure consists of two stages as presented in Section 3.2.2

3.2.1 Risk assessment terminology

Risk can be defined as the effect of uncertainty (BSI, 2011) and is often evaluated through a combination of the probability of an event occurring and its consequence (IRM, 2002). Risk assessment can be defined as an overall process of risk identification, risk analysis, and risk evaluation (BSI, 2010; Ayyub, 2014). Since the risk evaluation requires the involvement of comparing estimated levels of risk with risk criteria defined to determine the significance of the level and type of risk (BSI, 2010), this part might be excluded from the process when the assessed system is being developed. It is therefore, in this research, the risk assessment comprises two component risk identification and risk analysis (see Section 3.2.2).

3.2.2 Risk versus uncertainty

As described in section 2.6, the uncertain performance of track drainage components can be assigned to physical and operational uncertainties. In terms of contributing factors (risk), operational uncertainty can be related traffic (i.e. types of trains, commodities carried, speeds and loads). Whereas physical uncertainty can be connected with the subgrade, the environment, components, land use, design, maintenance, and installation. Smith *et al*. (2006) define uncertainty it as the chance of an event occurring where the probability distribution is generally not known.

According to the Institute for Transport Studies (2003), the difference between uncertainty and risk is that risk is the situation where there is a set of possible outcomes from a specific event, and the estimation of the probability and confidence level of each outcome is provided (see Figure 3.1). Uncertainty, on the other hand, is where there is a set of possible outcomes, but there is no available estimation of the probability of occurrence of an identified causal event (as in Figure 3.1b). This is in agreement with the definition provide by Smith *et al*. (2006) given above. Therefore, to address risk in the decision-making process, a transformation from uncertainty to a quantified risk is required. This includes the estimation of the probability of occurrence of a risk event.

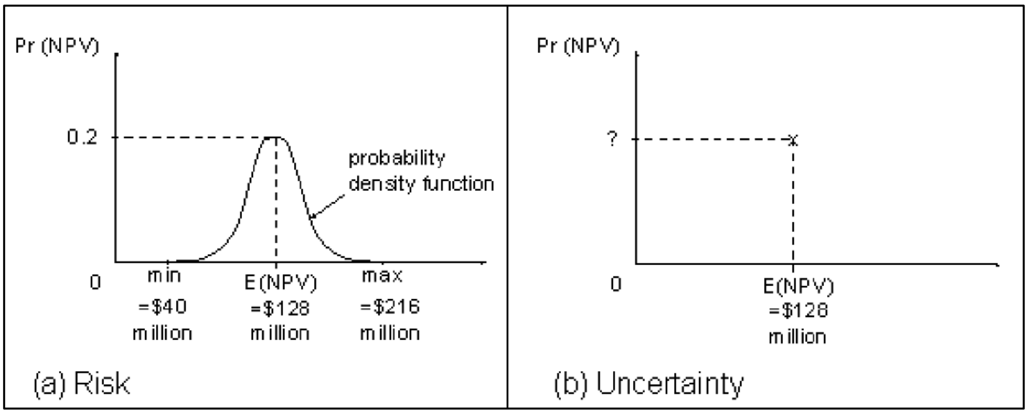


Figure 3.1 Risk versus uncertainty (Institute for Transport Studies, 2003)

3.2.1 Risk level

The level of risk, *RL*, is determined using the following equation (Huang *et al.*, 2006):

$$\boldsymbol{RL = \sum_{i=1}^{n} . Pi.Ii} \qquad \text{Eq. } 3.11$$

Where,

RL = risk level

Pi = Probability of failure, i = 1... n

Ii = Impact

The probability of failure and impact of each hazard or hazard group can be obtained from expert opinion or historical data (see below). The impacts are often quantified in monetary terms as a cost or financial consequence (Flanagan, 1999).

3.2.2 Risk assessment process

A risk assessment process is generally comprised of two main stages (White, 1995; BSI, 2010):

1. Risk identification, this first stage involves identifying failures and impacts;

2. Risk analysis, the second stage involves estimating risk probabilities and consequences as part of a risk quantification process;

3.2.2.1 Risk identification

The risk identification stage considers risks that potentially might be associated with a particular condition (e.g. poor drainage); the description of these risks is essential to ensure a proper understanding of the identified risk. Ayyub (2014) defined risk identification as the overall process of finding, recognising, and describing risks. The risk identification process involves using historical data, theoretical analysis, informed and expert opinions and determining stakeholders' needs.

3.2.2.2 Risk analysis methods

Risk analysis methods can be qualitative or quantitative in nature, or a hybrid of the two (e.g. qualitative-quantitative, semi-quantitative) (BSI, 2010; Marhavilas, 2011). Regarding the qualitative method, risks are analysed and represented via a linguistic scale and often by expert opinion/judgement (e.g. low, medium, high). Meanwhile, in the quantitative approach, the risk is quantified using mathematical relationships. Often historical data is used to develop these relationships, but where it is not available a combination of qualitative and quantitative, or semi-quantitative methods can be used (An *et al.*, 2006; BSI, 2010; Marhavilas, 2011).

3.2.3 Risk-informed for decision making

In recent years, there is a growing attention to a risk assessment approach that can be considered involvement of stakeholder when assessing the potential risk. This approach, namely risk-informed, concerns a deliberative process incorporating a set of performance measures and other considerations, to "inform" decision making This felt appropriate compare to a risk-based approach which is typically conducted by technical expert, without any involvement of stakeholder or public consultation (Zio and Pedroni, 2012).

3.3 Modelling Tools or Techniques for Quantitative Analysis

3.3.1 Overview of risk assessment techniques

There are a variety of techniques that can be used to perform each of the two components of risk assessment as shown in Table 3.1.

3.3.2 Expert elicitation

Often expert elicitation is used when there is (Bedford and Cooke, 2001):

- A scarcity of real data due to technical difficulties, cost limitation or the uniqueness of the situation under study.
- The existing data is incomplete or inappropriate and needs to be refined by a better estimation.

3.3.2.1 Focus group discussion

A focus group discussion (FGD) is organised to explore a specific set of issues. One of the important keys for running a FGD is interaction between participants (Kitzinger, 1994). This can be facilitated through, an engineering workshop to capture expert knowledge on the intended issues. According to Nuseibeh and Easterbrook (2000), a prototype model may provokes the workshop participants to involve properly in the discussion. In terms of interactive discussion between researcher and experts (e.g. from industry), the discussion regarding the proposed model concerns some advantages of an engineering workshop as follows (Nuseibeh and Easterbrook, 2000; Schellens and Valcke, 2006):

- Bridging the gap between theoretical aspects and practical point of views.

- Better understanding of the proposed model by involving task-oriented communication such as presentation, explicitation, evaluation.
- Development of a richer models.
- Model validation.

3.3.2.2 Questionnaire.

Identifying risks while historical data is not fully covered all potential risks can be challenging in respect to provide insight of those for a decision-making process. To be dealt with this issue, the questionnaire can be used to capture expert knowledge for identifying risks associated with a failure event, by informed their availability. To achieve this, a set of a self-completion questionnaire is designed and implemented. The requirements of this are described as follows (Robson and McCartan, 2010):

-Linking research objectives with the questions.

-Understandable questions and elicits proper estimation from the intended experts.

.

Table 3.1 Risk Assessment techniques and their applicability (after BSI, 2010)

No	Type of Risk Assessment Techniques	Can Provide Quantitative Output?	Risk assessment process			
			Risk Identification	Risk analysis		Level of risk
				Probability	Consequence	
1	**Look-Up Methods**					
	Check-list	No	SA[1]	NA	NA[2]	NA
	Preliminary hazard analysis	No	SA	NA	NA	NA
2	**Supporting Methods**					
	Structured interview and brainstorming	No	SA	NA	NA	NA
	Semi-quantification	Yes	A	A	SA	SA
	Delphi technique	No	SA	NA	NA	NA
	SWIFT Structured "what-if"	No	SA	SA	SA	SA
	Human reliability analysis (HRA)	Yes	SA	SA	SA	SA
3	**Scenario Analysis**					
	Root cause analysis (single loss analysis)	No	NA	SA	SA	SA
	Scenario Analysis	No	SA	A[3]	SA	A
	Business impact analysis	No	A	A	SA	A
	Fault tree analysis (FTA)	Yes	A	SA	NA	A
	Event tree analysis (ETA)	Yes	A	A	SA	A
	Cause and consequences analysis	Yes	A	SA	SA	A
	Cause and effect analysis	Yes	SA	NA	SA	NA
4	**Function Analysis**					
	FMEA (Failure Mode and Effect Analysis) and FMECA	Yes	SA	A	A	A
	Reliability-centred maintenance	Yes	SA	SA	SA	SA
	Sneak analysis (Sneak circuit analysis)	No	A	NA	NA	NA
	HAZOP (Hazard and operability studies)	No	SA	A	SA	A
	HACCP (Hazard analysis and critical control points)	No	SA	NA	SA	NA
5	**Controls Assessment**					
	LOPA (Layers of protection analysis)	Yes	A	A	SA	A
	Bow tie analysis	Yes	NA	SA	A	SA
6	**Statistical Methods**					
	Markov Analysis	Yes	A	NA	SA	NA
	Bayesian analysis	Yes	NA	NA	SA	NA
	Monte Carlo Simulation (MCS)	Yes	NA	A	SA	SA

[1] SA = Strongly applicable
[2] NA = Not applicable
[3] A = Applicable

As presented in Table 3.1, the techniques which may applicable to perform a modelling tool are described in below information of risk assessment applicability

3.3.3 Cause and effect analysis

A cause-and-effect analysis is a method to identify potential causes of an undesirable event or problem using a structured approach (BSI, 2010). The advantages of this technique are as follows:

- Problem identification and its potential causes can be facilitated by using a structured diagram approach;
- It allows for the identification of problem areas where further data is needed to be obtained for further study;
- An easy to use diagram can be developed to enable the relationships between the problem and its causes to be identified qualitatively.

Despite the advantages, there are the limitations to this technique as follows (BSI, 2010):

- It needs further analysis process for resulting recommendations.
- When the causal factors relationship becomes more complex, the interactions may not be considered adequately.

3.3.4 Contributing factor diagram (CFD)

Contributing factor diagram (CFD) is a technique to identify causes of failure using diagram. This technique can be categorized as an adaptive approach based on a technique, namely Root Cause Analysis (RCA). Similar with RCA (BSI, 2010)., CFD requires all of potential evidences gathered from a failure event. To utilise this technique, a group of experts is appointed to carry out the analysis; the experts are selected based on their competency on the specific knowledge on failure of the system. The difference between CFD and RCA is relied on the process after the causes of failure have been identified. CFD mainly focuses on tracking the causes whereas

RCA typically requires more steps, such as developing solutions, make recommodendations and implanting those (BSI, 2010)..

Despite its useful feature to describe a failure problem in pictorial form, CFD has some limitations as follows:

- Required experts may not be available.
- Lack of failure data data may affect the ability of this technique to be performed.
- It can not be utilised for quantitative analysis, unless the CFD be combined with another technique, e.g. fault tree.

3.3.5 Failure mode and effects analysis (FMEA)

Failure mode and effects analysis (FMEA) is a technique to observe a well-defined system through its components, involving all potential failure modes and the substantial effect of each failure on the entire system. This technique comprises of the following essential parts (White, 1995):

- component identification
- function
- failure mode and cause
- failure mode frequency
- failure mode effects
- detection
- corrective measures

The FMEA method has been utilised to evaluate the correctness of the technology or science with a well-defined structure and recorded historical failure data. However, the technique cannot perform various failure combinations (pathways) of a developing system where the causal factors, failure modes and the relationship are among those being examined.

3.3.6 Fault tree analysis (FTA)

Fault tree analysis (FTA) is a logical top-down, deductive technique, to identify and analyse causal factors (mid and basic event) which may cause a fault event (top event) in a descriptive tree diagram (BSI, 2010; Ma *et al*., 2013). An example of a fault tree for subgrade failure resulting from adverse weather on urban rail transit facilities shown in Figure 3.2

In a fault tree the relationships between events is described using Boolean logic. Therefore, a fault tree can be translated into an equivalent set of Boolean equations (Pandey, 2005). The relationship between causal factor and failure problem are connected using the OR-gate and AND-gate (see sections 3.3.6.1 and 3.3.6.2).

Fault tree analysis (FTA) is a deductive technique focusing on one particular event by providing a method for determining the causes of that event. Fault trees are constructed from events and gates. Basic events can be used to represent technical failures that lead to undesired (top) event, while intermediate events can represent operator errors that may exacerbate technical failures. The gates of the fault trees can be used to represent several ways in which machine and human failures combine to give rise to the undesired event. For instance, an AND-gate implies that both initial events need to occur to give rise to the intermediate event. Conversely, an OR-gate means that either of two initial events can give rise to the intermediate event. In the context of accident analysis, an OR-gate implies a lack of evidence; as more evidence becomes available, the certainty of which of the two initial events are true increases (Vesely *et al*., 1981; Kontogiannis *et al*., 2000; Harms-Ringdahl, 2001; Reniers *et al*., 2005; Yuhua and Datao, 2005; Hong *et al*., 2009).

3.3.6.1 The OR-gate

The OR-gate represents the **union** of events at the gate. For event Q with two input events A and B attached to the OR gate, the probability of the failure event is obtained as follows:

$$P(Q) = P(A)+P(B)-P(A\cap B) \qquad \text{Eq. 3.1}$$

or

$$P(Q) = P(A)+P(B)-P(A)P(B \mid A) \qquad \text{Eq. 3.2}$$

If A and B are **mutually exclusive** events then $P(A \cap B) = 0$ and

$$P(Q) = P(A)+P(B) \qquad \text{Eq. 3.3}$$

If A and B are **independent** events then $P(B \mid A) = P(B)$ and

$$P(Q) = P(A)+P(B)-P(A)P(B) \qquad \text{Eq. 3.4}$$

If event B is **completely** dependent on event A then $P(B \mid A) = 1$ and

$$P(Q) = P(A)+P(B)-P(A)(1) = P(B) \qquad \text{Eq. 3.5}$$

Therefore, the approximation of

$$P(Q) = P(A)+P(B) \qquad \text{Eq. 3.6}$$

is **always** a **conservative** estimate for the probability of event Q (because $P(A \cap B)$ is small compared with $P(A)+P(B)$ for very low probability events). Event Q will occur if any (at least) one of the input events to the OR-gate occur.

3.3.6.2 The AND-gate

This represents the **intersection** of events at the gate. For event Q with two input events A and B attached to the AND-gate, the probability is obtained as

$$P(Q) = P(A)P(B \mid A) = P(B)P(A \mid B) \qquad \text{Eq. 3.7}$$

If A and B are **independent** events then $P(B \mid A) = P(B)$ and$P(A \mid B) = P(A)$ therefore

$$P(Q) = P(A)P(B) \qquad \text{Eq. 3.8}$$

If A and B are **not independent**, then Q may be significantly greater than $P(A)P(B)$. Event Q is caused only if every (all) input event attached to the AND-gate occur.

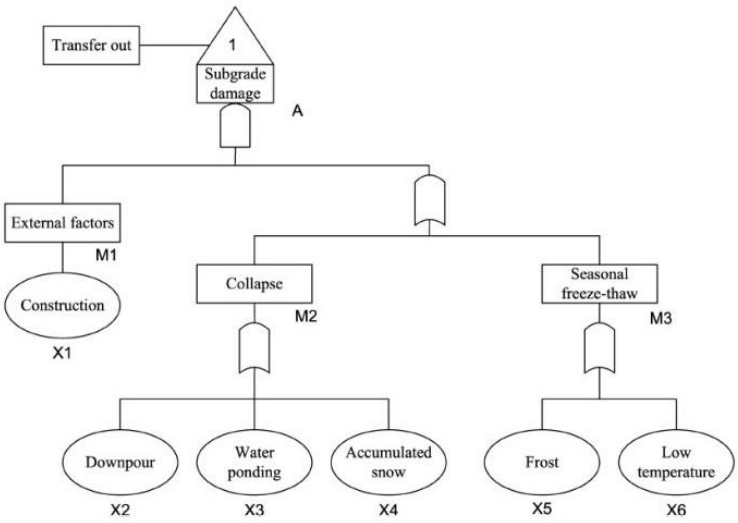


Figure 3.2 Fault tree example (Ma *et al*., 2013)

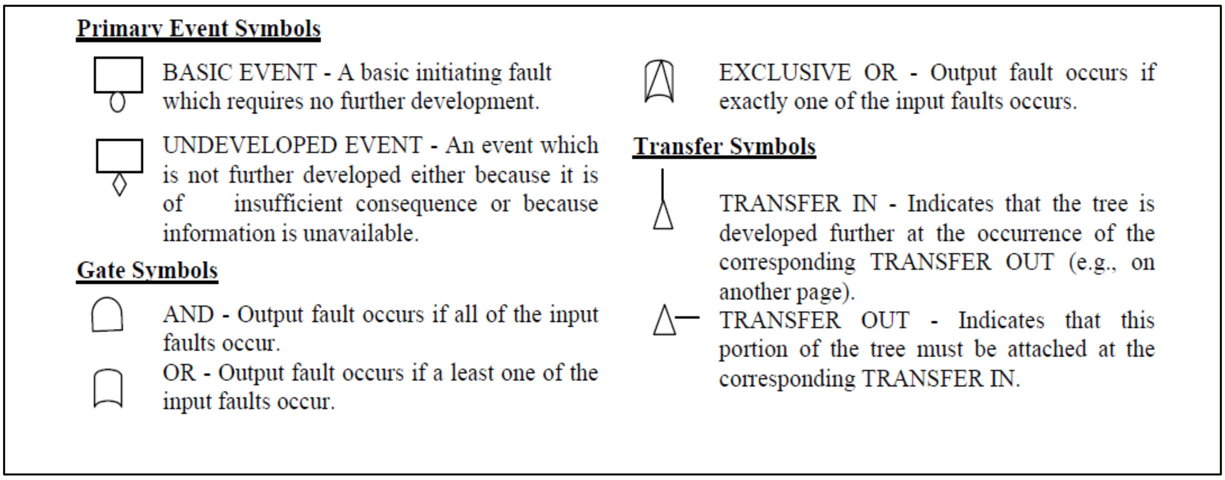


Figure 3.3 Fault tree analysis event symbols (Hossain *et al.*, 2010.)

In a qualitative approach, FTA can be used to identify potential risk (causal events) associated with a failure event (top event); whereas in a quantitative approach FTA is utilised to quantify the probability of a top event based on the basic event probability (see Table 3.8).

Table 3.2 FTA for qualitative and quantitative approach (BSI, 2010)

No	Use	Input Requirement	Process	Output
1	Qualitative approach for risk identification	• Understanding of system failure • Failure pathway/mode(s)	• Define top event and investigate its possible causes • Perform the failure mechanisms	• Pictorial fault tree which presents how the top event can occur involving the causal events
2	Quantitative approach for risk quantification	• Failure rates or • Probability of all basic events	• The probability of top event can be calculated based on probability assignment of basic event	• A list of minimal cut set (individual pathways to failure) or failure mode(s) • Top event probability

3.3.6.3 Strengths and limitations

The strengths of the FTA can be described as follows (BSI, 2010):

- It affords a disciplined approach which is highly systematic, but at the same time sufficiently flexible to allow for the analysis of a variety of factors, including human interactions and physical phenomena.
- The application of the "top-down" approach, implicit in the technique, focuses attention on those effects of failure which are directly related to the top event.
- FTA is especially useful for analysing systems with many interfaces and interactions.
- The pictorial representation leads to an easy understanding of the system behaviour and the factors included, but as the trees are often large, processing of fault trees may require computer systems. This feature enables more complex logical relationships to be included (e.g. AND and OR) but also makes the verification of the fault tree difficult.

Despite its strength, FTA has limitations. The applicability of a fault tree depends on its structure. Therefore, appropriate processes for tree development and validation are needed.

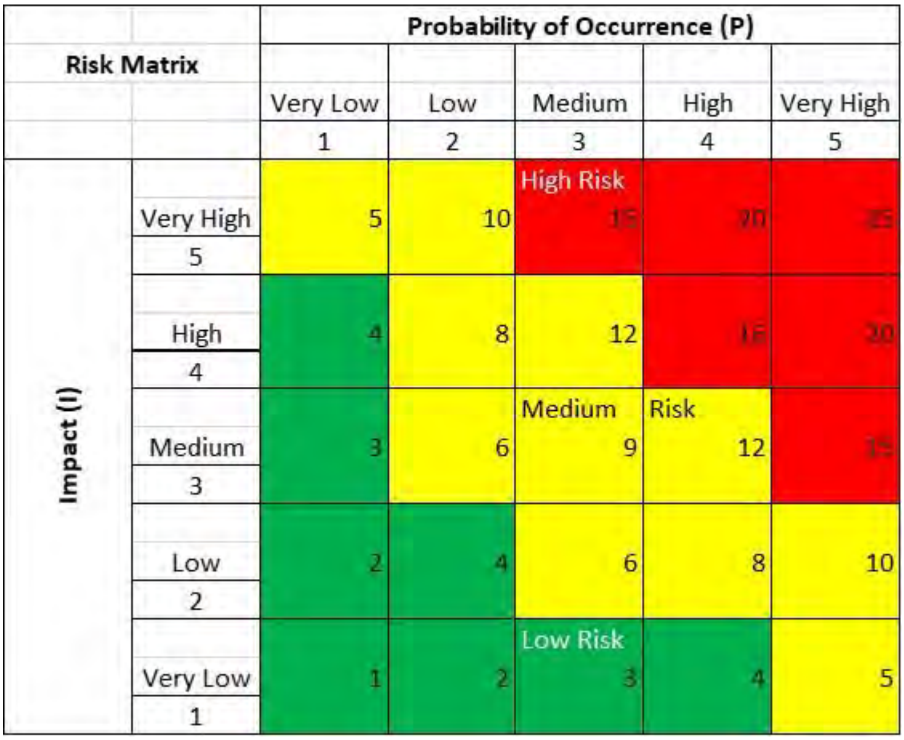
3.3.6.4 FTA evaluation

The following points are related to the ability of FTA as an analysis technique (Pandey, 2005):

- Can identify critical events and event combinations that lead to the top event;
- Can calculate the probability of the **top event** based on the probabilities of the **basic** and **undeveloped** events in the fault tree;
- It enables two types of analysis, namely; qualitative; quantitative.

3.4 Risk Semi-quantification

Risk semi-quantification is often utilised to identify for all possible risks those which require further detailed analysis (i.e. quantification). A semi-quantification risk matrix (impact/probability of occurrence matrix) is often adopted to categorise the identified risks into low, medium, and high (see Figure 3.4). A risk is determined from the multiplication of the probability of occurrence (an integer between 1 and 5) and the impact (presenting as an integer from 1 to 5).



Risk Matrix		Probability of Occurrence (P)				
		Very Low	Low	Medium	High	Very High
		1	2	3	4	5
Impact (I)	Very High 5	5	10	High Risk 15	20	25
	High 4	4	8	12	16	20
	Medium 3	3	6	Medium 9	Risk 12	15
	Low 2	2	4	6	8	10
	Very Low 1	1	2	Low Risk 3	4	5

Figure 3.4 Risk matrix

3.5 Risk Quantification

An analytical model is required to facilitate risk quantification for obtaining outcomes of the defined parameters (Ayyub, 2014). Regarding to this, the estimation of frequency of occurrence and the potential impacts as parameters of risk event need to model and quantified. Sections 3.5.1-3.5.5 provide procedure to model these parameters incorporating probabilistic formula and Monte Carlo simulation (MCS).

3.5.1 Frequency of occurrence and failure rate estimation

Failure rate $\lambda(t)$ is defined by equation 3.9 as follows (Billinton and Allan, 1987):

$$\lambda(t) = \frac{number\ of\ failures\ per\ unit\ time}{number\ of\ components\ exposed\ to\ failure} \qquad \text{Eq. 3.9}$$

Table.3.3 Referenced dam failure rates (Ayyub, 2014)

Area	Failures	Total Dams	Period (Years)	Rate per Dam-Year
United States	33	1764	41	4.5×10^{-4}
	12	3100	14	2.8×10^{-4}
	74	4974	23	6.5×10^{-4}
	1	(dam-year = 4500)		2.2×10^{-4}
World	125	7500	40	4.2×10^{-4}
	9	7833	6	1.9×10^{-4}
Japan	1046	276,971	16	2.4×10^{-4}
Spain	150	1620	145	6.6×10^{-4}
Great Britain	20	2000	150	0.7×10^{-4}

As an example, Table 3.4 provides information which can be used to determine dam failure rates in various parts of the world (Ayyub, 2014). From Table 3.4 and using equation 3.9 he failure rate per dam-year in the United States is calculated as follows:

$$\begin{aligned}\lambda Dam(US) &= Dam\ failure\ rate\ in\ the\ US\\ &= \frac{number\ of\ failures\ per\ unit\ time}{number\ of\ components\ exposed\ to\ failure}\\ &= \frac{33\ failures\ per\ 41\ Years}{1764\ Dams} = \frac{33\ failures}{1764\ Dams * 41\ Years}\\ &= \frac{4.5E-04\ failure}{Dam.Year} = 4.5E-04\ Failure\ rate\ per\ Dam-Year\end{aligned}$$

3.5.2 Probability of occurrence estimation

Probability of occurrence of a causal event can be calculated using Poisson process equation (Ayyub, 2011) which is presented by equation 3.10 as follows:

$$P_{Xt}(x) = \begin{cases} \frac{(\lambda t)^{x} \exp(-\lambda t)}{x!} \\ 0 \end{cases} \qquad \text{Eq. 3.10}$$

$PX_t(x)$ = Poisson probability of occurrence of causal event Xt, x time(s) within t time period

λ = Failure rate

x = 0.1.2.3……n occurrence time(s)

t = time period (e.g. in the next 5 years)

3.5.3 Risk quantification using Monte Carlo simulation

The process for estimating risk parameters (i.e. likelihood, impacts) may involve complex computations with various scoring inputs and statistical distributions. Therefore¸ a simulation technique for aggregation to estimate the likelihood of the quantified probability is required. A widely used technique for this process is Monte Carlo Simulation (MCS) (Garlick, 2017).

MCS can be used for risk analysis, especially when statistical data doesn't exist or is lacking (An *et al.,* 2011). MCS became popular in physics and operational research fields, and is now widely used in various fields, including engineering, physics, research and development, business, and finance (Mun, 2006).

This method is used to evaluate the effect of uncertainty by considering the random variable as a distribution of potential values each with a probability of occurrence. The uniform, triangular, normal and log normal distributions are commonly used distributions for this purpose (see Figure 3.8). The output of a MCS is a range of possible outcomes each with a relative frequency or likelihood of occurrence (BSI, 2010).

Raychauduri (2008) pointed out that the result of the MCS is computed by statistical analysis accompanying repeated random sampling. The analysis approach can be categorized as what-if analysis, which has the variation of the input parameters and is called case-based modelling (Figure 3.6); whereas the common mathematical model considers some input parameters for computation using mathematical expressions and produces one or more output (Figure 3.5).

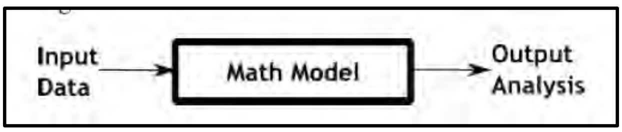


Figure 3.5 Mathematical models (Raychaunduri, 2008)

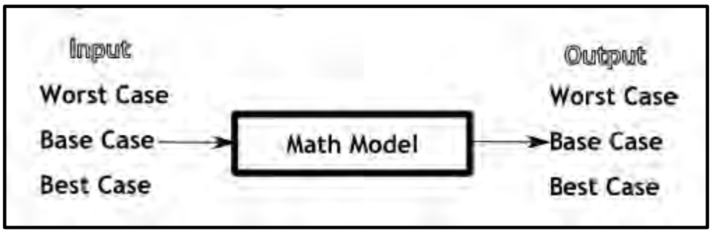


Figure 3.6 Case-based modelling (Raychaunduri, 2008)

As shown in Figure 3.4, a deterministic model is often called a base case due to the most likely input values. However, for the model considering the risk which contains the probabilistic matter, the various input parameters and scenarios will be associated with the analysis (Raychaunduri, 2008).

A MCS consists of the following steps: static model generation (using the most likely or base case as the input parameters of the deterministic model), input distribution identification, random variable generation, analysis and decision making (Raychaunduri, 2008). These are described below.

The literature describes a number of applications of MCS for infrastructure associated risk assessments. Ng and Fairfield (2002) used Monte Carlo methods for predicting the probability of the collapse of a masonry arch bridge with input parameters affected by collapse load predictions under certain conditions, such as live load dispersal angle; material bulk unit weights; backfill lateral pressure mobilisation; angle of shearing resistance; and Boussinesq's limiting live load influence. The results were compared to a real case, namely the Barlae Bridge for validation.

Clark *et al*. (2010) analysed and visualized risk and uncertainty for a capital budgeting of a MRI scanner project by mapping all possible outcomes using MCS. Input parameters included product mix, reimbursement rates, volume (number of scans), collection, period, and operating costs. The outcomes of their analysis were the probability and frequency of the net present value (NPV) of various project alternatives (options).

Flanagan (1993), used MCS to estimate cost based on historical cost data of building projects. The simulation was applied for estimating the competitive project cost accompanied by various cost parameters (Figure 3.7); this includes preliminaries, substructure, and superstructure, internal finishes, mechanical and electrical services, external works, fittings and furnishings. (Flanagan, 1993). Whilst Barraza (2010) proposed the project time contingency using Monte Carlo simulation for a stochastic approach. The input for the simulation is the activities' duration variability to obtain the planned, target durations, and time contingency.

El Cheikh and Burrow (2016) developed an integrated canal asset and risk management framework which considers data uncertainty within infrastructure maintenance decision making. They developed a probabilistic risk based approach to examine maintenance in which asset deterioration (ageing) and the cost and impact of maintenance were considered to be uncertain. Within El Cheikh's and Burrow's approach MCS was utilized to determine the uncertainty of dominant asset condition. A second MCS model utilized the asset condition uncertainty to identify a realistic range of maintenance costs.

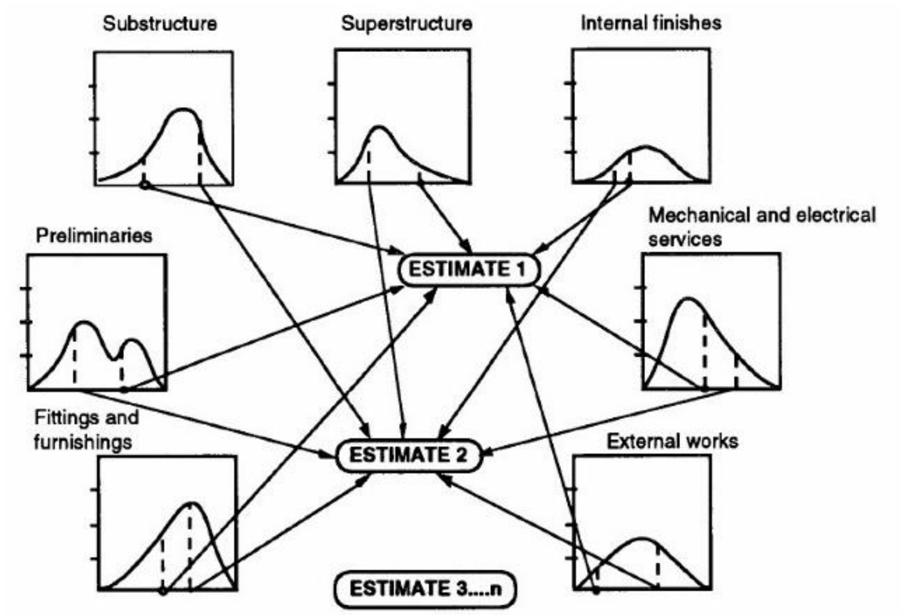


Figure 3.7 Illustration of various input parameters for project cost estimation (Flanagan, 1993)

3.5.3.1 Basic Steps for Performing a Monte Carlo Simulation

A Monte Carlo simulation (MCS) technique can be divided into different steps. Those steps could vary based on the scope of the problem; however, some basic steps that should be included in any analysis are outlined below (O'Connor and Kleyner, 2012):

a) Step 1: Define the problem and the overall objectives of the study. Evaluate the available data and outcome expectations.
b) Step 2: Define the system and create a parametric model, e.g. y = f(x) = f(x1, x2, ..., xq), where x=1,….,n
c) Step 3: Design the simulation. Quantities of interest need to be collected, such as the probability distributions for each of the inputs. Define how many simulation runs should be used. The number of runs, m is affected by the complexity of the model and the sought accuracy of results
d) Step 4: Determine input distribution to model uncertainty.
e) Step 5: Run the model with the set of distribution inputs, and store the results as yi.
f) Step 6: Repeat steps 4 and 5 for i = 1 to m.

g) Step 7: Analyse the results statistics, confidence intervals, histograms, best fit distribution, or any other statistical measure.

The above steps have been wide adopted by a variety of risk analysis software, e.g. @Risk^{TM} (Palisade Corporation, 2017).

3.5.4 Determining the input uncertainty in the risk model

In order to determine the uncertainty of the values of the inputs, resulting from expert elicitation (see Section 3.3.2) and or historical data, a number of distributions are commonly used. These distributions include triangular (triangle), uniform, BetaPERT, general cumulative and the discrete distribution (see Figure 3.8)

Although a variety of distributions in Figure 3.8 can be used to perform input uncertainty in the risk model, triangular and BetaPert distributions are frequently used for this purpose (see Sections 3.5.4.1and 3.5.4.2)

3.5.4.1 Triangular distribution

Triangular distribution is the most commonly used distribution for modelling expert elicitation. In this distribution, three variables, namely the minimum, most likely and maximum values of all possible values (see Figure 3.8 (a)) are obtained (often from expert elicitation). A MCS is then used to quantify the distribution in terms of ranges of possible values and their frequency of occurrence (Vose, 2008).

3.5.4.2 BetaPert distribution

The BetaPert distribution is a frequently used distribution for modelling expert opinion in estimating project duration incorporating PERT networks. The main inputs and illustration of this distribution are given in Figure 3.8 (c).

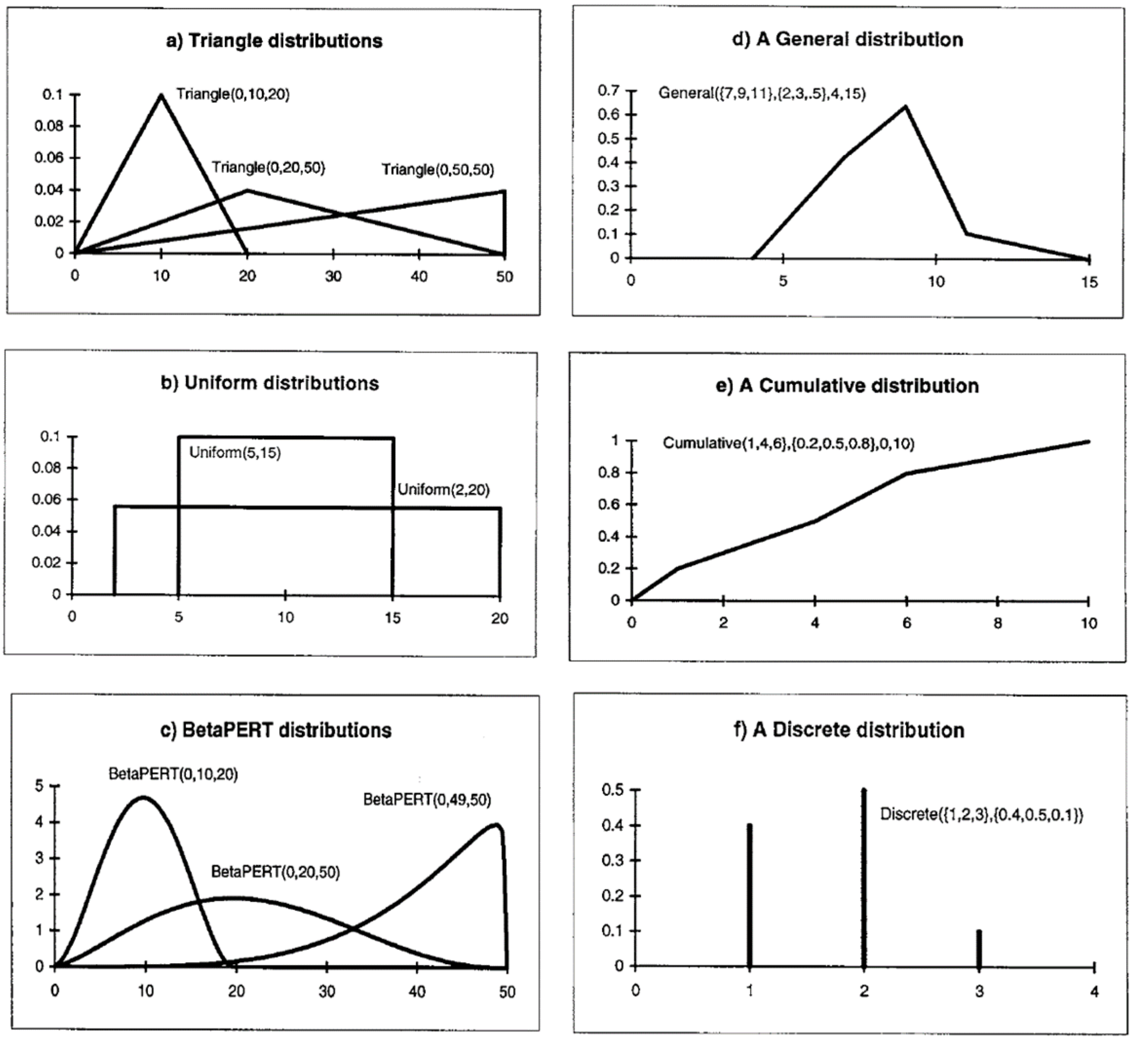


Figure 3.8 Illustrations of various probability distributions for Monte Carlo simulation (Vose, 2008)

3.5.5 Determining the most influental MCS inputs in the risk model using Tornado graph

In terms of MCS, tornado graph is utilised to present an overview to identify the the degree of influence of input distribution upon the change in value of the output. In other word, the graph is useful for identifying the key variables and uncertain parameters that are driving the result of the model. According to Neufville, Scholtes, and Stefan. (2011), tornado graph summarizes the relative effects of variations of several inputs over their ranges under the assumption that the other variables remain at their base values. In addition, this graph gives a measurement of the input distribution's influence using a horizontal bar which is plotted the variables from the top down in decreasing size of variations; it is apparent that the result a bit like a tornado.

3.5.5.1 Tornado graph's arrangement steps

To peform a tornado graph using an analysis software e.g. @Risk (Palisade Corporation, 2017), the following steps are typically arranged (Dionisio, 2018):

1. The baseline is the overall simulated mean of the output.
2. Each selected input distribution in this graph is represented by a double-side bar (i.e. left and right edges) which has numbers at its edges.
3. A horizontal bar is drawn by estimating average of output values resulting based on the lowest and highest inputs among a justified number of iterations respectively. @RISK divides those ordered iterations into 10 bins or "scenarios"; with 10,000 iterations, the first bin contains the 1,000 iterations; the second bin contains the 1,000 iterations with the 1,001st to 2,000th; and so on to the last bin (10,000 iterations).
4. @RISK puts all the iterations in order by ascending values of the inputs; this software computes the average of the output values within each bin.
5. @RISK ranks the ten output averages from the ten bins. The lowest of the ten output averages becomes the number at the left edge of the bar for this input (input low), and the highest of the ten output averages becomes the number at the right edge of the bar (input high).

3.6 Cost Benefit Analysis (CBA)

Cost-benefit analysis (CBA) is an appraisal tool used to appraise investments by comparing different investment strategies. A cost-benefit analysis identifies and estimates the costs and benefits of a project, programme or activity in monetary terms thereby enabling the comparison of various project alternatives (Nas, 1996; Commonwealth of Australia, 2006).

The notion of benefit in CBA mostly refers to the selection of various alternatives of a project, programme or activity, in respect to the allocation of scarce resources effectively (Nas, 1986; Snell, 1997 Brent, 2006; Boardman, 2017). In transport infrastructure, for example, Snell (1997) states that cost reductions are the main consideration for the benefits of improvements to transport infrastructure. These include user and non-user benefits; whereas costs correspond to construction expenditures, operation and maintenance (Nas, 1996, 2016; Snell, 1997).

3.6.1 CBA procedure

According to Nas (1996; 2016), the CBA consists of the following steps:

1. Identify both tangible and intangible benefits and costs.
2. Estimate expected costs and benefits in a specific monetary unit.
3. Quantify the appraisal values of multiyear project, programme or activity based on the standard criterion of net present value (NPV); if the decision-making process needs an additional parameter, the internal rate of return (IRR) can be used.
4. Define a specific discount rate for reporting the NPV values
5. Compare costs and benefits (benefit-cost ratios).
6. Select the desirable option among various alternatives. In this stage, the proposed alternatives are ranked by at least one of the three selection criteria as follows:
    a. B-C ratio>1

b. NPV>0

c. IRR>market or private rate of return

3.6.2 CBA formulation

The following formulae are used to calculate the above three selection criteria (Boardman *et al.*, 2017):

B-C ratio

$$BCR = \frac{PV(B)}{PV(C)} = \frac{\sum_{t=0}^{n}\frac{Bt}{(1+i)^t}}{\sum_{t=0}^{n}\frac{Ct}{(1+i)^t}} \qquad \text{Eq. 3.12}$$

NPV

$$PV(B) = \sum_{t=0}^{n}\frac{Bt}{(1+i)^t} \qquad \text{Eq. 3.13}$$

$$PV(C) = \sum_{t=0}^{n}\frac{Ct}{(1+i)^t} \qquad \text{Eq. 3.14}$$

$$\text{NPV} = PV(B) - PV(C) = \sum_{t=0}^{n}\frac{Bt}{(1+i)^t} - \sum_{t=0}^{n}\frac{Ct}{(1+i)^t} \qquad \text{Eq. 3.15}$$

Where:

PV (B) = present value of benefit

PV(C) = present value of cost

t = year =0, 1, 2, 3………. n

i = discount rate

IRR

Internal rate of return (IRR) is the discount rate at which the NPV is zero

3.2.4 CBA formula for railway track drainage

For the purposes of this research benefit is defined as the range of potential cost saving (or risk reduction) due to impact reduction or prevention of a maintenance scenario. Cost is defined as the intervention cost to mitigate the occurrence of the identified risks. Evidently this assumes that the cost impact values result in benefits, when the occurrence of failure or defective is mitigated, by applying suitable interventions or maintenance.

3.7 Risk Assessment in Practice

Those working in high-risk industries such as nuclear power plants, military, oil and gas, chemical processing and mining pioneered risk assessment approaches to deal with severe or catastrophic events. The notion of high-risk industries usually refers to industries that may involve radiation, explosives, high levels of fatalities and severe financial losses. Risk assessment in high-risk industries includes identifying failure mechanisms and impact modelling, monetary loss estimation, impact prediction and mitigation and probabilistic safety management. For example, in the chemical processing industry risk assessments aims to present an impact scenario incorporating the probabilistic level of failure (Charvet *et.al.,* 2011), visual simulation of an explosive event (Zhang and Chen, 2013) and monetary loss prediction of a catastrophic event (Kleindorfer *et al.*, 2012).

Following the work initiated by those working in high-risk industries risk assessment approaches have been adopted in a variety of infrastructure associated industries. In infrastructure associated with public usage, this has in part been driven by increasing public awareness of the adverse outcomes or impacts of a failure event. These industries include bridge engineering (e.g. Biondini *et al*, 2008), airports (e.g.; Keokhumcheng, 2012), tunnelling (Qu *et al.*, 2011), roads (Schlotjes *et al.*, 2013), and urban drainage (e.g. Ana *et al.*, 2009). Table 3.5 provides a summary of the literature to this end. Since drainage risk failure is of particular reference to this research, Section 3.8 discusses the application of risk assessment in the railway sector, whilst Section 3.9 assesses studies associated drainage asset risk failure

Table 3.4 Application of risk assessment to undertake uncertainty in various public infrastructure research

Type of Infrastructure	Contribution	Uncertainty Factor	Technique(s)	Purpose	Author(s)
Bridge Engineering	Structural damage modelling for cable stay bridges	component, environmental, maintenance	Scenario, Monte Carlo Simulation (MCS)	Perform structural damage by quantification of uncertainty	Biondini et al. (2008)
	New method for aerostatic stability of suspension bridges	component, environmental (wind loads)	Monte Carlo Simulation (MCS)	Probabilistic analysis	Cheng et al. (2003)
Airport	Flood assessment framework	environmental (flooding)	Scenario	Perfom flood impact	Keokhumcheng et al. (2012)
	Runway incursion hazard assessment	human error, operation, design.	Fault Tree Analysis (FTA) Analytic Hierarchy Process (AHP)	Perform probability Impact, weighting factors	Kim and Yang (2012)
Tunnel	Quantitative risk assessment	component, traffic, fire	FTA, ETA Event Tree Analysis (ETA)	Risk mapping	Qu et al. (2011)
	A risk management methodology	environmental, subgrade (ground surface settlement)	risk management procedure	Perform impact tunnelling work	Qian Fang et al. (2011)
Road	Failure mechanisms framework	design, component, environmental, construction, traffic	descriptive FTA, contributing factors diagram	Perform failure modes	Schlotjes et al. (2013)
	Pavement failure prediction procedure	design, component, environmental, construction, traffic	descriptive FTA Support Vector Machines (SVM)	Perform failure modes and types	Schlotjes et al. (2015)
	Pavement deterioration model	component, environmental	Scenario MCS	Perform scerario, parameters likelyhood	M Anyala et al. (2014)
Urban Drainage	Application for quantifying uncertainty	component, environmental	Multicriteria Decision Making (MCDM)	Quantifying uncertainty and prioritization of sewer rehabilitation	Ana et al. (2009)

3.8 Risk Assessment in the Railway Industry

Risk assessment approaches have been used in the railway industry for various purposes including hazardous material transport (e.g. Barkan, 2008), rolling stock safety assessment (as in An *et al*., 2011), incident model (Bearfield *et al*., 2013), fire risk (Camillo *et al*., 2013). Cross wind risk (Freda and Solari, 2010), snow-avalanches risk (Larsson-Kraik, 2012), adverse weather on urban rail facilities (Ma *et al.*, 2013), track buckling (Nguyen, 2012), track condition (Rhayma *et al*., 2011), and signalling (Zhang *et al.*, 2013). A number of studies identified from the literature are summarised in Table 3.5.

3.8.1 Risk management to inform decision making in the railway industry

Various studies have advocated the use of risk management to inform decision making in the railway industry, typically to identify potentially harmful events and quantify their frequency of occurrence and impact. Such studies include those associated with safety and the degradation of track infrastructure. For example, derailment (Liu *et al*., 2012) and failure of rolling stock (An *et al*., 2007); the safe operation of infrastructure including tunnels (Beard, 2010), level crossings (Berrado *et al.*, 2010), security threats ranging from vandalism to terrorism (Flammini *et al.*, 2008; Sanchez, 2011); the impact of ballast fouling on drainage performance (Tennakoon *et al.*, 2012), earthwork failure (Okada and Sugiyama, 1994; Crapper, 2014), railway foundation failure risk (Huang *et al.,* 2006), and infrastructure maintenance (Chiachío *et al.*, 2017).

A number of other studies focus on the affect of outside agents (weather, flooding, landslides and earthquakes). For example, flooding risk and its impacts on the operation of conventional rail in the UK (McBain *et al,*, 2010; Penning-Rowsell *et al.*, 2013), track disruption due to landslides (Ko *et al.*, 2005) and earthquakes (Pitilakis *et al.*, 2006).

A risk-informed approach to deal with economic impacts has also been considered in the literature as in cost overruns and demand shortfalls in urban rail (Flyvbjerg, 2007) and investment appraisal of rail projects (El-Cheik *et al.*, 2013).

In terms of poor drainage mechanisms of ballasted railway track, a probabilistic fault tree which relates the failure event and its causes has been developed (Usman *et al*., 2017). There is however a paucity of research on railway drainage risk.

Table 3.5 Risk assessment application in the railway industry for addressing uncertainty

Research Topic	Contribution	Uncertainty Factor	Technique(s)	Author(s)
Hazardous material Transport	Risk reduction framework for improving railway tank.	Component, Operational	Probabilistic Risk Analysis	Barkan (2008)
	Risk assessment framework	Component, Operational	HazOp, FTA	Cozzani et al. (2007)
Safety Management	Safety risk management framework	Maintenance, Operational	FAHP	An et al. (2007)
Incident	Incident model	Operational	ETA, BN	Bearfield et al. (2013)
Fire Risk	Analysis methodology for fire risk	Component, Operational	ETA, MCS	Camillo et al. (2013)
Crosswind Risk	Probabilistic model for crosswind risk	Environmental	Probabilistic analysis	Freda and Solari (2010)
Snow-avalanches Risk	Snow-avalanches assessment	Environmental	Risk Matrix ETA,FTA, Cost-benefit risk	Larsson-Kraik (2012)
Adverse Weather	Adverse Weather assessment	Environmental, Design, Maintenance, Subgrade	FTA, FAHP	Ma et al. (2013)
Track Buckling	Track Buckling assessment	Encironmental, Component, Maintenance	MCS	Nguyen et al. (2012)
Track Condition	Probabilistic estimation of railway ktrack conditionprocedure	Component, Maintenance	Historical Field Data MCS	Rhayma et al. (2011)
Sinalling System	Assessment of railway signalling system	Component, Maintenance	FMECA, FAHP	Zhang et al. (2013)

3.9 Risk Assessment Approach on Railway Drainage

Risk assessment approach on railway drainage has rarely been done in the last decade. Recently, the ongoing efforts to utilise this approach focus on the development of a degradation model of railway drainage combining flood model (Wu *et al.*, 2019), engineering model incorporating expert elicitationto identify risks associated with inadequate drainage (Usmena *et al.*, 2019), sensor technology for remotely monitoring the performance and condition of drainage systems (Devan, 2019).

Wu *et. al*. (2019) predict the degradation of a variety of railway drainage asset using a Markov Chain model to inform a flood risk estimation model. The degradation rate is estimated by considering the influence of the characteristics of asset construction material, size, shape and location. To this end, a combined model (deterioration and flood risk) is being tested on several sites across the UK. Whilst Usman *et al* (2019) proposes a risk identification procedure using expert elicitation can inform the decision makers about the availability of risks which are contributed as causes of defective or failed of subsurface and surface drainage assets. Expert elicitation was utilised in two occasions; first, a focus group discussion (FGD) for reviewing, improving, and validating the proposed risks which was presented as an engineering model incorporating a fault tree (FT) structure; second, a discussion and questionnaire for justifying the availability of risks at the selected site as case study. The procedure is demonstrated using data obtained on the UK railway network.

Moreover, Devan (2019) invistigates the use of sensor technology to monitor remotely the performance and condition of drainage systems in order to move towards a risk-based approach to inspection and maintenance. This sensor, namely TrackWater which able to collect real time data allowing degradation rates to be predicted and enabling proactive maintenance to be undertaken before a failure occur. The TrackWater sensor is an Internet of Things (IoT) approach to rail water management and currently focuses on piped drainage systems with sensors installed in catchpits. This can be used to measure the silt and water level in a catchpit which may lead to silting and flooding events.

Despite the paucity of studies in railway drainage risk, in the highways sector, drainage risk-informed studies are more prevalent. Barnet (2017) for example, developed an approach informed by expert opinion to identify and quantify the risks of highway drainage flooding, and the potential causes and impacts of extreme weather events on Sweden's national road network were investigated by Kalantari and Folkeson (2013). Because of its potential severe impacts, the flood risk of urban drainage has been studied extensively and indeed risk assessment forms an integral component of the ASCE Standard Guidelines for the Design, Installation, and Operation and Maintenance of Urban Subsurface Drainage (ASCE, 2006).

In this regard, Coulthard and Frostick (2010) formulated an approach based on spatial map analysis taking, into account the performance of pumping stations and sewer networks to investigate the causes of flooding in the UK city of Hull. Veldhuis et al. (2009, 2011) proposed a fault tree-Monte Carlo simulation model to identify and quantify the major factors contributing to urban flooding and demonstrated their approach for Haarlem in the Netherlands. Risk-informed approaches have also been used to model the deterioration of urban drainage assets, storm water pipes and sewers (Ana and Bauwens, 2010; Tran *et al*., 2008; Baah *et al.,* 2015; Rodríguez, 2012) and for managing urban flood risk (; McBain *et al*, 2010; Merz *et al.*, 2010; Balsels *et al.,* 2012,; Kandilioti and Makropoulos, 2012).

3.10 Summary

Risk assessment has been adopted in various industries in order to identify and quantify risks and their associated impacts. In the railway industry the approach has been used typically to identify potentially harmful or failure events and quantify their frequency of occurrence and impacts, However, there has been little risk associated research on railway track drainage.

In the case of a lack of historical data, expert judgement can be used to quantify probability of occurrence (likelihood) and impact of risk events.

In terms of the development of a risk-informed model, various techniques can be used, however, due to the limitation of a single technique, a combination of appropriate techniques may be needed. Accordingly, a combination of the contributing factors' diagram (CFD), fault tree analysis (FTA), semi-quantitative, and Monte Carlo simulation could be adopted to achieve the objectives of a model.

A risk-informed approach yields a range of probabilistic estimations of risk value instead of the single value that would be provided by a deterministic approach. These ranges are associated with the probability of occurrence of the identified risks and the cost impacts. Such an approach would seem to be suitable for railway drainage risk assessment and its use is investigated in the remaining chapters of this thesis.

4 METHODOLOGY

4.1 Introduction

The literature review has shown that there has been as yet no systematic research to develop a risk-based assessment framework for the appraisal of ballasted railway track drainage maintenance. This framework can be used to plan appropriate drainage interventions by facilitating the prioritisation of preventive maintenance of those areas of the track at greatest failure risk. The research methodology for establishing a theoretical framework (see Section 4.3) to assess the risk associated with poor drainage of ballasted railway track is presented in this chapter. Section 4.2 describes the methodology used to conduct the research.

4.2 Research Methodology

The methodological approach that has been taken in this study is summarised in Figure 4.1, which shows how the research objectives identified in Section 1.3 are to be achieved. The outlined methodology is categorised into four stages comprising: literature review; building the risk-informed framework based on a theoretical concept; model development; and; case studies. The above stages are as follows:

1. Review the literature: A literature review was carried out primarily to:
    a. Identify and understand the relative importance of the factors (i.e. environmental, design, construction, components, subgrade, land use, maintenance and traffic) which may lead to poor ballasted railway track drainage. This review has been described in Chapter 2.
    b. Identify an appropriate risk-informed modelling framework which could be utilized by railway asset managers to prioritise railway drainage maintenance. Chapter 3 describes this aspect of the research.

c. Identify potential modelling techniques which may be suitable for the risk-informed framework. These techniques were compared and contrasted to identify the most suitable for the task at hand

2. Building the risk-informed framework: The framework was developed theoretically based on risk assessment approach and by so doing it allows the identification, analysis and evaluation of railway track drainage risk. Section 4.3 provides this aspect of the research.
3. Model development: The literature identified that the framework should consist of two parts, namely a risk-based engineering model and a risk-informed cost (impact) model. The engineering model was developed to identify the causal factors of drainage failure and provide a means to quantify the probabilities of the occurrence of drainage failure. The engineering model was developed from the literature review and through expert elicitation. The risk-informed cost model was developed to appraisal the socio-economic impacts associated with poor track drainage so that appropriate maintenance action may be undertaken or planned. In the engineering model, experts were involved in a half day drainage workshop to validate the proposed fault tree (FT) structure and suggest additional risk items based on industrial point of view. The above models will integrated using a combination of various techniques identified from the literature (see above). Possible approaches have been presented in Chapter 3. The engineering and cost models debelopment are presented in Sections 4.5 and 4.8
4. Demonstrate the applicability of the framework via case studies. The developed framework was demonstrated through a risk-informed quantification procedure (see Sections 4.19 and 4.11) using data obtained from three sites on the UK railway network. The sites were selected as they were susceptible to flooding in recent years which may caused by poor drainage of ballasted railway track (see Chapter 6)

5. In this stage, expert who has proper knowledge and experiences on the selected sites assisted to identifty the availability of risk items on the selected sites Chapter 6, 7 and 8 describe the sites in detail.

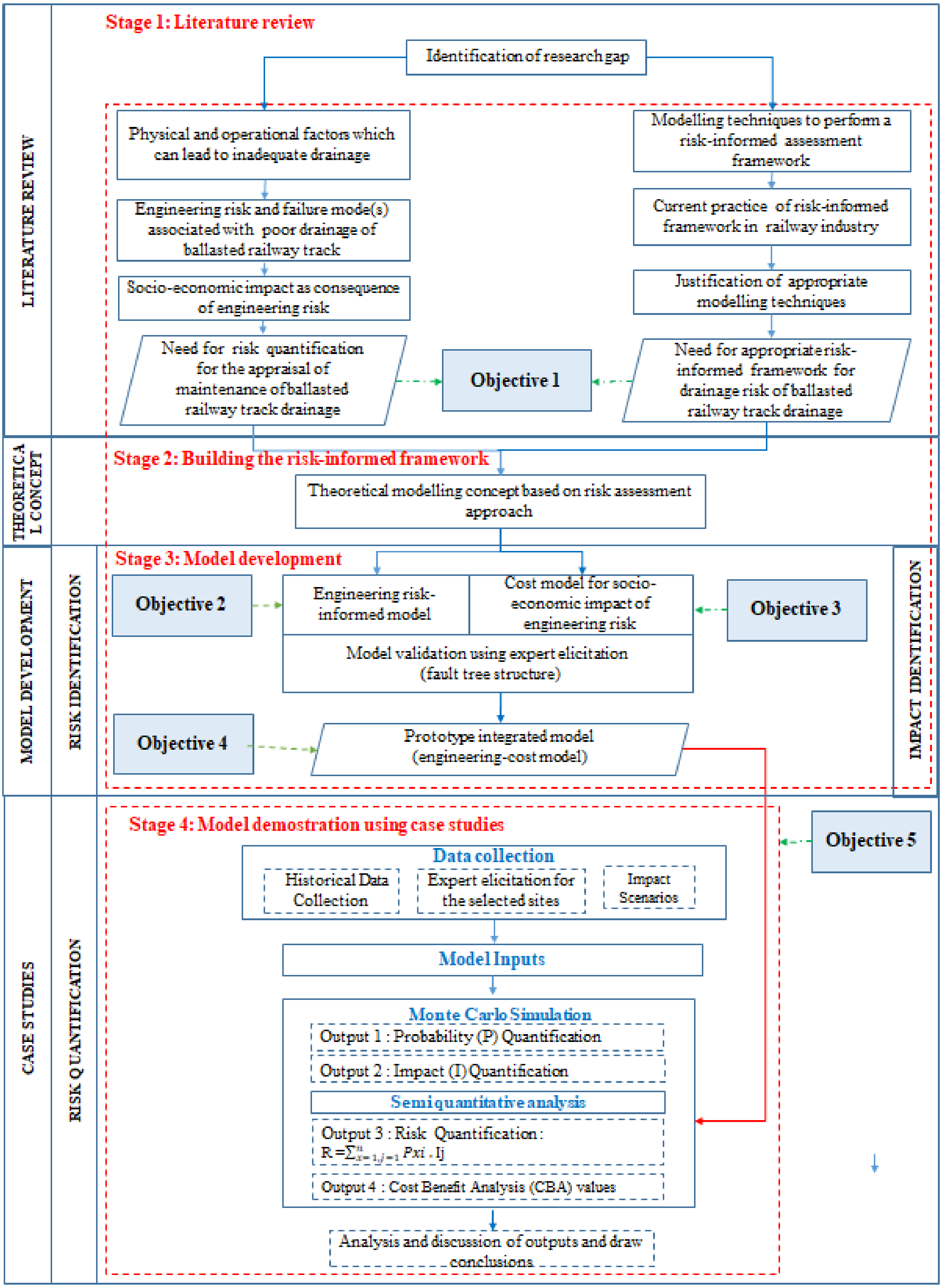


Figure 4.1 Schematic research methodology

4.3 Theoretical Framework

This research develops a network level, risk-informed framework for assessing railway drainage failure. It does so in order to identify those parts of the railway network at the greatest risk of drainage failure. Doing so will aid drainage asset managers to apportion funds for preventative maintenance.

Such a framework should comprise of two elements (BSI, 2010; Ayyub, 2014):

I. Risk identification, in order to identify the factors that contribute towards inadequate drainage (i.e. contributing factors) (see Section 4.4).

II. Risk semi-quantification and quantification (see Sections 4.10–4.11), which involves: estimating and quantifying the probability and impact of drainage failure resulting from identified risks; evaluating the risk to a section of railway track using various quantification processes in order to evaluate the risk of the drainage failing on a particular section of railway track; and assisting drainage asset manager to prioritize maintenance.

The framework is summarised in Figure 4.2, elaborated in Figure 4.3-Figure 4.5 and described in detail below. The framework comprises three modules as follows:

a. First module: Engineering model

   The engineering model is designated to identify drainage associated risks and assign probabilities of occurrence to the risks (see Figure 4.3). The development of this model is presented in Section 4.6

b. Second module: Cost model

   The cost model is appointed to determine the risk impacts (see Figure 4.4). Section 4.8 describes this model in detail

c. Third module: Integrated model incorporating preventive maintenance appraisal

The integrated model is assigned to determine risk values. The estimated risk values are used further for the appraisal of drainage maintenance (see Figure 4.5). The development of the integrated model and appraisal procedure are presented in Sections 4.10, 4.11, and 4.12.

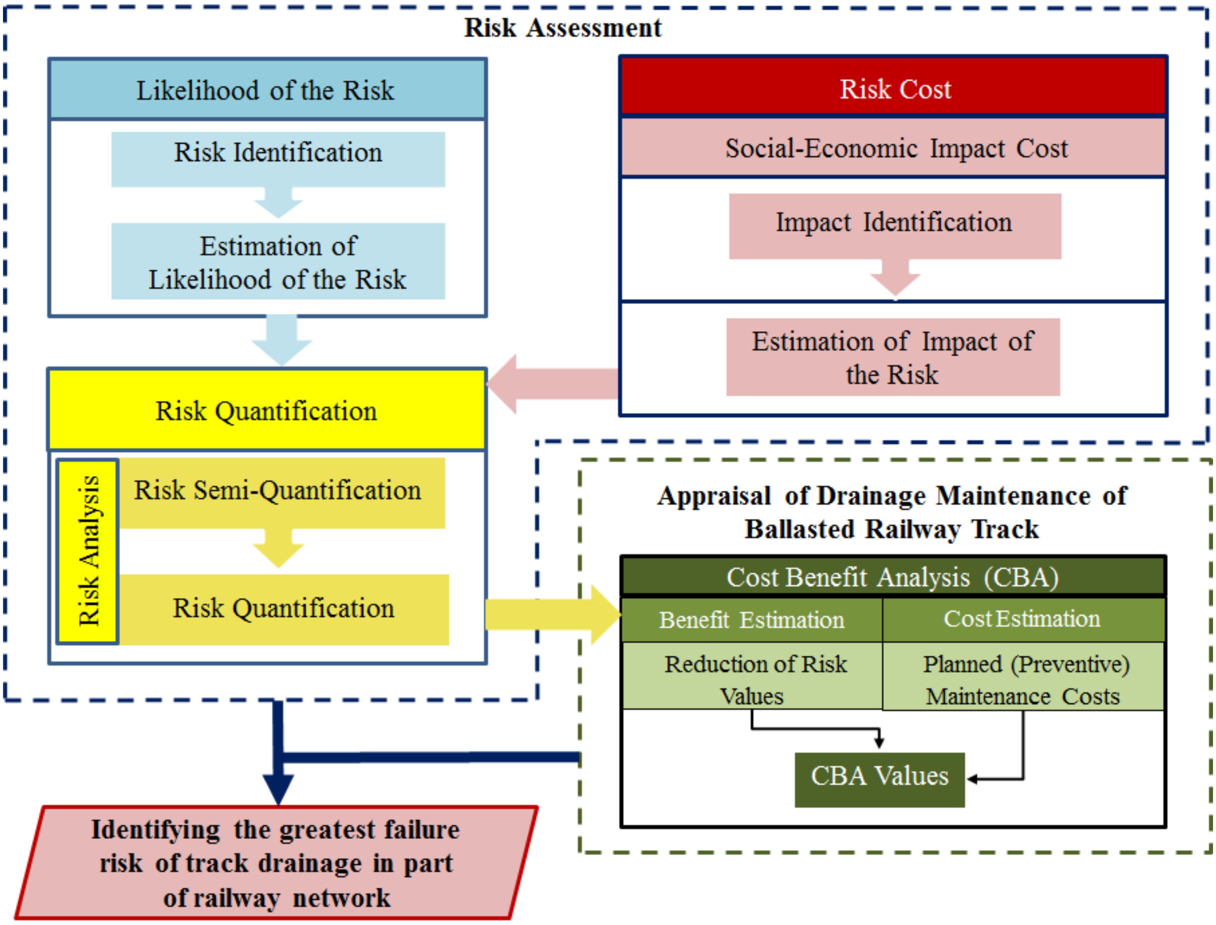


Figure 4.2 Theoretical model

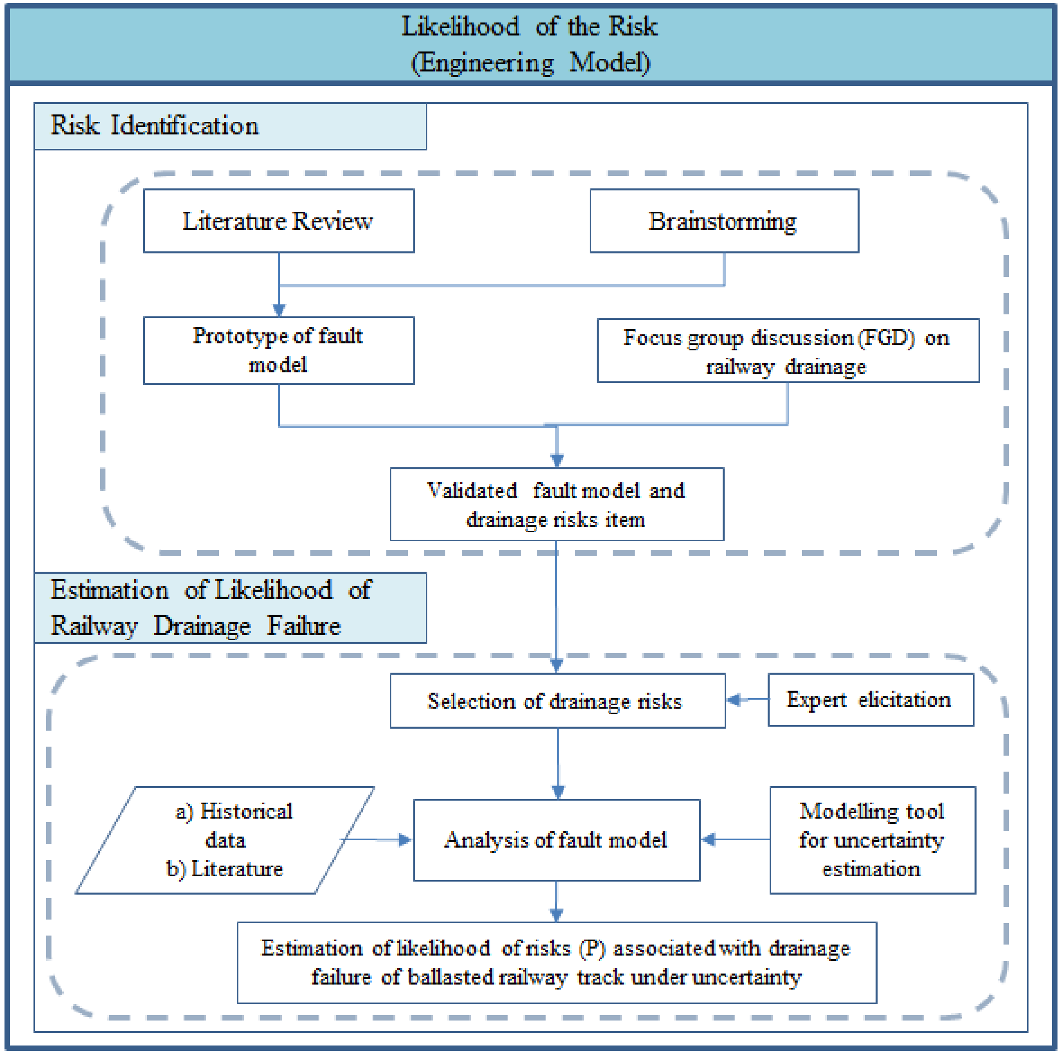


Figure 4.3 Module 1: Engineering model

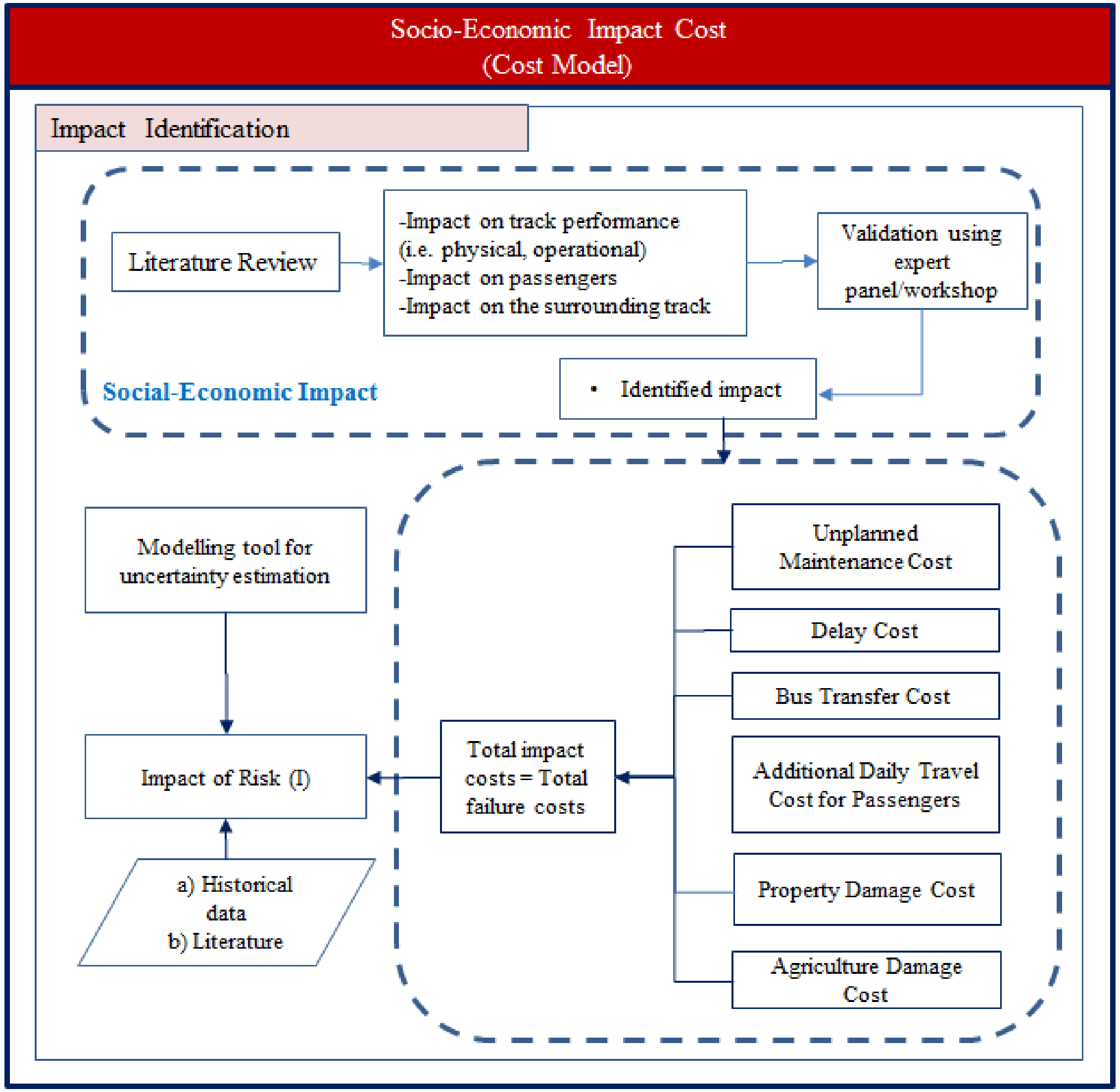


Figure 4.4 Module 2: Cost Model

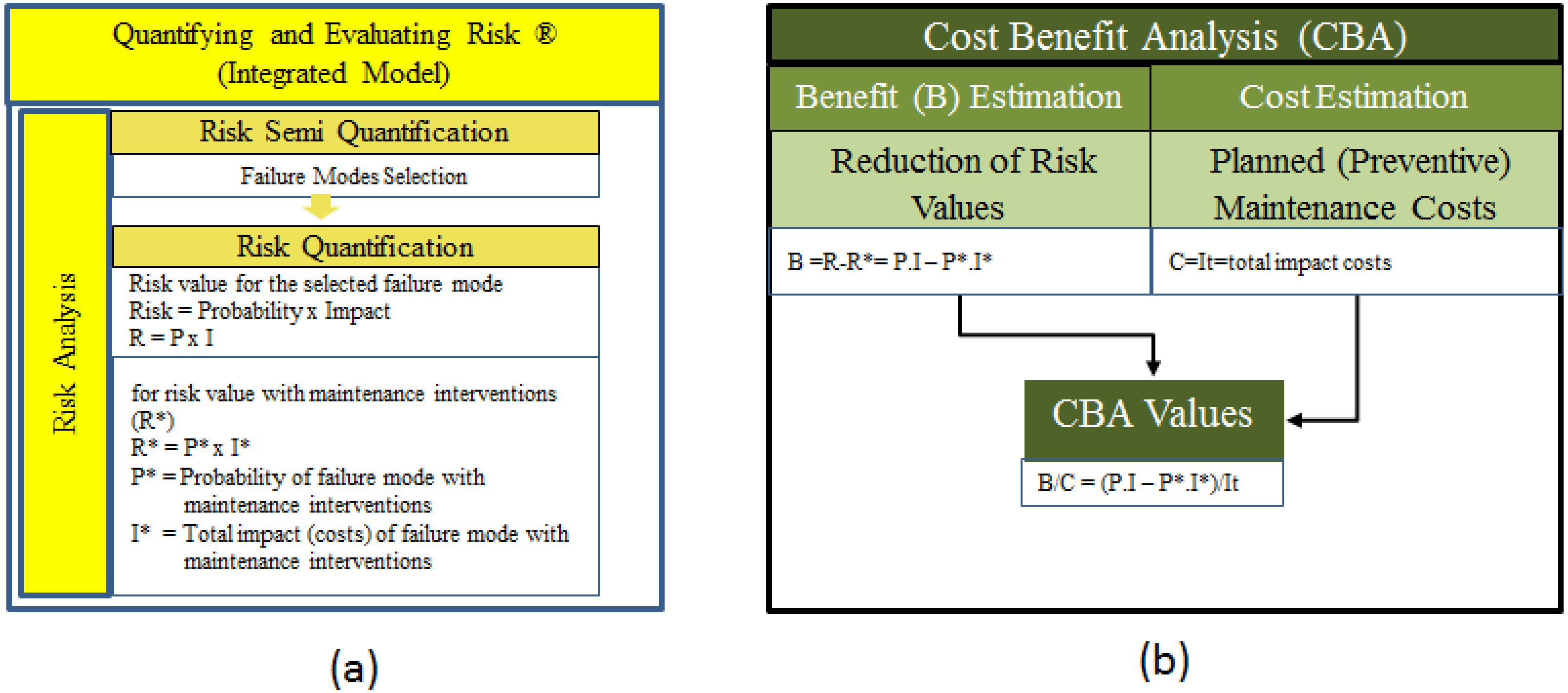


Figure 4.5 Module 3: Integrated model (a) and maintenance appraisal (b)

4.3.1 Homogenous sections of railway track Homogenous sections of railway track

The term 'homogeneous section' refers to a ballasted railway track section that shares similar characteristics. In terms of track drainage risk, a homogenous section is assumed to be subject to similar fallout when a drainage fails or becomes defective. The length of a homogeneous section is typically 1/8 mile (approximately 200m); it is a measure used for various monitoring activities in the rail industry. For example, Le Pen *et al.* (2014) point out that Network Rail (UK) uses 1/8-mile intervals to monitor track geometry (using standard deviation of vertical geometry), whereas the Portuguese Railway uses a 200m interval to measure track defects, using standard deviations of longitudinal-levelling and of horizontal alignment (Andrade and Teixeira, 2014).

4.4 Risk Identification

To identify the risks to drainage performance, a literature review was undertaken, accompanied by brainstorming and reference to expert opinion. Expert opinion was canvased via a workshop held at the University of Birmingham on the 7th September 2017, attended by nine members of Network Rail's drainage team and two University of Birmingham academics. Initially, eight broad categories of risk were identified see as shown in Section 2.8 With these eight risks in mind, discrete risks were identified for each of the eight categories. These are shown in Table 4.1-Table 4.3.

4.5 Engineering Model

An engineering model was established, which links the risk to the adequate performance of drainage assets (identified in Section 2.6) to the probability of failure occurring as a result of the risks discussed above. There are several modelling tools that can be used to systematically link the failure of a system and its components to the causes of these failures.

The methods include (see):

1. Contributing factor diagrams (CFD)
2. Fault trees (FT)
3. Event trees (ET)
4. Failure modes and effect analysis (FMEA)

The contributing factor diagram is used to construct a specific problem. It entails mapping variables (i.e. risks) and is presented in graphical form (e.g. a circle, ellipse). Each variable may consist of other variables (Koller, 2005; Ayyub, 2014). This diagram can be used to map the potential contributing factors involved in a drainage failure.

With the fault tree approach, the main objective is to determine a particular failure in a system, known as the 'top event', by assessing the contributing factors ('mid' and 'basic' 'events'). This approach is known as 'backward logic" (Bedford and Cooke, 2001; BS, 2010). It is useful as a means to map the causal relationship between the failure event and its contributing factors and to identify the interaction between components and subcomponents.

Event tree analysis (ETA) is an inductive approach that can be used to map the sequence underlying a problem in a tree-like, logical structure (using what is known as forward logic). Every branch in this tree maps two cases, one successful and one unsuccessful (Ayyub, 2014; BS, 2010; Bedford and Cooke, 2001). However, this might inhibit this tool to model the problem with any number of branching in its node.

According to Ayyub (2014), the FMEA approach is an inductive modelling approach. It identifies failure mechanisms (modes) of the identified component and the impacts on the surrounding components and the system as a whole. More details about this approach is provided in Section 3.1.3. The FMEA assesses the identified risks based on the value of what is known as a risk priority number (RPN). The RPN's value is computed by multiplying the rating of three main variables, each of which correspond to a risk's occurrence, severity, and detection. This tool can be most effectively used when the system is well-defined. However, its implementation is limited for developing systems, where historical data of failure rates may be missing or incomplete.

When it comes poor track drainage problems, the objectives of the engineering model model are:

- To relate component failure to contributory factors
- To quantitatively map the probability that a failure will occur on the basis of contributory factors.

Accordingly, the following criteria were devised to select the most appropriate of the three modelling approaches:

1) The tool can be used to understand failure mechanisms of drainage of ballasted railway track in a logical manner; this means it must have a focus on the poor drainage event, failure mode(s) and causal influences.
2) The tool should be able to quantify the probability of an asset failing using a range of data sources (e.g. historical, literature) and through discussion with experts.
3) The tool can be used to aggregate the above data and provide a range of likely values.

4.6 Engineering Model Development

As shown above, the advantages and limitations of various tools are considered in order to justify the intended modelling tools. Therefore, a combination of the Contribution Factor Diagram (CFD) the Fault Tree (FT) approaches was chosen for the analysis here. Doing so brings a number of advantages (BSI, 2010):

- It uses a pictorial approach to describe the interaction between failure events, failure modes and their causal factors (i.e. risks) in a logical manner. This, it is felt, makes it a suitable tool for drainage engineers.
- FTs can be used to provide qualitative and quantitative analyses, which makes them ideally suited to scrutinising railway infrastructure drainage failures, given that numerical failure data and expert opinion is likely to be required.
- FTs can be combined with other techniques.

Section 3.1.4 describes Fault Trees in more detail.

The approach adopted to develop the FT for the task at hand consisted of the following steps (Usman *et al*., 2017):

1. Identify from the literature the major subsurface and surface track drainage asset types.
2. Determine, by means of a literature review, the potential failure modes associated with each subsurface and surface track drainage asset, such as blocked, collapsed, over-capacity or clogged filters. A failure mode is taken to be a specific defect or failure type for a drainage asset.
3. Identify the potential causal factors for each failure mode (see Section 2.4) associated with each asset type, using a CFD (see Figures 4.7 to 4.12). This process helps to associate identified risks or causal factors (see Section 2.5 and Tables 4.1-4.3) with the physical

consequences posed by the risk occurring to a drainage asset.

4. Separate the causal factors identified in step 2 into a hierarchy of basic, mid-level and undesired events (i.e. failures) (see column 3 in Tables 4.1, 4.2, and 4.3).
5. Arrange the basic, mid-level and undesired events into a Fault Tree (see Figures 4.13 – 4.18).
6. Determine the Boolean relationships (i.e. 'or', 'and') between the causal factors and the failure mechanisms (see Figures 4.13 to 4.18)

Once the Fault Tree has been developed using a step by step approach to identify the basic and mid-level events (see Section 4.6.1), expert advised was elicited in to verify its structure and the identified risks. Thereafter, the probabilities are aggregated using the approach described in Section 4.7 This will allow us to assess the likelihood of inadequate track drainage (i.e. the undesired event).

The above approach is illustrated below by means of examples.

<u>Step 1: Identifying the drainage asset types</u>

The literature review (see Section 2.3 – 2.4) identified the following drainage asset categories:

1. Subsurface drainage (i.e. pipes, catchpits and manholes)
2. Surface drainage (i.e. channel drains and ditches, outfall, and culvert)

<u>Step 2: Determining the failure modes</u>

For each identified asset type failure, modes were determined from the literature. These are summarised by asset type in Table 4.3. For example, for pipes, the identified failure modes are: a blocked pipe (D1), a collapsed pipe (D2), inadequate capacity of a pipe (D3) and filter media problems (D4).

<u>Step 3: Brainstorming/Contributing Factor Diagrams</u>

Brainstorming was used to develop CFD for each drainage asset group. These are shown in Figure 4.6 to Figure 4.11. For example, Figure 4.9 shows the causal factors accompanying defective or failed channel drains and ditches; we can see that failures sequence through one of its FT branches. Heavy rainfall (X6) resulted in excessive water infiltration to the track bed (H1), which then resulted in softening below drain level (G1). This then resulted in settlement due to a change in gradient (F1), which in turn has resulted in silting channel drain and ditches (E12), which has then resulted in blocked channel drains and ditches (D8). This culminates in failing/defective channel drains and ditches (C3).

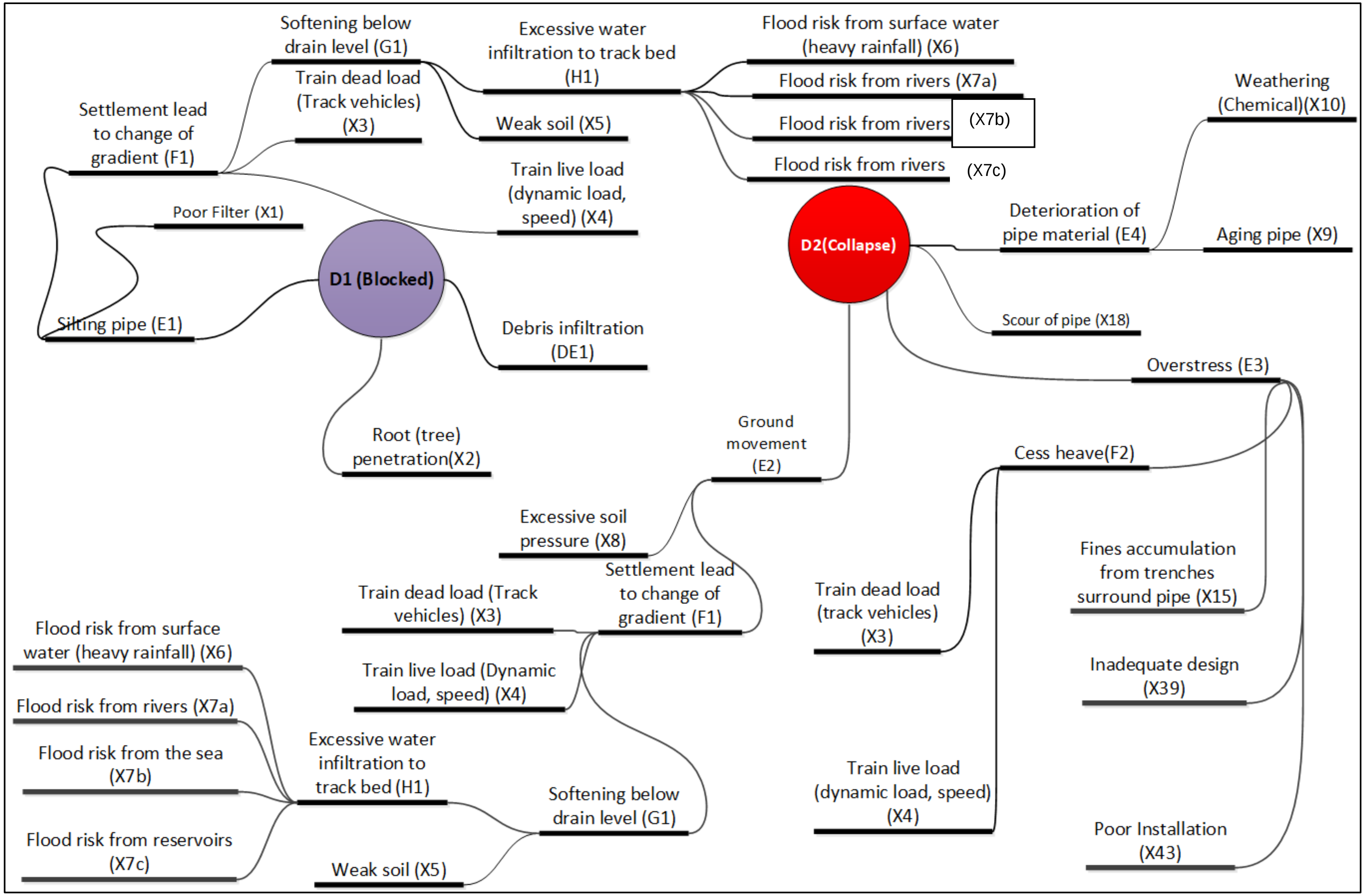


Figure 4.6 Contributing factors diagram for pipes (C1), assigning blocked and collapse failure modes

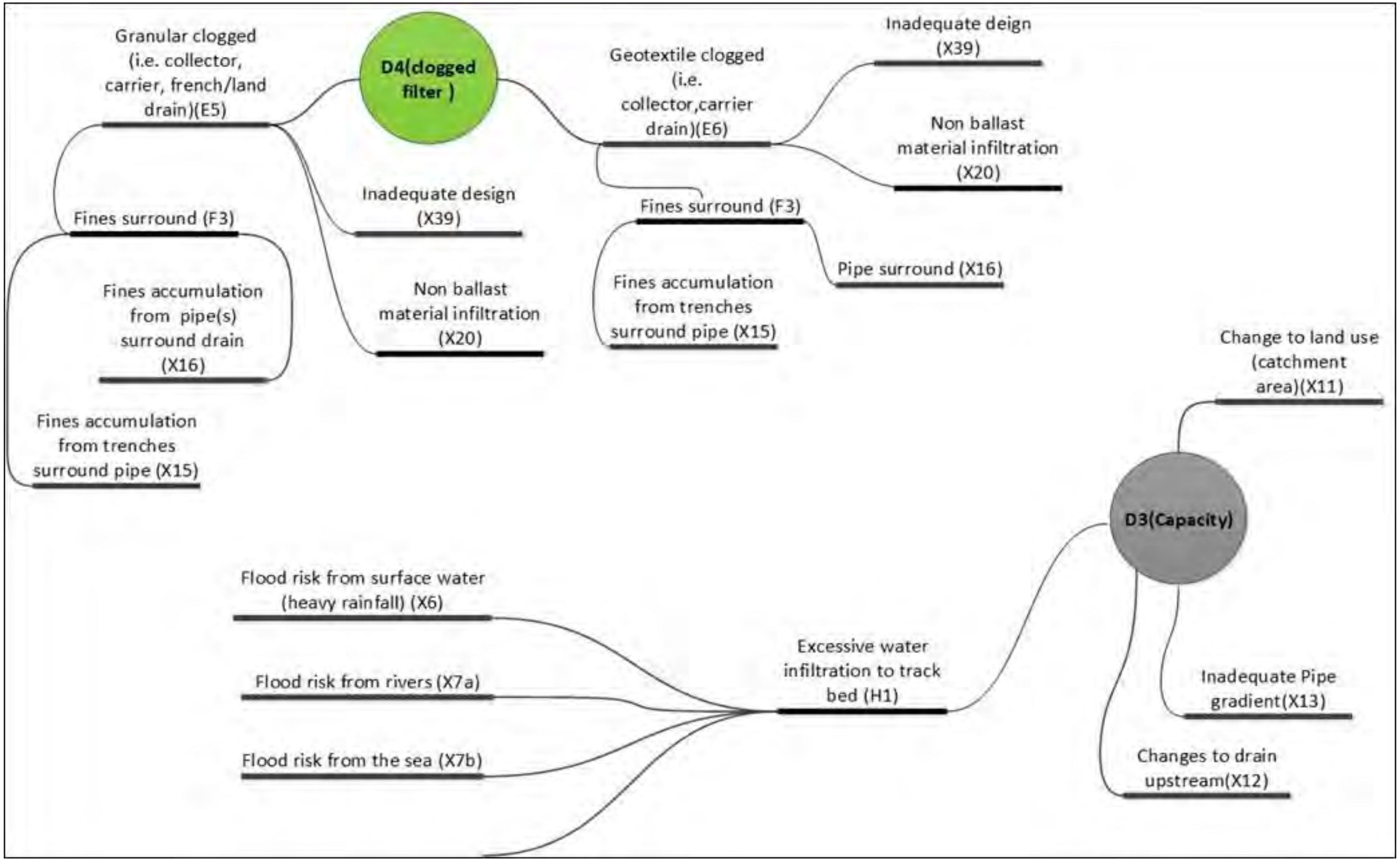


Figure 4.7 Contributing factors diagram for pipe (C1), assigning inadequate capacity and clogged filter

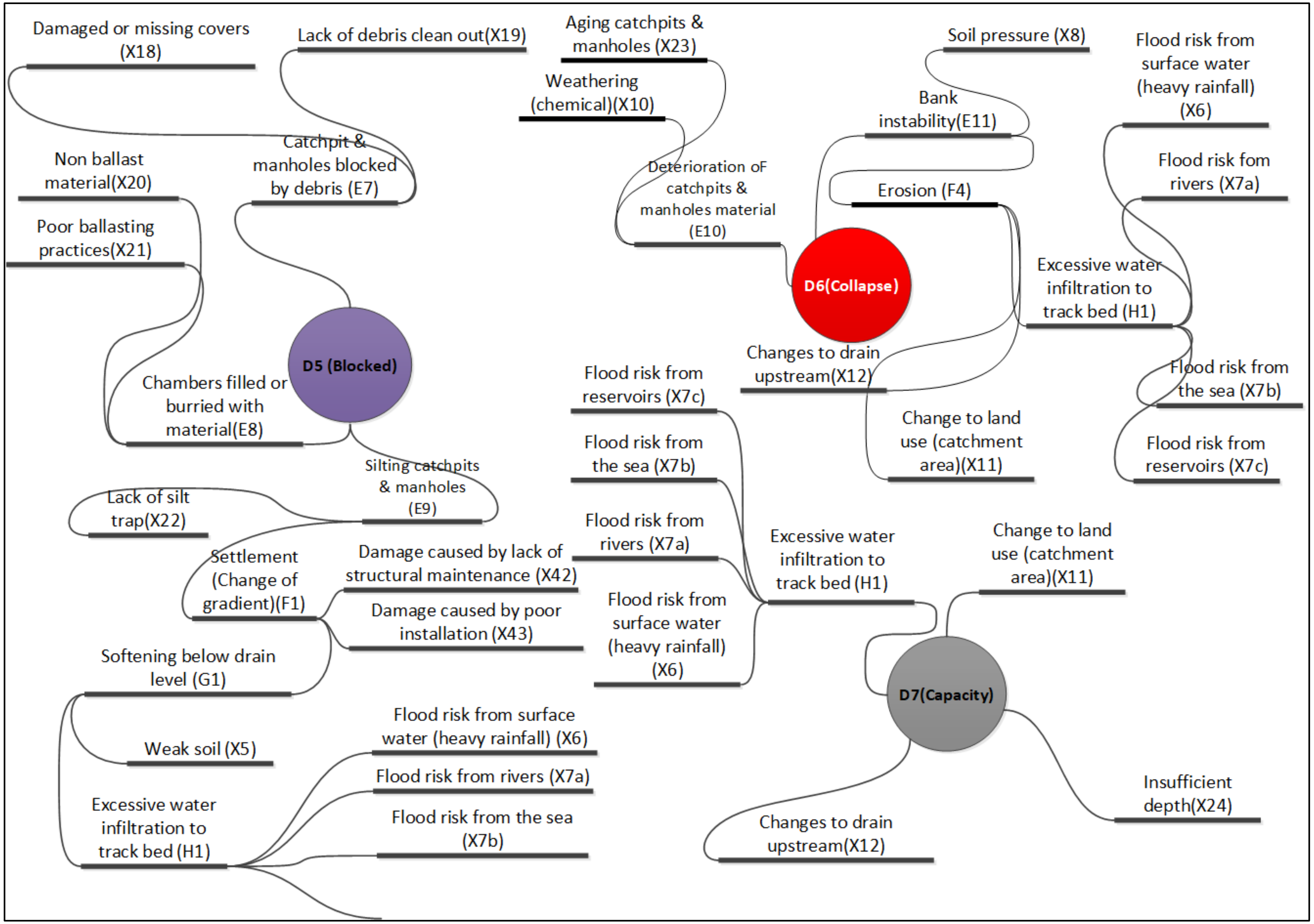


Figure 4.8 Contributing factors diagram for catchpits and manholes (C2)

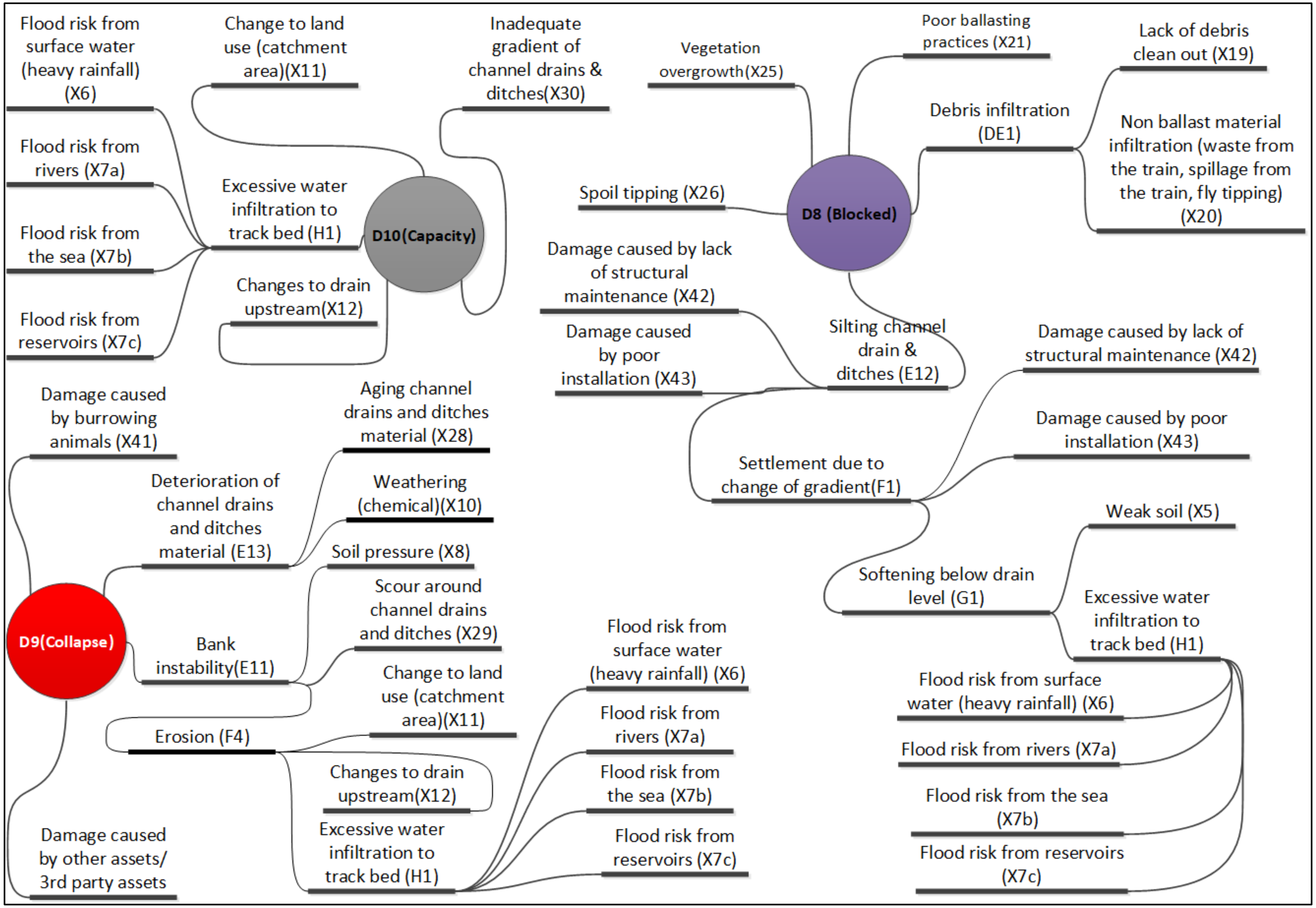


Figure 4.9 Contributing factors diagram for channel drains and ditches (C3)

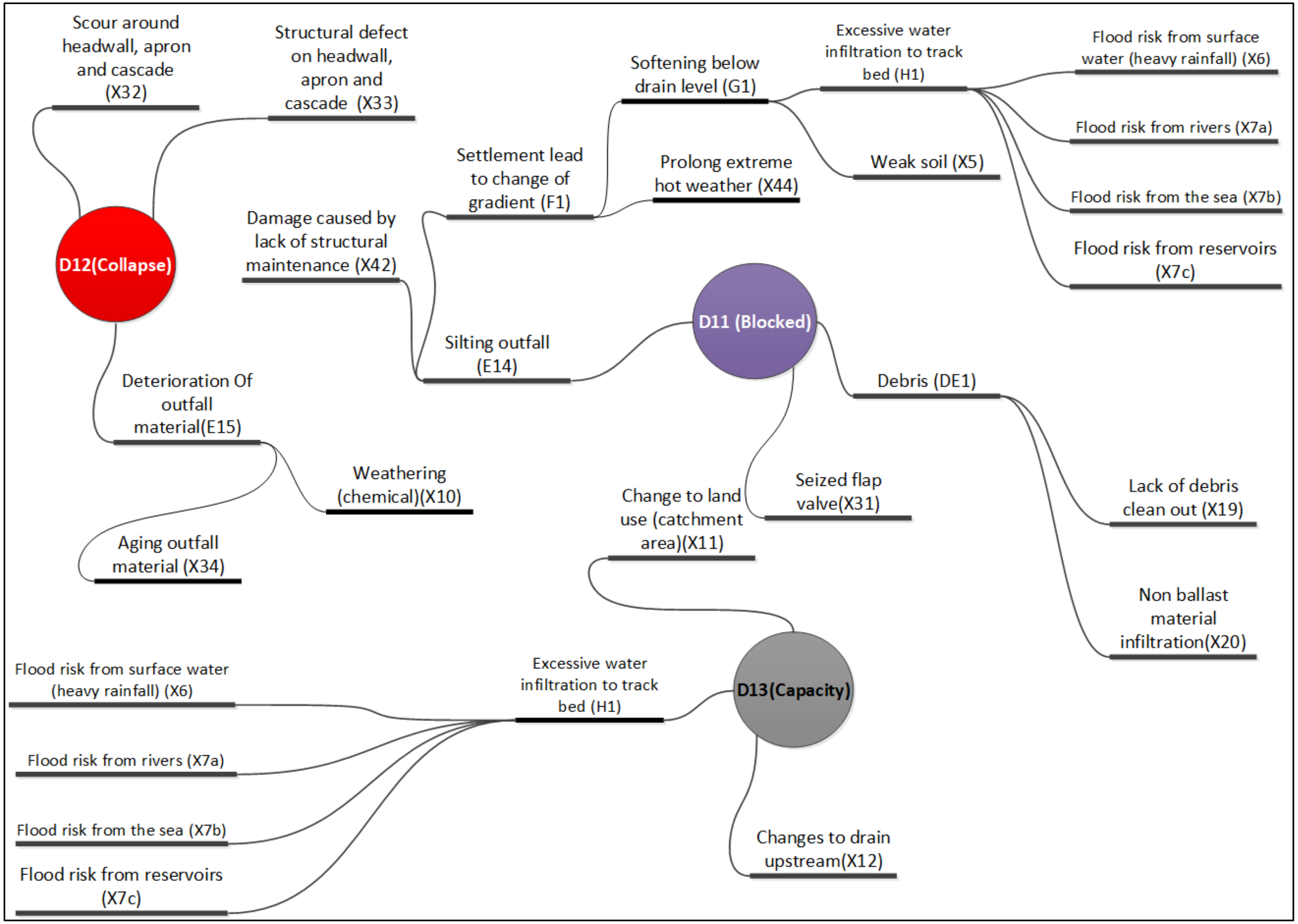


Figure 4.10 Contributing factors diagram for outfall (C4)

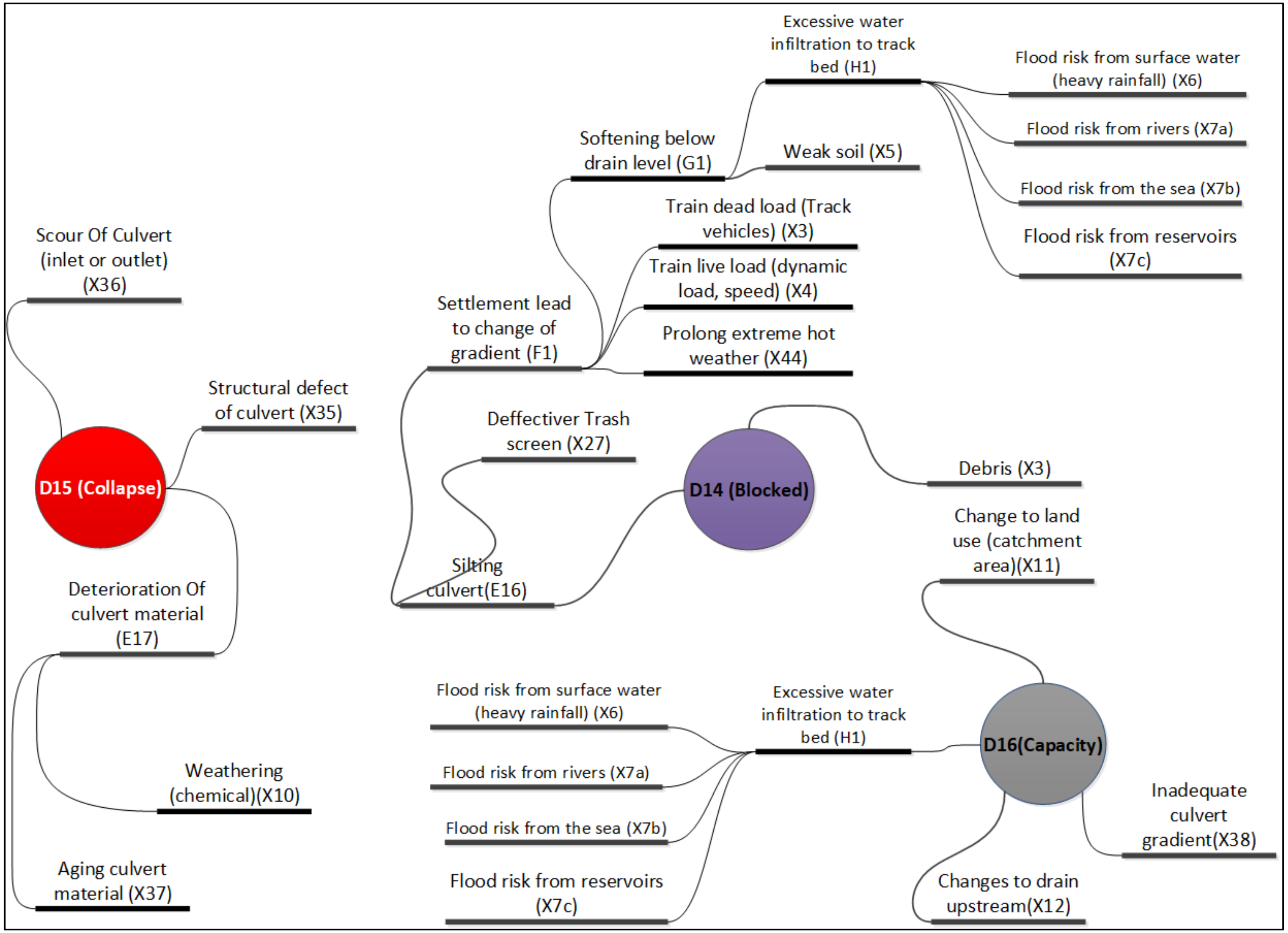


Figure 4.11 Contributing factors diagram for culvert (C5)

Steps 4: Causal Factor separation

The causal factors were separated into basic, mid and top (undesired) events, using a combination of information available in the literature and via the workshop described above. Table 4.1 lists the causal factors affiliated with the basic events, which are defined as an event that has no further causal factors (BSI, 2010). Table 4.2 and Table 4.3 present a list of causal factors affiliated with the mid and the top event (i.e. inadequate or poor drainage) respectively. From these tables it can be seen that a total of 46 basic events, 48 mid events, and 1 top event were identified

Table 4.1 Causal factors of poor railway track drainage (basic event)

Code	Causal Event/ Risk Item	Type	Contributing Factor
X1	Poor filter	Basic event	Subgrade
X2	Root (tree) penetration	Basic event	Environmental
X3	Train dead load (track vehicles) overloading.	Basic event	Traffic
X4	Train live load (dynamic load, speed) overloading.	Basic event	Traffic
X5	Weak soil	Basic event	Subgrade
X6	Flood risk from surface water (heavy rainfall)	Basic event	Environmental
X7a	Flood risk from rivers	Basic event	Environmental
X7b	Flood risk from the sea	Basic event	Environmental
X7c	Flood risk from reservoirs	Basic event	Environmental
X8	Excessive soil pressure	Basic event	Subgrade
X9	Aging pipe	Basic event	Component
X10	Weathering (chemical)	Basic event	Environmental
X11	Change to land use (catchment area)	Basic event	Land use
X12	Changes to drain upstream	Basic event	Land use
X13	Inadequate pipe gradient	Basic event	Design
X14	Inappropriate design of granular filter	Basic event	Design
X15	Fines accumulation from trenches surround pipe	Basic event	Maintenance
X16	Fines accumulation from pipe(s) surround drain	Basic event	Maintenance
X17	Inappropriate design of geotextile filter	Basic event	Design
X18	Scour of pipe	Basic event	Environmental
X19	Lack of debris clean out	Basic event	Maintenance
X20	Non ballast material infiltration	Basic event	Maintenance
	(waste from the train, spillage from the train, fly tipping)		
X21	Poor ballasting practices	Basic event	Maintenance
X22	Lack of silt trap	Basic event	Design
X23	Aging catchpits and manholes	Basic event	Component
X24	Insufficient depth catchpits and manholes	Basic event	Design
X25	Vegetation overgrowth	Basic event	Maintenance
X26	Spoil tipping	Basic event	Maintenance
X27	Defective trash screen	Basic event	Maintenance
X28	Aging channel drains and ditches material	Basic event	Component
X29	Scour around channel drains and ditches	Basic event	Environmental
X30	Inadequate gradient of channel drains and ditches	Basic event	Design
X31	Seized flap valve	Basic event	Component
X32	Scour around headwall, apron and cascade	Basic event	Environmental
X33	Structural defect on headwall, apron and cascade	Basic event	Component
X34	Aging outfall material	Basic event	Component
X35	Structural defect of culvert	Basic event	Component
X36	Sour of culvert (inlet or outlet)	Basic event	Environmental
X37	Aging culver material	Basic event	Component
X38	Inadequate culvert gradient	Basic event	Design
X39	Inadequate design (i.e. inadequate data, inappropriate product selection)	Basic event	Design
X40	Damage caused by other assets/ 3rd party assets	Basic event	Land Use
X41	Damage caused by burrowing animals	Basic event	Maintenance
X42	Damage caused by lack of structural maintenance	Basic event	Maintenance
X43	Damage caused by poor installation	Basic event	Installation
X44	Prolong extreme hot weather	Basic event	Environmental

Table 4.2 Causal factor of poor railway track drainage (mid event)

Code	Causal Event/ Risk Item	Type	Contributing Factor
H1	Excessive water infiltration to track bed	Mid event	Environmental
G1	Softening below drain level	Mid event	Subgrade
F1	Settlement due to change of gradient	Mid event	Subgrade
F2	Cess heave	Mid event	Subgrade
F3	Fines accumulation from surround pipe	Mid event	Maintenance
F4	Erosion	Mid event	Environmental
F5	Damaged or missing covers of catchpits and manholes	Mid event	Maintenance
E1	Silting pipe	Mid event	Maintenance
E2	Ground movement	Mid event	Subgrade
E3	Overstress	Mid event	Traffic
E4	Deterioration of pipe material	Mid event	Component
E5	Granular clogged (i.e. Collector, carrier, french/land drain)	Mid event	Design
E6	Geotextile clogged (i.e. Collector, carrier drain)	Mid event	Design
E7	Catchpits and manholes blocked by debris	Mid event	Maintenance
E8	Chambers filled or burried with material	Mid event	Maintenance
E9	Silting catchpits and manholes	Mid event	Maintenance
E10	Deterioration of catchpits and manholes material	Mid event	Deterioration
E11	Bank instability	Mid event	Subgrade
E12	Silting channel drain and ditches	Mid event	Maintenance
E13	Deterioration of channel drains and ditches material	Mid event	Component
E14	Silting outfall	Mid event	Maintenance
E15	Deterioration of outfall material	Mid event	Component
E16	Silting culvert	Mid event	Maintenance
E17	Deterioration of culvert material	Mid event	Component
DE1	Debris infiltration	Mid event	Maintenance

Table 4.3 Causal factor of poor railway track drainage (i.e. mid events, top event)

Code	Causal Event/ Risk Item	Type	Failure Mode
D1	Blocked pipe	Mid event	Pipe failure
D2	Collapsed pipe	Mid event	Pipe failure
D3	Inadequate capacity of pipe	Mid event	Pipe failure
D4	Filter media problem of surrounding pipe	Mid event	Pipe failure
D5	Blocked catchpits and manholes	Mid event	Catchpits and manholes failure
D6	Collapsed catchpits and manholes	Mid event	Catchpits and manholes failure
D7	Inadequate capacity of catchpits and manholes	Mid event	Catchpits and manholes failure
D8	Blocked channel drains and ditches	Mid event	Channel drains and ditches failure
D9	Collapsed channel drains and ditches	Mid event	Channel drains and ditches failure
D10	Inadequate capacity of channel drains and ditches	Mid event	Channel drains and ditches failure
D11	Blocked outfall	Mid event	Outfall failure
D12	Collapsed outfall	Mid event	Outfall failure
D13	Inadequate capacity of outfall	Mid event	Outfall failure
D14	Blocked culvert	Mid event	Culvert failure
D15	Collapsed culvert	Mid event	Culvert failure
D16	Inadequate capacity of culvert	Mid event	Culvert failure
C1	Defective of failed pipe	Mid event	Pipe failure
C2	Defective or failed catchpits and manholes	Mid event	Catchpits and manholes failure
C3	Defective or failed channel drains and ditches	Mid event	Channel drains and ditches failure
C4	Defective or failed outfall	Mid event	Outfall failure
C5	Defective or failed culvert	Mid event	Culvert failure
B1	Defective or failed subsurface track drainage	Mid event	Subsurface track drainage failure
B2	Defective or failed surface track drainage	Mid event	Surface track draunage failure
Code	**Undesired Event**	**Type**	**Failure Mode**
A1	Poor track drainage (i.e. Subsurface drainage, surface drainage)	Top Event	Track drainage failure

Step 5: Fault Tree Creations

Standard graphical symbols, defined in Figure 3.3, were used to build the fault trees.

4.6.1 The Verified FTA of poor drainage on ballasted railway track

As shown in Figure 4.12, the fault tree for poor railway track drainage (A1) is comprised of subsurface drainage (B1) and surface drainage (B2), using the 'OR' gate. Figure 4.12 also shows that B1 consists of C1 (a defective or failed pipe) and C2 (defective or failed catch-pits and manholes), which are combined using the 'OR' gate. Similarly, B2 incorporates C3 (defective or failed channel drains and ditches), C2 (defective or failed outfall), and C3 (defective or failed culvert) using the 'OR' gates. An output is generated by an 'OR' gate if at least one of the inputs occurs. For example, in Figure 4.12, the relationship between A1, B1 and B2 denotes that at least one failure (B1 or B2) event needs to exist for failure A1 to occur. A similar relationship is outlined in the intersection of B1, C1, C2, and B2, and C3, C4, and C5.

The causal factors associated with subsurface (C1 and C2) and surface (C3, C4 and C5) track drainage components are denoted by five Transfer in triangles (sub-fault trees). The respective Transfer in Triangles are elaborated in the sub-fault trees shown in Figure 4.13 – Figure 4.17 respectively and are described further below.

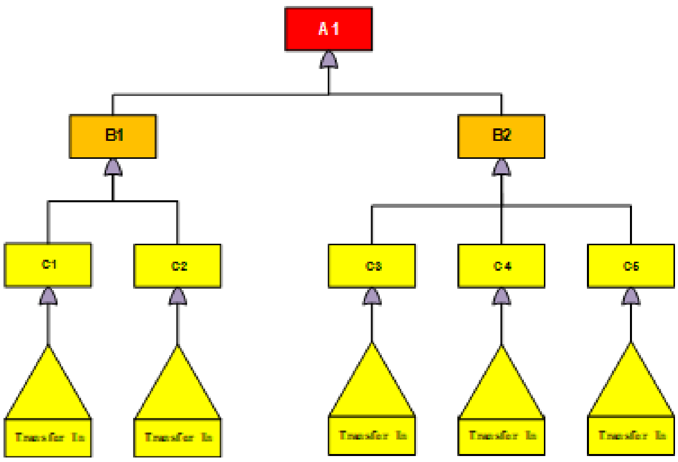


Figure 4.12 Fault tree (FT) chart for poor drainage of ballasted railway track (A1)

4.6.1.1 Subsurface Track Drainage Failure

Sub-fault trees for C1 (defective or failed pipe) and C2 (defective or failed catchpits and manholes) are presented in Figures Figure 4.13 and Figure 4.14. C1 is associated with four failure modes, each linked by 'OR' gates. These failure modes are D1 (blocked pipe), D2 (collapsed pipe), D3 (inadequate pipe capacity), D4 (filter media problems with surrounding pipe). A catchpits and manholes failure (C2) relies upon D5 (blocked catchpits and manholes), D6 (collapsed catchpits and manholes) and D7 (inadequate capacity of catchpits and manholes).

Although the logic gates in Figure 4.13 and Figure 4.14 are mostly 'OR' gates, F2 (cess heave) event relies on X3 (train dead load - track vehicle - overloading) AND X4 (train live load - dynamic load, speed - overloading.) AND G1 (softening below drain level), using the 'AND' gate. This means those X3, X3 and G1 need to occur for F2 to take place.

4.6.2 Independent Events

Veldhuis *et al*. (2011) assumed that rainfall, soil and system component conditions (i.e. pipes, basins, and surface infiltration and sewer capacity) and flood and blockage events are independent, given the ability of the whole urban drainage system to return to its initial conditions between two events. Hence, in terms of using a probabilistic fault tree to account for poor track drainage, all of the events were assumed to be independent. This means that the probability of the occurrence of any contributing factor is not affected by any other.

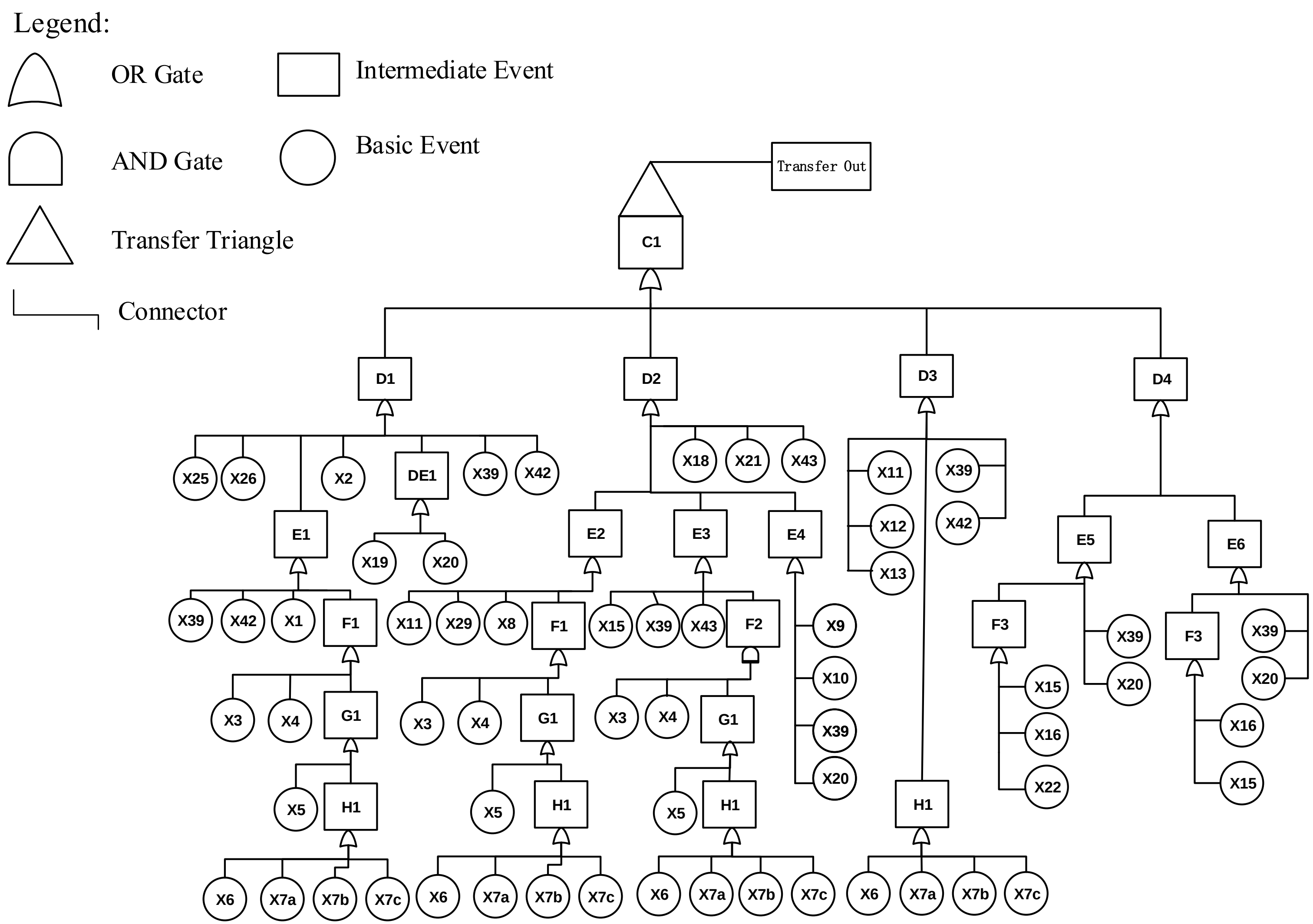


Figure 4.13 Sub-fault tree chart for failure/defective pipes (C1)

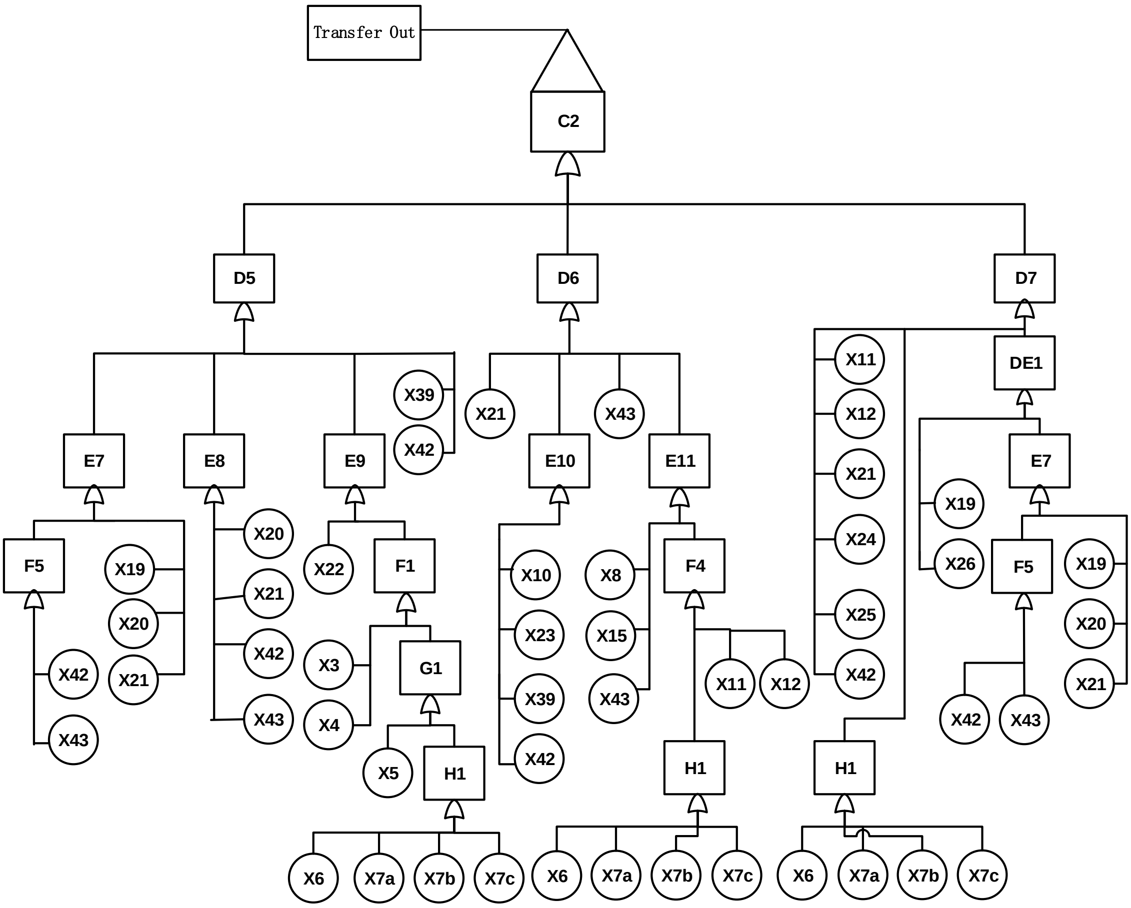


Figure 4.14 Sub-fault tree chart for catchpits and manholes (C2)

4.6.2.1 Surface Track Drainage Failure Paths

The failure of the three asset types associated with track drainage (channel drains and ditches, outfalls and culverts) are described by the sub-fault trees shown in Figure 4.15, Figure 4.16 and Figure 4.17 respectively. Channel drain and ditches (C3) failure occurs if at least one out of three intermediate events occur, i.e. D8 (blocked channel drains and ditches), D9 (collapsed channel drains and ditches), D10 (inadequate capacity of channel drains and ditches) (see Figure 4.15). Outfall failure (C4) can occur because of D11 (blocked outfall) OR D12 (collapsed outfall) OR D13 (inadequate capacity of outfall) (see Figure 4.16). Similarly, the factors contributing to culvert failure (C5) are D14 (blocked culvert) OR D15 (collapsed culvert) OR D16 (inadequate capacity of culvert) (see Figure 4.17).

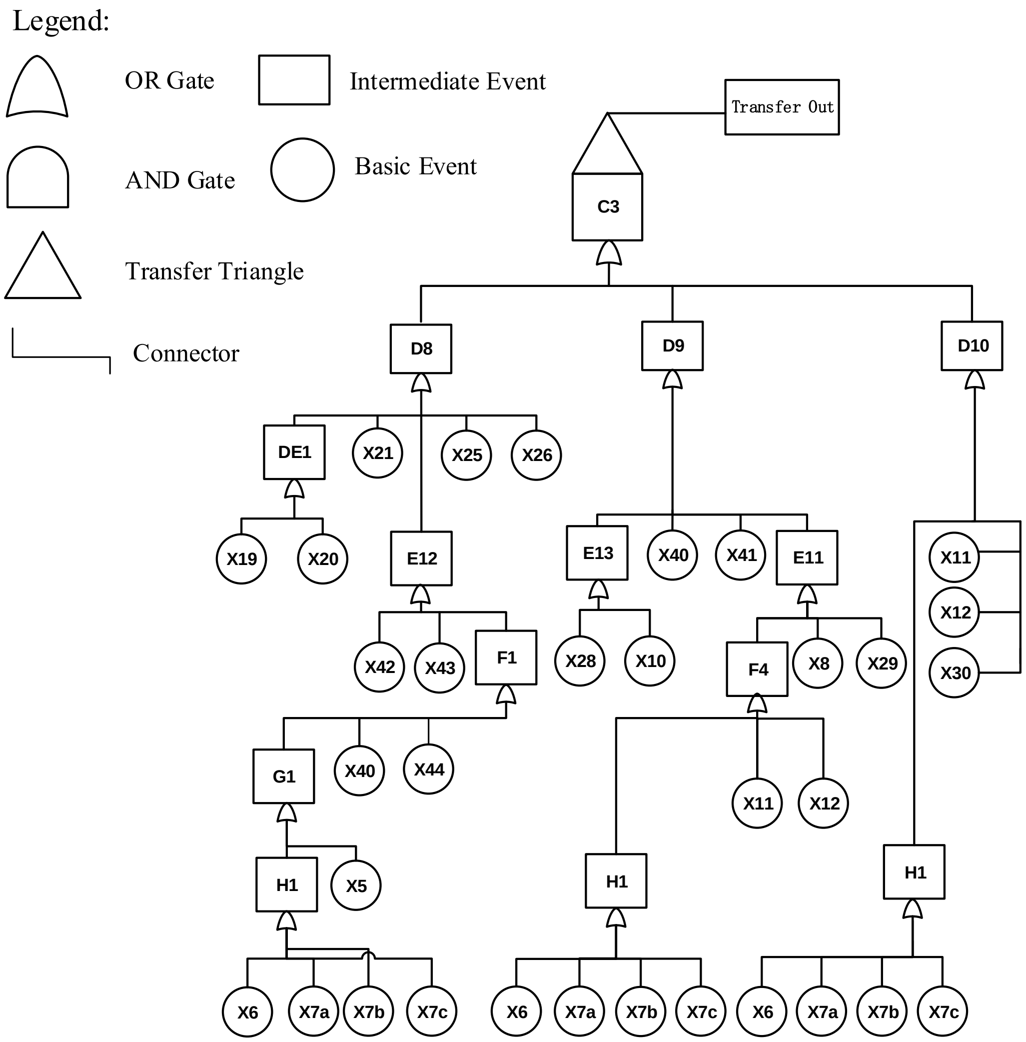


Figure 4.15 Sub-fault tree chart for channel drains and ditches (C3)

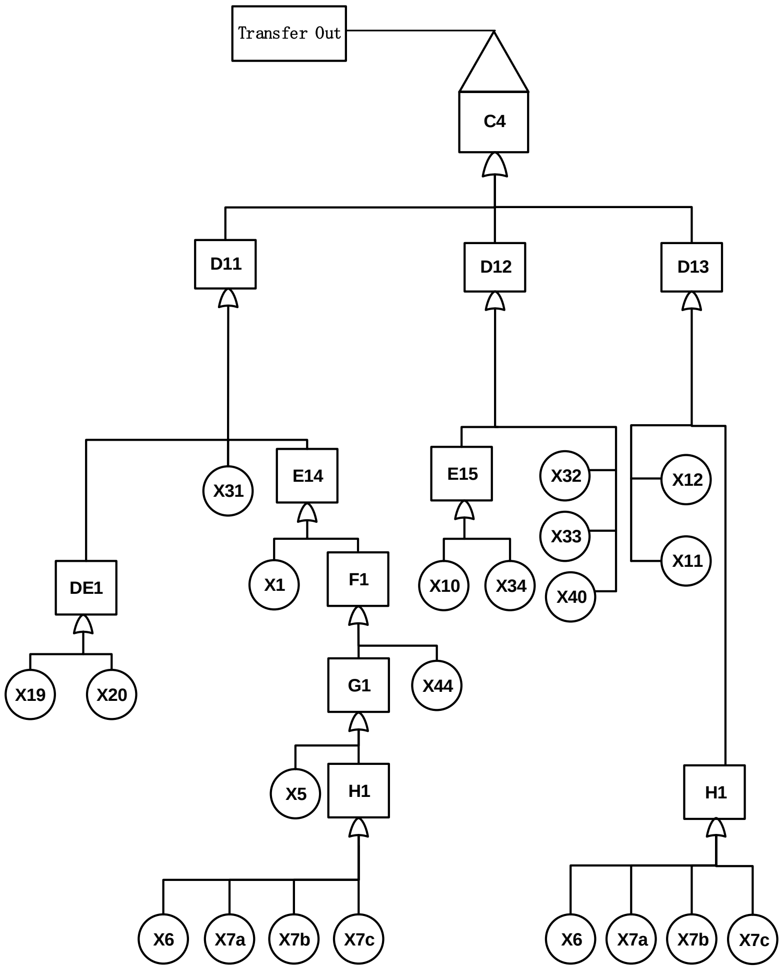


Figure 4.16 Sub-fault tree chart for outfall (C4)

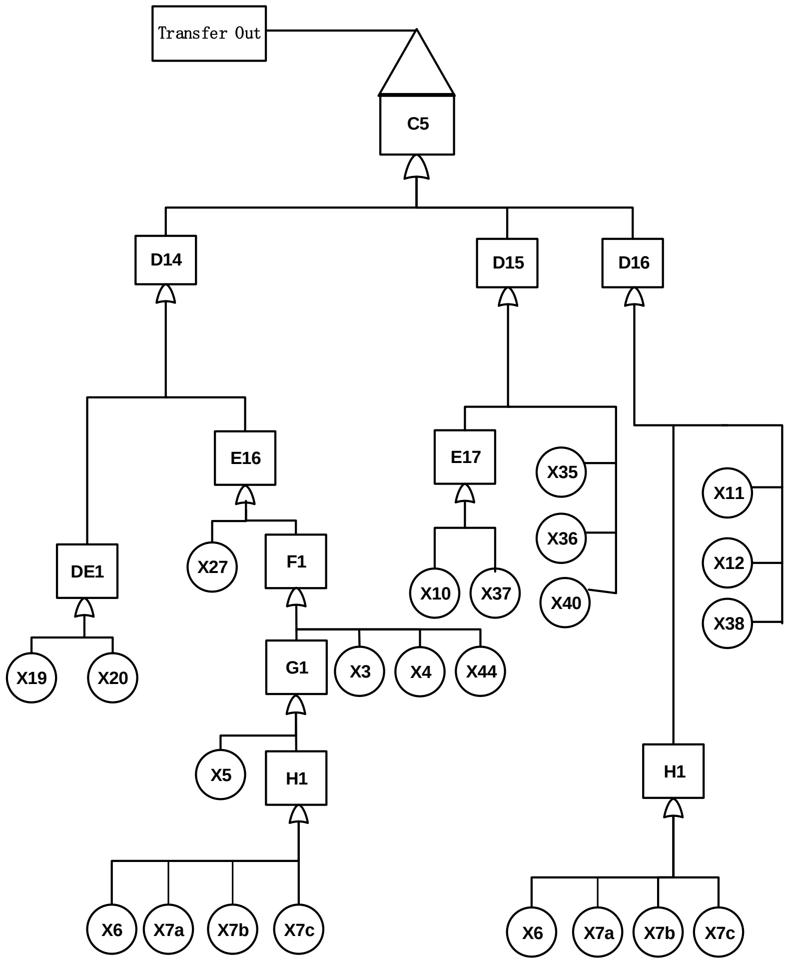


Figure 4.17 Sub-fault tree chart for culvert (C5)

4.6.3 Quantitative Analysis of Probabilistic Fault Trees

4.6.3.1 Minimal Cut Set

In fault tree analysis, the importance of basic events in the whole FT structure can be assessed by analysing the minimal cut sets of all combinations of the basic events. A cut set is a list of basic events which, if they all occur, will cause the top event to occur, whereas a minimal cut set is a list of minimal basic events excluding redundant events, the occurrence of which may lead the top event to occur (BSI, 2010; Clemens and Sverdrup, 2002; Andrews, 1998)

According to Ma *et al.* (2013), although the algebra of sets is often applied to calculate the minimal cut sets, a simple analysis can be adopted when the OR gate dominates the whole structure of the FT. This simple analysis focuses only on the cut sets with an AND gate. This simple analysis was applied to the Fault Tree developed for this research; it yielded the following minimal cut sets:

{X1}, {X2}, {X3}, {X4}, {X5}, {X6}, {X7a}, {X7b}, {X7c}, {X8}, {X3,X4,X5}, {X3,X4,X6}, {X3,X4,X7a}, {X3,X4,X7b}, {X3,X4,X7c}, {X9}, {X10},{X11},{X12},{X13}, {X14},{X15},{X16},{X17}, {X18},{X19}.{X20}, {X21}, {X22}, {X23}, {X24}, {X25}, {X26}, {X27}, {X28}, {X29}, {X30}, {X31}, {X32}, {X33}, {X34}, {X35}, {X36}, {X37}, {X38}, {X39}, {X40}, {X41}, {X42}. {X43}, {X44}

The above 51 minimal cut sets show the sufficient 51 basic events or combinations therein that can lead to poor subsurface and surface drainage being the top event.

4.6.3.2 Fault Tree Importance Analysis

Fault tree importance analysis shows the influence of a basic event to the top event, based on its structural importance in the fault tree. Structure importance analysis is used to determine the relative importance of every basic event influencing the top event (Chen *et al.*, 2014). Zhao and Wang (2011) propose the following expression to determine the relative importance, IØ, of basic event i (Xi).

$$I\emptyset(Xi) = \frac{1}{k}\sum_{j=1}^{m}\frac{1}{Rj} \qquad \text{Eq 4.1}$$

Where *k* is the total number of minimal cut sets, *m* is the total number of minimal cut sets containing basic event X*i*, where R*j* is the total number of basic events of the minimal cut set *j* containing basic event X*i*.

As an example, consider the basic event X3, which occurs in six minimal cut sets (m=6). Those are {X3], {X3, X4, X5}, {X3, X4, X6}, {X3, X4, X7a}, {X3, X4, X7b}, {X3, X4, X7c}. The R1 in {X3}, R2 in {X3, X4, X5}, R3 in {X3, X4, X6}, R4 in {X3, X4, X7a}, R5 in {X3, X4, X7b}, and R6 in {X3, X4, X7c} consist of one and three events respectively (R1=1 and R2, R3, R4, R5, R6 =3).

$$I\emptyset(X3) = \frac{1}{51}\sum_{j=1}^{6}\frac{1}{Rj} = \frac{1}{51} * (\frac{1}{1} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3}) = 0.0523$$

Following a similar analysis, it can be shown that:

$$I\emptyset(X1) = \frac{1}{51}\sum_{j=1}^{1}\frac{1}{Rj} = \frac{1}{52} * (\frac{1}{1}) = 0.0196$$

The results of this calculation are as follows:

X1=X2=X8=X9=X10=X11=X12=X13=X14=X15=X16=X17=X18=X19=X20=

X21=X22=X23=X24=X25=X26=X27=X28=X29=X30=X31=X32=X33=X34=X35=

X36=X37= X38=X39=X40=X41=X42=X43=X44

0.0196, X3=X4=X5=X6=X7a=X7b=X7c= 0.0523.

Accordingly, the relative importance of basic events influencing the top event (drainage failure) are:

X3=X4=X5=X6=X7a=X7b=X7c >

X1=X2=X8=X9=X10=X11=X12=X13=X14=X15=X16=X17=X18=X19=X20=

X21=X22=X23=X24=X25=X26=X27=X28=X29=X30=X31=X32=X33=X34=X35=

X36=X37=X38=X39=X40=X41=X42=X43=X44

Accordingly, the following five contributing factors have the greatest influence on drainage system failure:

- X3 = Train dead load (track vehicles) overloading.
- X4 = Train live load (dynamic load, speed) overloading.
- X5 = Weak soil
- X6 = Flood risk from surface water (heavy rainfall)
- X7a = Flood risk from rivers
- X7b = Flood risk from the sea
- X7c = Flood risk from reservoirs

According to Limnios (2013), Boolean algebra administers the FT gates with different roles. The 'or' gate represent the relationship between FT's events, whereas the 'and' gate assigns to intersection. For example, if the probability of event C is a union between the probability of independent events A and C, the Boolean relation is written as:

$$P(C) = P(A) \cup P(B) = P(A) + P(B) \qquad \text{Eq 4.2}$$

On the other hand, if the probability of event C is an intersection of the probability of independent events A and C, the Boolean relation is written as:

$$P(C) = P(A) \cap P(B) = P(A) * P(B) \quad \text{Eq. 4.3}$$

In the case of the failure of drainage assets, for example, the following Boolean algebra are presented in order to show the relationship between an undesired event or top event (event A1) with defective or failed subsurface drainage (event B1) and surface drainage (event B2):

$$P(A1) = P(B1) \cup P(B2) = P(B1) + P(B2) \quad \text{Eq 4.4}$$

Similarly, the relationship between F2 (cess heave), X3 (train dead load (track vehicles) overloading), X4 (train live load (dynamic load, speed) overloading), and G1 (softening below drain level) are presented as follows (see Fig. 5.9):

$$P(F2) = P(X3) \cap P(X4) \cap P(G1) = P(X3) * P(X4) * P(G1) \quad \text{Eq 4.5}$$

4.7 Estimation of the Likelihood of Risks Associated with Ballasted Railway Drainage Failure

As described above, FT is used to map the failure (top) event and its causal (basic) events using Boolean algebraic rules. This means that the likelihood of risks associated with the poor drainage of ballasted railway track can be estimated if the probability of the occurrence of basic events is provided. Veldhuis *et al.* (2011) point out the procedure for quantifying FT in order to obtain the probability of the occurrence of the basic event, as follows:

- They determine a failure probability model that suits the developed FT. They assumed that the probability of the occurrence of events is a Poisson process, which suggests that this will occur in any specified short period of time and will be approximately proportional to the length of that time period.

- The events occur in disjoint time (i.e. they are independent events).
- In a homogeneous Poisson process, the average rate of occurrence (failure rate) of a specific event per unit of time is constant.

The above assumes that the basic events act independently. In the case of urban drainage, this assumption is discussed by Veldhuis *et al.* (2011); they were able to make this judgement, since they postulated that the system, including all its various components (e.g. pipes, basins, surfaces infiltration capacity), returned to its initial state between two events (i.e. successive floods). Therefore, it is possible to adopt a similar assumption when it comes to the drainage system for a ballasted railway track, since one of the most important influences in the developed FT is flood risk from surface water (caused by heavy rainfall). For example, if a blockage occurs to channel drains or ditches on the UK rail network due to excessive water infiltration induced by heavy rainfall, it is likely that this can be solved progressively by the permanent way team within a short time.

Under those conditions, the risks associated with the poor drainage of ballasted railway track in a fixed period of time is a Poisson distributed variable. The probability of the occurrence of a causal event can be calculated using the Poisson process equation (Ayyub, 2016; Veldhuis *et al.*, 2011) which is presented using equation 5.6 as follows:

$$P_{X_t}(x) = \begin{cases} \frac{(\lambda t)^x \exp(-\lambda t)}{x!} \\ 0 \end{cases} \qquad \text{Eq 4.6}$$

$P_{X_i}(x)$: the probability of x occurrences in a period of time t

λ : failure rate, the average rate of occurrence of events per time unit

x : 0.1.2.3……n occurrence time(s)

t : time period (e.g. in the next 5 years)

where failure rate $\lambda(t)$ is defined by equation 3.9 (see Section 3.5)

4.8 Cost Model

The cost model was developed to determine the impacts associated with track drainage failure in monetary terms. This model takes into account of the following impacts[1]:

4.8.1 Unplanned maintenance costs

Unplanned maintenance costs are associated with damage to:

a) The track substructure, caused by water, which remains in the track substructure for a substantial period of time and causes a number of problems, including 'wet bed' (see Section 2.7.1).
b) Drainage components caused by excessive water infiltration to the surrounding track, e.g. water may cause bank instability, leading to the collapse of channel drains and ditches.
c) Signalling caused by water, which remains undrained and may lead to "short circuiting" and disruption to core functionality.

Unplanned maintenance costs might also be associated with defective drainage components. For example, in a flooding event, the accumulation of debris or vegetation overgrowth in the

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[1] These impacts are described in more detail in sections 4.8.1 to 4.8.6 The approach used to combine the total costs is described in Section 4.8.7.

channel drains and ditches may lead to a partial or full blockage event. This may exacerbate the impacts of initial flooding events.

4.8.2 Delay costs

Delay costs are associated with the compensation paid by train operators due to incidents associated with poor drainage. These can be assigned as follows:

a) Delay costs due track closures

b) Delay costs due to speed restrictions

c) Delay costs due to cancellations

4.8.3 Additional passenger travel costs

Additional passenger travel costs are an additional cost faced by passengers due to track disruption associated with drainage failure incidents.

4.8.4 Bus transfer cost

Costs for transporting passengers from the incident site or station to their intended destination;

4.8.5 Property damage cost

Property damage costs are associated with damage to property. There are two elements:

a) Residential costs

b) Non-residential costs

4.8.6 Farming land damage costs

Farming land damage costs occur because of localised flooding associated with poor drainage of ballasted railway track

4.8.7 Total cost impacts

Total impact is a sum of total cost impacts associated with the poor drainage of ballasted railway track.

4.9 Model Verification Workshop

As discussed in the previous chapter, the ability of a FT to perform appropriately depends on how it is structured. Therefore, it was deemed necessary to validate the structure of the proposed FT by canvassing the opinion of a number of experts. Similarly, it was also considered necessary to confirm the components of the socio-economic impact model. This was achieved via a focus group discussion (FGD) involving nine drainage and risk assessment experts from Network Rail, and two academics, one of whom has expertise in track drainage and the other in risk assessment.

The FGD took place during a half-day workshop and consisted of the following three sessions:

1. The first session involved introducing and validating the engineering model which is performed as FT structure for subsurface and surface drainage;
2. The second session involved validating the components of the model concerning the cost impacts discussed above. There was also discussion on criteria used to select the case studies.
3. The third session involved discussing the criteria of case studies draw from the UK rail network, used to quantify the probability of failure or defective track drainage occuring (i.e. subsurface, surface) and their potential impacts.

4.10 Risk Semi-Quantification

Typically, risk semi-quantification consists of assigning identified risks into low, medium, and high categories. In terms of the framework presented here, the risk semi-quantification process was used to identify those risks that require further analysis (i.e. quantification). Such a process was necessary because of the large number of identified risks and their possible associated pathways.

Usually in risk semi-quantification, a simple procedure is used to estimate the probability that each risk will occur, using an integer scale of 1 to 5, where 1 represents a low probability and 5 a high probability (Ayyub, 2014). Similarly, the impact of the risk is assessed using a similar scale (1= very low impact and 5 = very high impact). Finally, the risk score is obtained by multiplying the score for the probability of occurrence by the score for the impact. Figure 3.4 shows a resulting risk matrix, wherein risk scores of between 1 and 4 represent 'low', 5 to 10 represent 'medium' and scores 15 and above represent 'high' risk. The ranges of low, medium and high impact probabilities and risks are illustrated in Chapter 3

4.11 Risk quantification

Risk is the product of weighting the probability of risk events occurring (P) and the impacts (I) of those risks (see Eq 5.8). Risk quanitification involves assigning values to these parameters. In the proposed framework, an engineering based model was developed to determine the probability of the risk events occurring. Alongside this, a social-economic model was established to quantify the impact of an associated drainage failure event.

The quantification of drainage risk for a section of railway track consists of quantifying the probabilities that an identified risk will occur in a particular section and the impact of poor drainage within that section. These two components are combined to provide a risk score for that section of track. Risk scores determined for each section of track within a railway network can be compared in order to allow for the prioritisation of investment. The quantification the risk of drainage asset failures, using FT analysis, was described in Sections 4.6.3 and 4.7. The risk of drainage asset failure was described in Section 4.6. This section describes the model developed to account for the frequency of occurrence of risks and the impact of failure, in order to provide a risk score for a particular section of track.

Following BSI (2010), the risk value for poor drainage on a section of ballasted railway track can be determined as follows:

$$R = P_A * I_T \quad \text{Eq 4.7}$$

Where:

R : Risk value

P_A : Probability of occurrence of an undesired (poor drainage) event on ballasted railway track

I_T : Total impact (cost) due to the incident associated with poor drainage on ballasted railway track

In term of the drainage components on ballasted railway track (see Figure 5.8), the risk can be determined as follows:

$$R_{Ci} = P_{Ci} * I_T \quad \text{Eq 4.8}$$

Where:

R_{Ci} : Risk value of defective or failed drainage component on ballasted railway track

P_{Ci} : Probability of the failure of or defection of a the drainages component on ballasted railway track

I_{TCi} : Total impact (cost) of the defection or failure of a drainage component on ballasted railway track

Since the processes used to determine both the probability and impacts of a failure can be regarded as uncertain, it was necessary to identify an approach to take into account these uncertainties.

According to BSI (2010), there are several formal methods that can be used to quantify risk. Table 5.4 shows the attributes of these to be dealt with uncertainties with respect to risk semi quantification and quantification. The attributes of these approaches are presented in terms of:

- the methods used, such as scenario analysis, function analysis, and statistical methods,
- the resources and capabilities required to adopt the technique (i.e. data aqusition, expertise)
- the nature and degree of uncertainty that can be conceived using those techniques,
- the complexity of the problem
- the ability to provide a measurable output.

Of the techniques in Table 4.4, event tree analysis decomposes every branch (causal event) into two cases (see Section 3.5). Thus, because we are interested in the study of multiple cases, this technique was excluded. Of the remaining three methods, failure mode and effect analysis (FMEA), Markov analysis, and Bayesian analysis could not be adopted, as these modelling tools require a well-defined system and relatively complete historical data. Therefore, a combination of fault tree (FT) analysis, which was used to identify risk (see Section 5.3.2) and Monte Carlo analysis were used to undertake risk semi-quantification and quantification; the

FT was used to derive a tree structure and transform it into Boolean algebraic terms (see Section 3.6.4.3); Monte Carlo analysis, otherwise known as Monte Carlo Simulation (MCS), is used to derive the quantified risk parameters (i.e. the likelihood and probability of an occurrence) by aggregating various inputs within a specific type of distribution.

The common types of distribution used for risk assessment are triangular distributions, or PERT distributions (BSI, 2010). Although a triangular distribution has similar properties to a PERT distribution (see Section 3.6.4), the former, in many cases, is more intuitive, for example, when it relies upon expert consultation (Cretu *et al*., 2011; Vose, 2008). Through graphical comparison, we can see in Figure 3.8 that one advantage of PERT distribution is that it offers smoother tails that may better represent uncertainty (Cretu *et al*., 2011). Therefore, the PERT distribution was selected to model risk (i.e. the probability of an occurrence) associated with drainage asset failure.

The relationship between input and output can be defined using a mathematical formula as a representation of a quantitative model (BSI 2010, Ayyub 2001). This is performed by integrating an engineering model (FT structure) and cost model. MCS involves running a number of calculations, *N,* known as simulations, by sampling various inputs in order to obtain N possible outcomes (see Section 3.6.3).

Table 4.4 Attributes of a risk assessment tool (Source: BSI 2010)

Type of risk assessment technique	Description	Rtelevance of influencing factors			Can provide Quantitative output
		Resources and capability	Nature and degree of uncertainty	Complexity	
SUPPORTING METHOD					
Brainstorming	Brainstorming may be stimulated by prompts or by one-on-one.	Low	Low	Low	No
SCENARIO ANALYSIS					
Fault tree analysis	A technique which starts with the undesired event (top event) and determines all the ways in which it could occur. These are displayed graphically in a logical tree diagram. Once the fault tree has been developed, consideration should be given to ways of reducing or eliminating potential causes / souurces	High	High	Medium	Yes
Event tree analysis	Using inductive reasoning to translate probabilities of different initiating events into possible outcomes	Medium	Medium	Medium	Yes
FUNCTION ANALYSIS					
FMEA	FMEA (Failure Mode and Effect Analysis) is a technique which identifies failure modes and mechanisms, and their effects	Medium	Medium	Medium	Yes
STATISTICAL METHODS					
Markov analysis	Markov analysis, sometimes called State-space analysis, is commonly used in the analysis of repairable complex systems that can exist in multiple states, including various degraded states	High	Low	High	Yes
Monte Carlo analysis	Monte Carlo simulation is used to establish the aggregate variation in a system resulting from variations in the system, for a number of inputs, where each input has a defined distribution and the inputs are related to the output via defined relationships. The analysis can be used for a specific model where the interactions of the various inputs can be mathematically defined. The inputs can be based upon a variety of distribution types according to the nature of the uncertainty they are intended to represent. For risk assessment, triangular distributions or beta distributions are commonly used	High	Low	High	Yes
Bayesian analysis	A statistical procedure which utilizes prior distribution data to assess the probability of the result. Bayesian analysis depends upon the accuracy of the prior distribution to deduce an accurate result. Bayesian belief networks model cause-and-effect in a variety of domains by capturing probabilistic relationships of variable inputs to derive a result	High	Low	High	Yes

4.12 Cost Benefit Analysis (CBA)

Furthermore, a cost benefit analysis (CBA) was performed to help drainage asset managers to decide upon appropriate preventive maintenance and to mitigate the social-economic impacts associated with poor drainage of ballasted railway track. The CBA is presented using the following formula (Vanmarcke, 2009):

$$BCR = \frac{PV(B)}{PV(C)} \qquad \text{Eq 4.9}$$

$$Bt = I_T - I_{TPt} \qquad \text{Eq 4.10}$$

$$Ct = PMct \qquad \text{Eq 4.11}$$

$$PV(B) = \sum_0^n \frac{(Bt)}{(1+r)^n} = \sum_0^n \frac{(ITt - ITPt)}{(1+r)^n} \qquad \text{Eq 4.12}$$

$$PV(C) = \sum_0^n \frac{(Ct)}{(1+r)^n} = \sum_0^n \frac{PMct}{(1+r)^n} \qquad \text{Eq 4.12}$$

$$NPV = PV(B) - PV(C) \qquad \text{Eq 4.13}$$

Where,

BCR : benefit-cost ratio

NPV : net present value

PV(B) : present value of expected benefits

Bt : benefit at time *t*

PV(C) : present value of costs

Ct : cost at time *t*

I_{Tt} : the annual monetary losses (total social-economic impacts) without added planned (preventive) maintenance at time *t*

I_{TPt} : the annual monetary losses (total social-economic impacts) with added planned (preventive) maintenance at time *t*

PMct : planned (preventive) maintenance costs at *time t*

r : *r* is the discount rate

4.13 Summary

This chapter has described the development of a network level risk-based framework for railway ballasted track drainage that can be used to assess the risk of failure of discrete sections of a railway and prioritise maintenance expenditure. The framework consists of three modules for (i) identifying and quantifying drainage associated risks using an engineering model (module 1) (ii) determining the risk impacts using a cost model (module 2) (iii) determining risk values using an integrated model in respect to tmaintenance appraisal of drainage assets.

The risks to adequate railway drainage performance were determined through a review of the literature and by consulting expert opinion. A Fault Tree was constructed, which identified risks and related these to drainage asset failure types. This helped to determine the probability of the risk event occurring. The probabilities can be quantified using the Fault Tree by drawing upon historical data, expert opinion or a combination therein. In addition to its primary function, the Fault Tree also provides the drainage asset manager with a tool to help them identify causes of poor drainage and thereby consider appropriate preventative measures. Six categories of potential socio-economic impacts (cost) were identified, namely unplanned maintenance, delay costs, additional passenger travel costs, bus transfer costs, property damage costs, and farming land damage costs.

The developed FT and the identified impacts were validated through a half day workshop attended by drainage and risk experts from Network Rail and academia. The risk evaluation component of the framework combines the likelihood of the occurrence of risk events and the impacts of drainage failure to determine overall risk scores for sections of a railway network using cost benefit analysis. In order to deal with uncertainty when quantifying risks (i.e. in establishing the probabilities of a particular outcome and the range of plausible financial impacts) a Monte Carlo Simulation process was proposed.

Moreover, to conduct an appraisal for track drainage, an engineering and cost model was combined to more accurately provide risk values and perform a cost benefit analysis (CBA) so that asset managers would be better able to decide upon appropriate preventive maintenance.

The applicability of the theoretical framework is demonstrated in Chapters 5 to 8 using case studies taken from the UK railway network.

5 DATA FOR CASE STUDIES

5.1 Introduction

This chapter and the three that follow discuss three case studies of the UK rail network in order to assess the applicability of the framework for railway risk assessment described in Chapter 4. This chapter is devoted to describing the data obtained for the case studies Chapter 6 shows how MCS can be used to estimate the likelihood of railway drainage risk. The social and economic impacts and risk values of this event are quantified in Chapters 7 and 8..

5.2 Selected Sites

As described in Section 4.9, a drainage workshop with practitioners and academics was held to verify the suitability of the framework. Following the advice of those partaking in the workshop it was decided to focus on one type of drainage asset, namely channel drains and ditches (C3, see Figure 4.15), for the case study presented in this work. The reasons for this was partly because of the availability of data and also because it was felt that such a case study would provide sufficient examples to demonstrate the framework developed in this research. In this chapter, defects associated with, or the failure of this component (C3), are examined using the model in order to quantify the probability of its occurrence across three sites on the UK rail network.

Following the drainage workshop, a special arrangement half day workshop at NR York office was conducted to select potential sites for case studies. The workshop was used to validate the framework with respect to the three sites with a senior drainage engineer. The sites are described in further detail in Sections 5.2.1, 5.2.2, and 5.2.3. These were: Ardsley Tunnel, Clay Cross

Tunnel, and Draycott.All three sites are located in Leeds and Darby. The routes are in NR's LNE (London North Eastern) region. The rationale behind selecting these sites are as follows:

- Historical data of incidents recorded over the last ten years confirm that the sites are prone to risks associated with poor drainage of ballasted railway track. This was indicated by frequent flooding events that had substantial consequences (e.g. delays, unplanned maintenance, etc.). This period was chosen based on the fact that the incidents have been well documented electronically and stored in an integrated database, for example the drainage assets map was arranged in 2013.
- The data concerning drainage assets mapping was available and could be used to analyse risks.
- The availability of NR's expertise (i.e.the senior drainage engineer) for the purpose of selecting the sites and determining the availability of risks to drainage assets.

The following data for the case studies were obtained from the senior drainage engineer:

- Incident data assessed on inadequate drainage
- A map of drainage assets (see Appendix 4)

The senior drainage engineers also provided expert knowledge by determine the presence of risks at the three sites (see Section 5.4).

Additional data were ontained from other sources including flood map from UK's Environmental Agency, a variety of map from Digimap-Ordnance Survey associated with the selected sites (i.e. topography, geology, soil strength).

5.2.1 Ardsley Tunnel

Ardsley Tunnel is located near Leeds. It was built on the railway section with cuttings at either ends. The length of the tunnel is 205.74 m (Railway Codes, 2018) whereas the length of C3 drainage assets (channel drains and ditches) is 1207.01 m (from mileage I180.0880 to

181.0440). Incident data shows that problems are likely to occur on this part of the track, shown by the number of times the rails became submerged over the last ten years. Thus, a homogeneous section after the tunnel gate, towards Leeds, was chosen. The rationale behind the selection of this section in particular are as follows:

- This section was built in the middle of earthworks cutting, meaning it is likely to be prone to excessive water dissipating from the top of the cutting when C3 drainage assets are defective or when they fail. These assets function as a catch drain.
- The C3 are built besides a wetland area and ponds, which are subject to various risks, for example scour risk.

Figure 5.1 shows an aerial view of the Ardsley tunnel site. Figure 5.2 shows the selected homogenous section (i.e. the Ardsley Tunnel portal, towards Leeds). Figure 5.3 shows the drainage assets on the site.

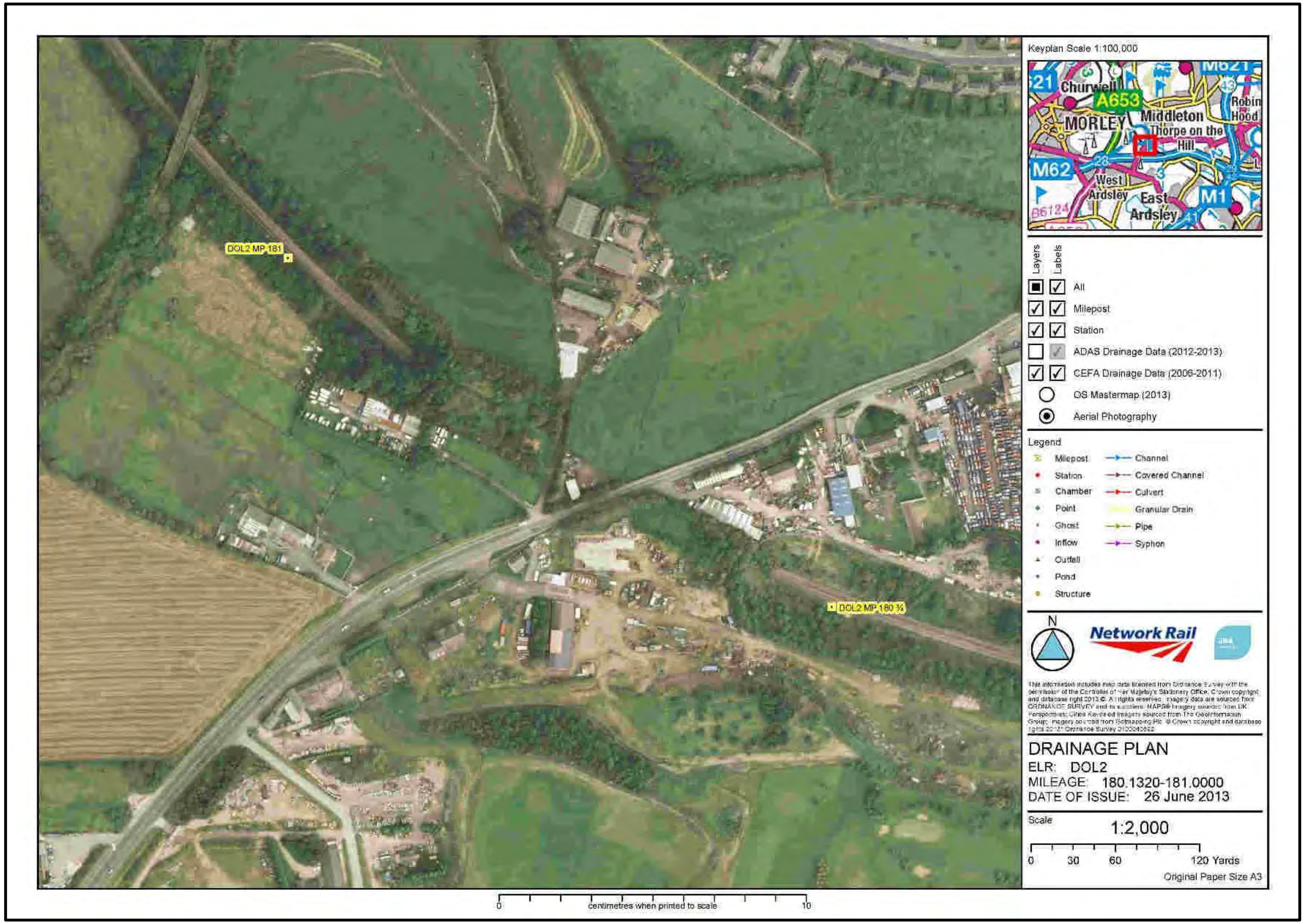


Figure 5.1 Aerial view of Ardsley Tunnel site, source Network Rail (2013a)

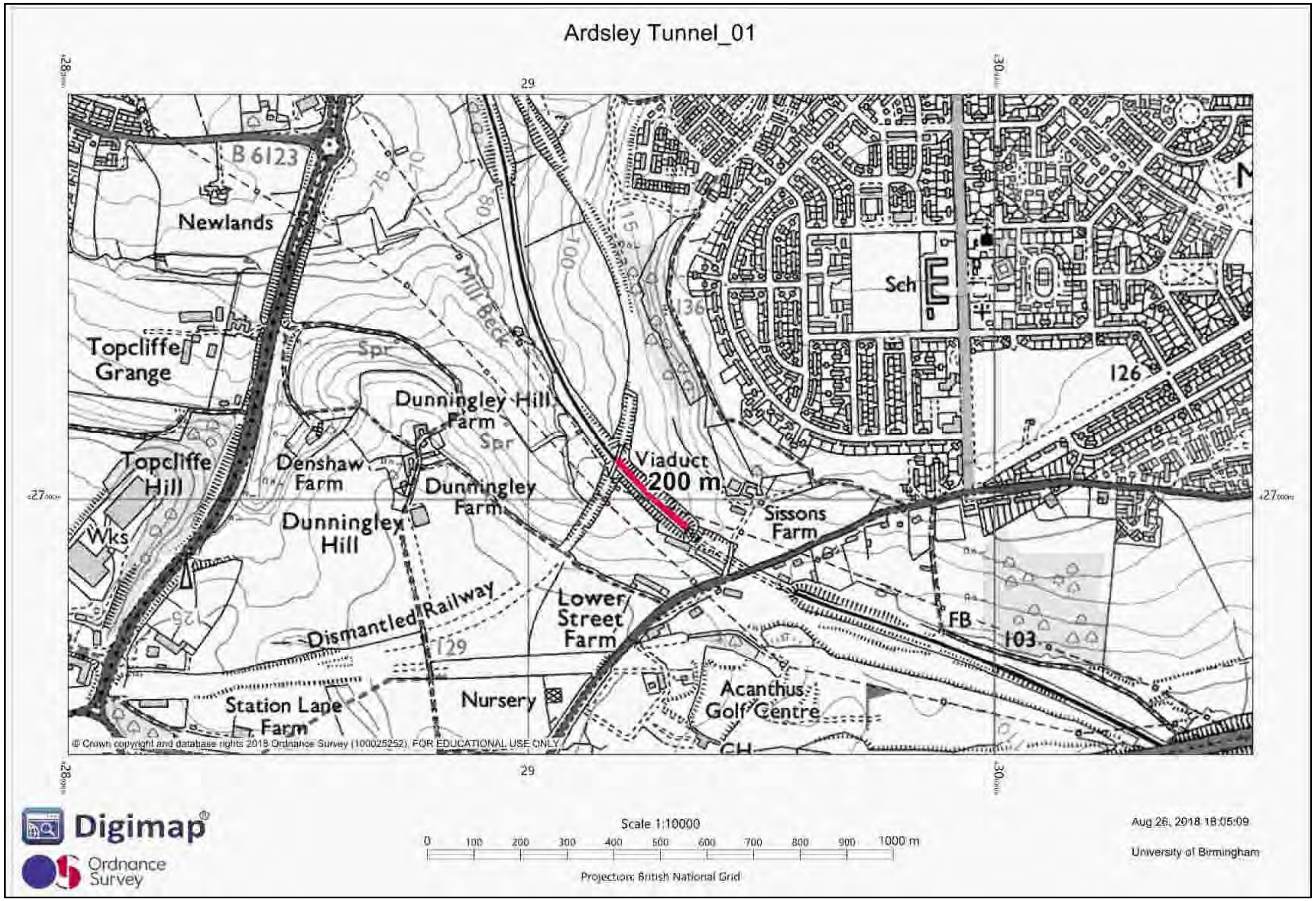


Figure 5.2 Homogeneous section of Ardsley Tunnel site, after Ordnance Survey (2018a)

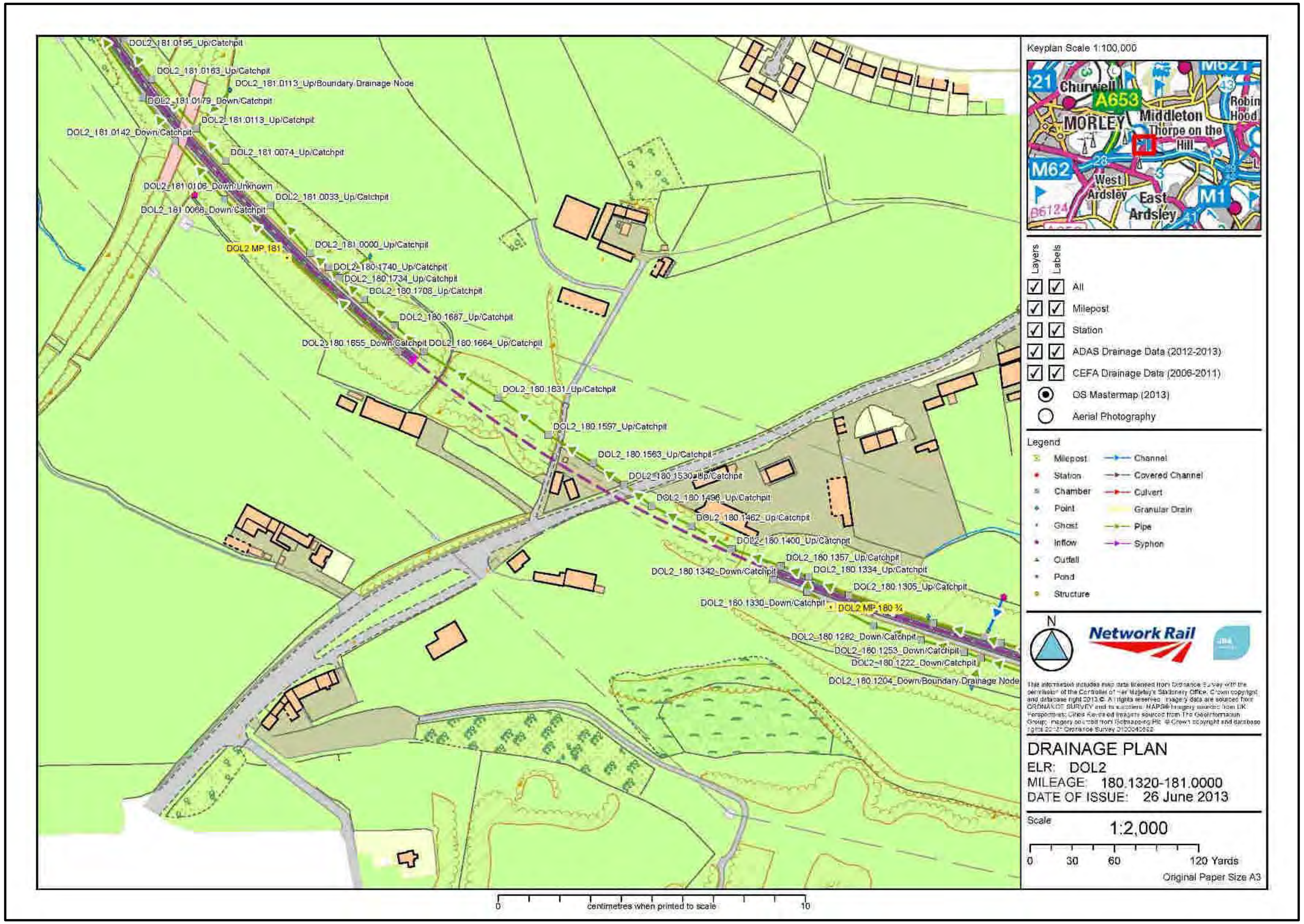


Figure 5.3 Map of drainage assets at Ardsley Tunnel site (Network Rail, 2013b)

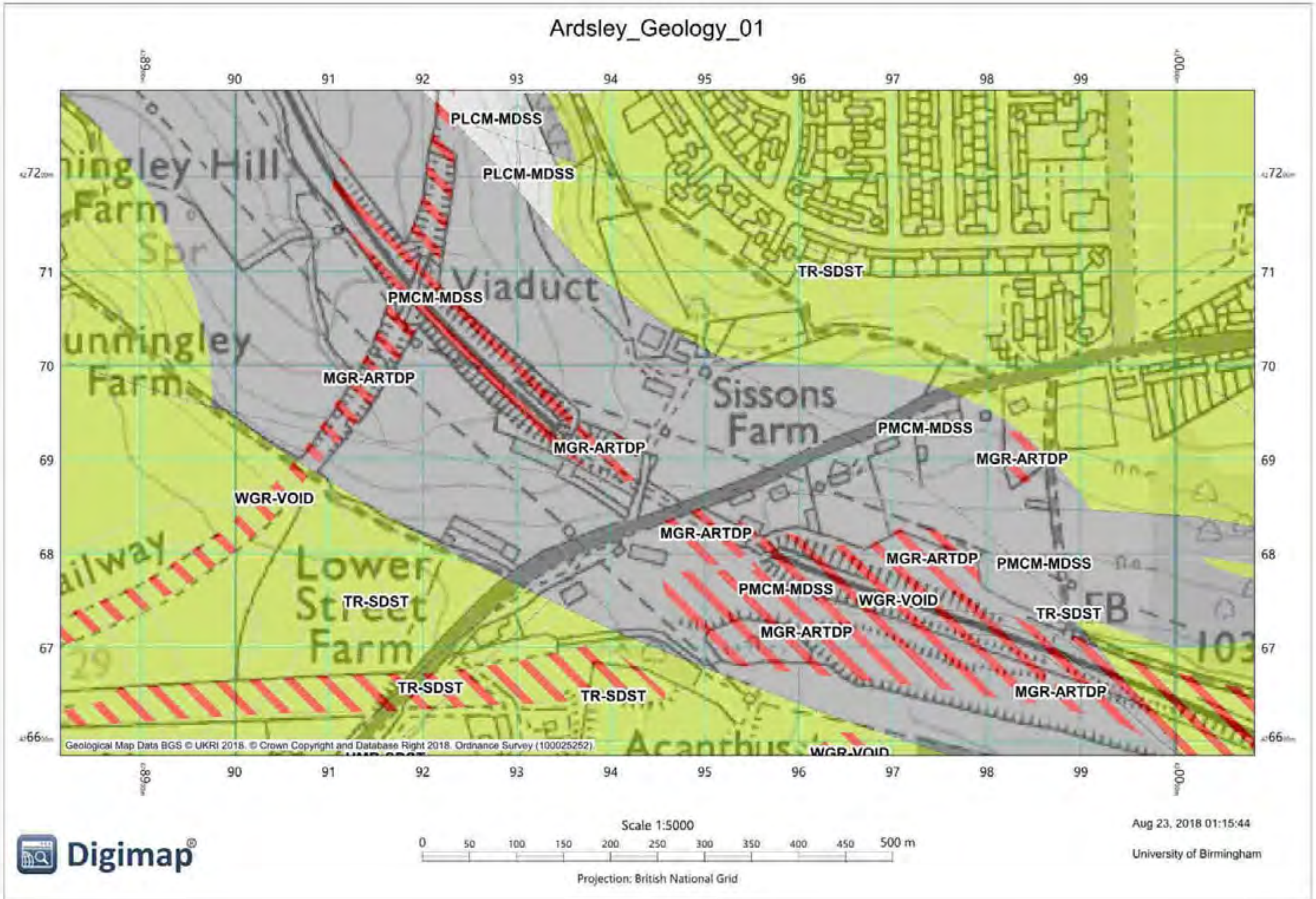


Figure 5.4 Geology map of Ardsley Tunnel site, (Ordnance Survey, 2018b)

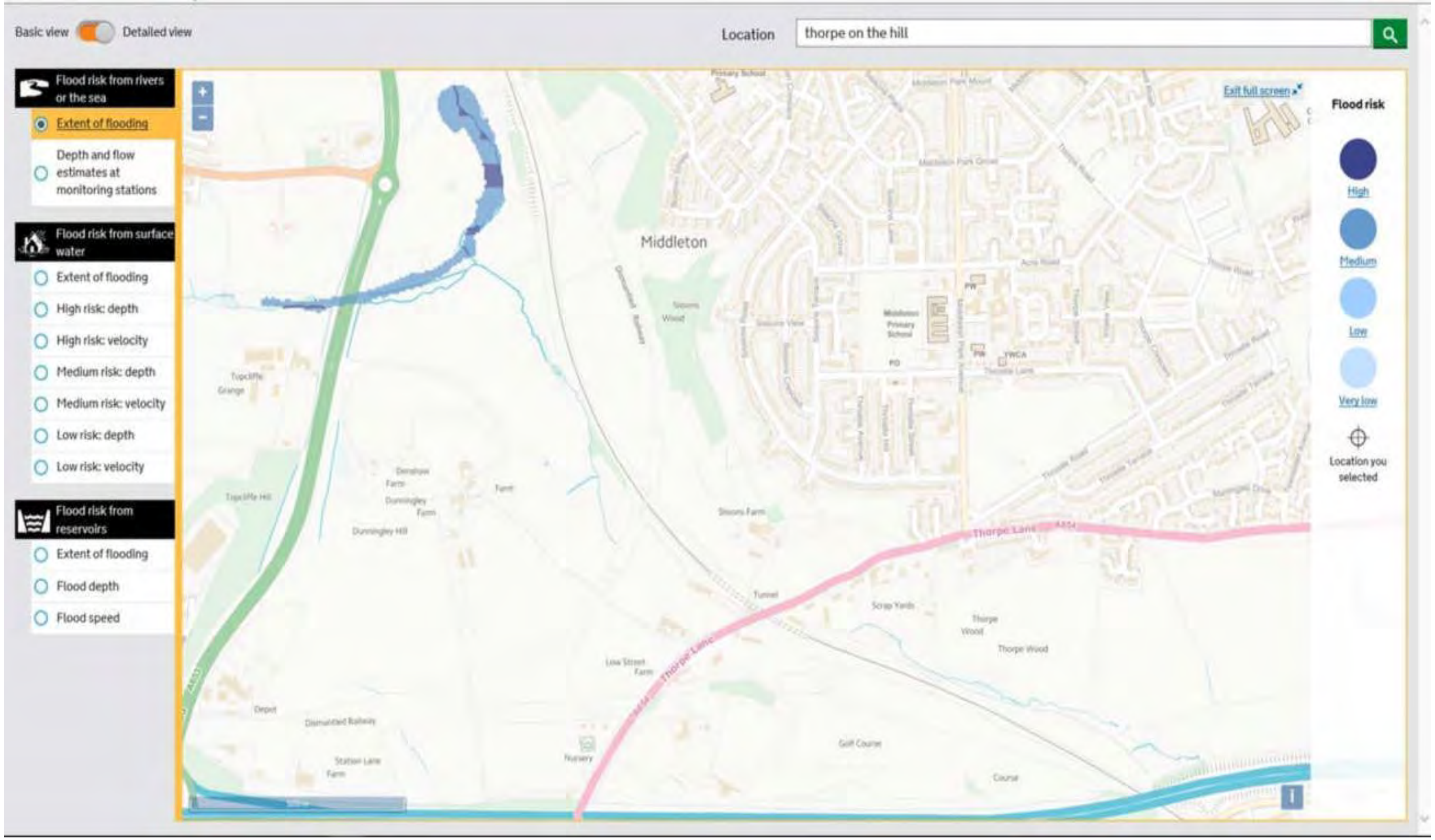


Figure 5.5 Flood risk from rivers at Ardsley Tunnel site, after Environment Agency (2018a)

5.2.2 Clay Cross Tunnel

The Clay Cross Tunnel is located near Derbyshire. The length of the tunnel is 1,631.29 m (Railway Codes, 2018) whereas the length of each side of the C3 drainage assets (channel drains and ditches) are 993.95m. In terms of NR's milleage, this section is positioned between 147.0484 and 147.1527. For the case study, a 200 m (1/8 mile) homogeneous section at the tunnel outlet was chosen (see Figure 5.7). The rationale for the selection of this section are as follows:

- This section is in the middle of an earthwork cutting, which is likely to mean it is prone to excessive water dissipating from the top of the cutting, leading to a failure of C3 drainage assets, given that these assets function as a catch drain.
- The C3 assets are built adjacent to a wet land area and ponds; this exposes them to various risks, including scour risk.

An aerial view of the homogeneous section at Clay Cross Tunnel is presented in Figure 5.6; the red line in the yellow circle illustrates the homogeneous track section selected (see Figure 5.7). Figure 5.8 shows the mapping of drainage assets on this site.

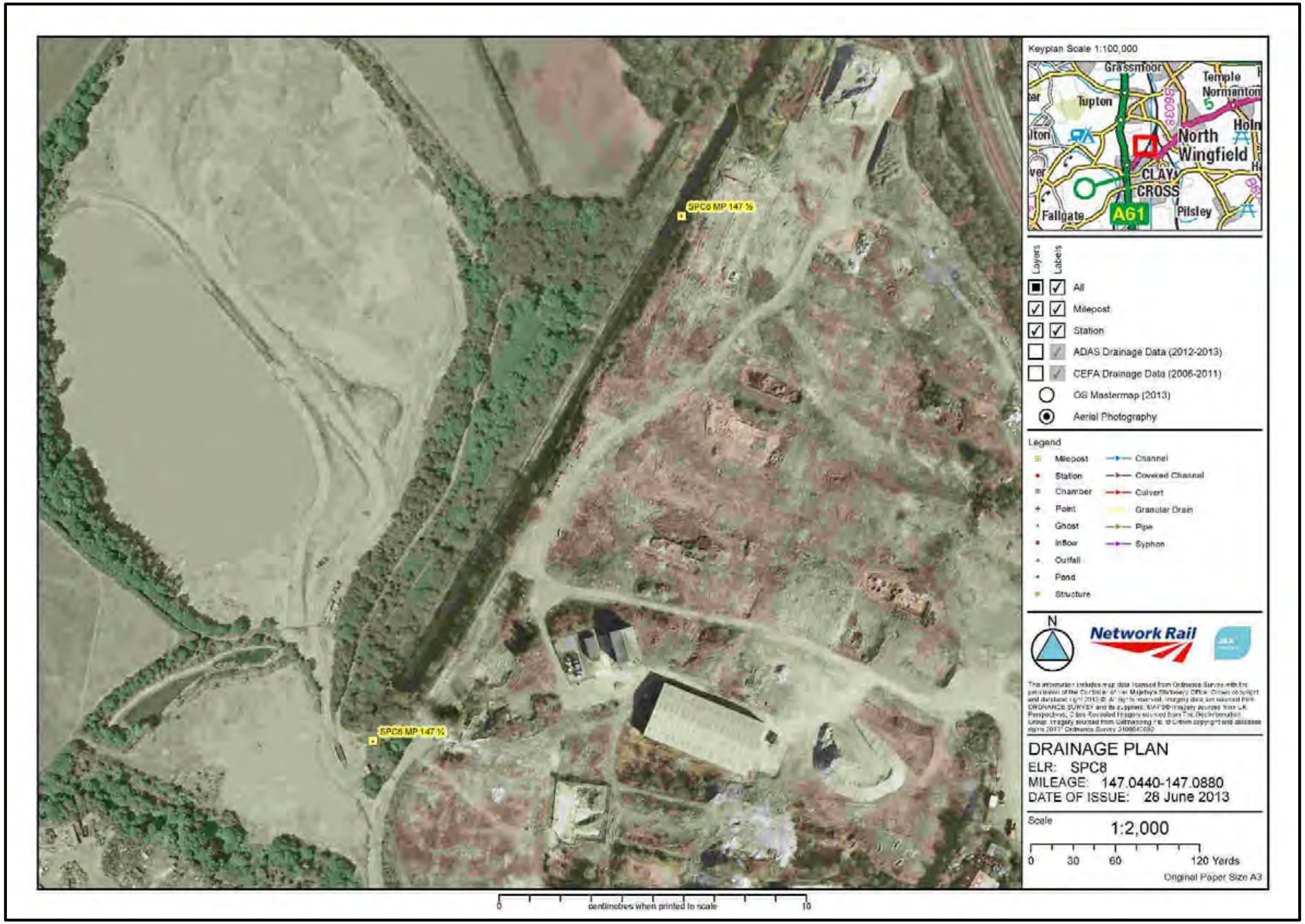


Figure 5.6 Aerial view of Clay Cross site (Network Rail, 2013c)

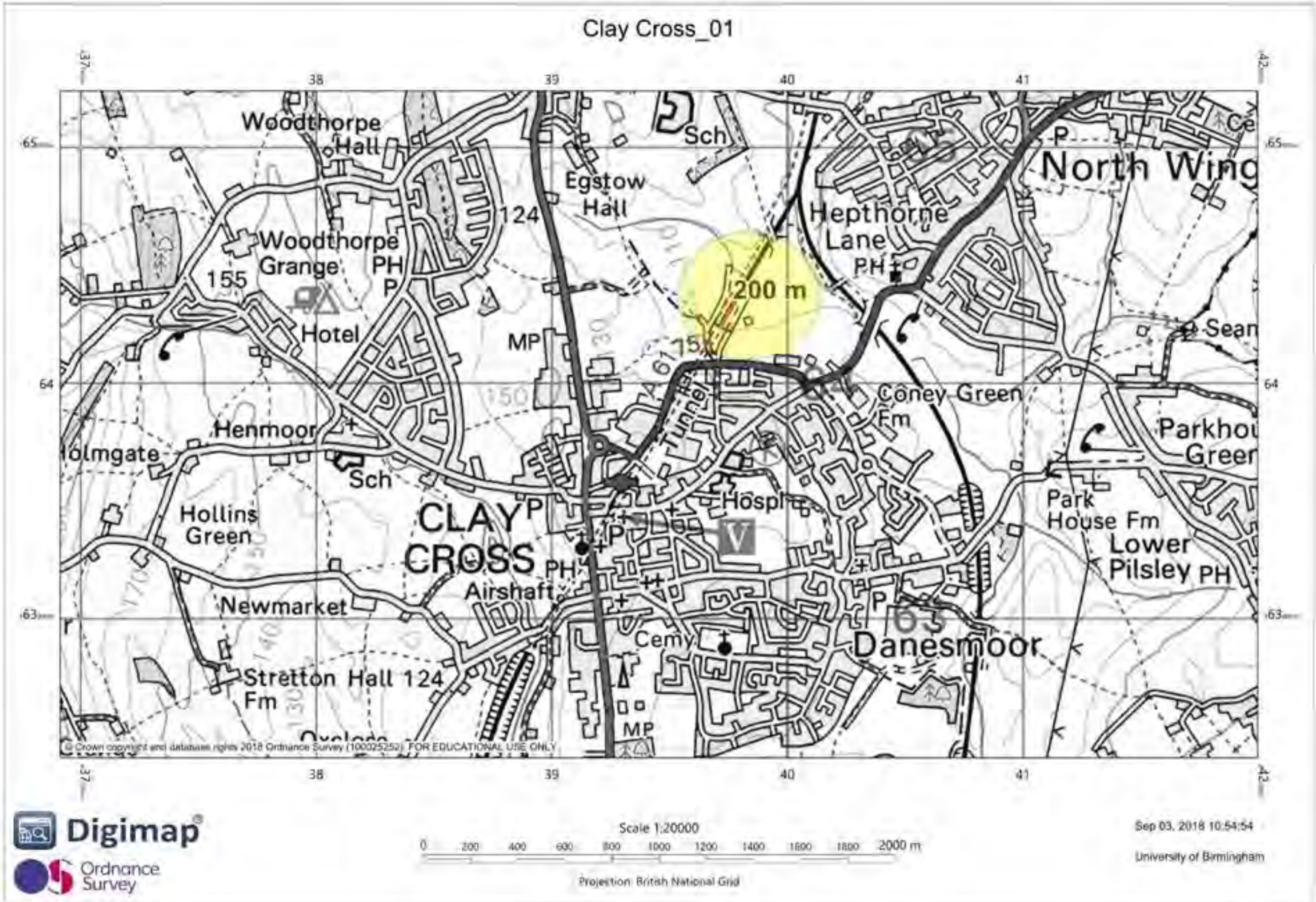


Figure 5.7 Homogeneous section of Clay Cross Tunnel site, source after Ordnance Survey (2018c)

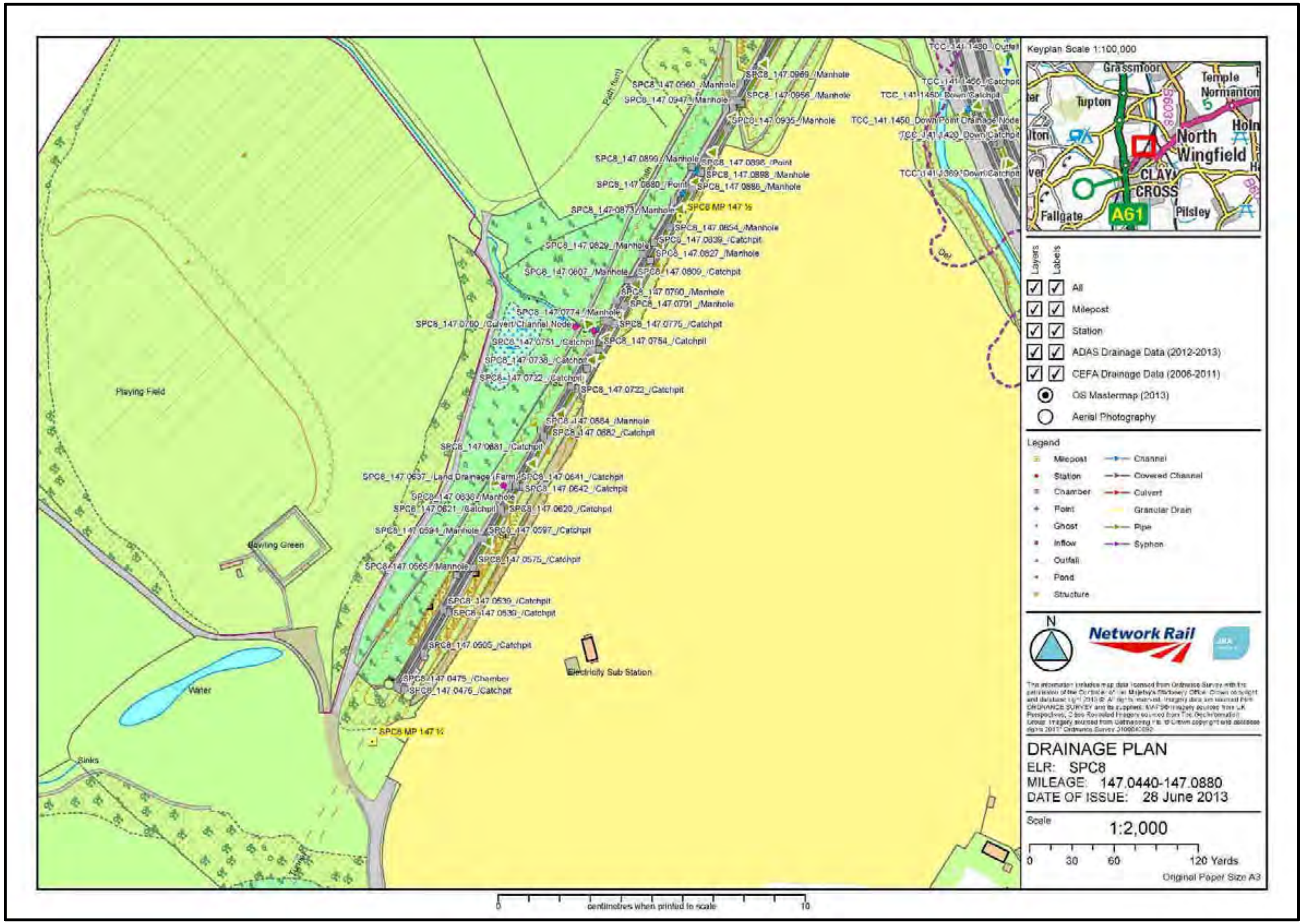


Figure 5.8 Map of drainage assets at Clay Cross site source Network Rail (2013d)

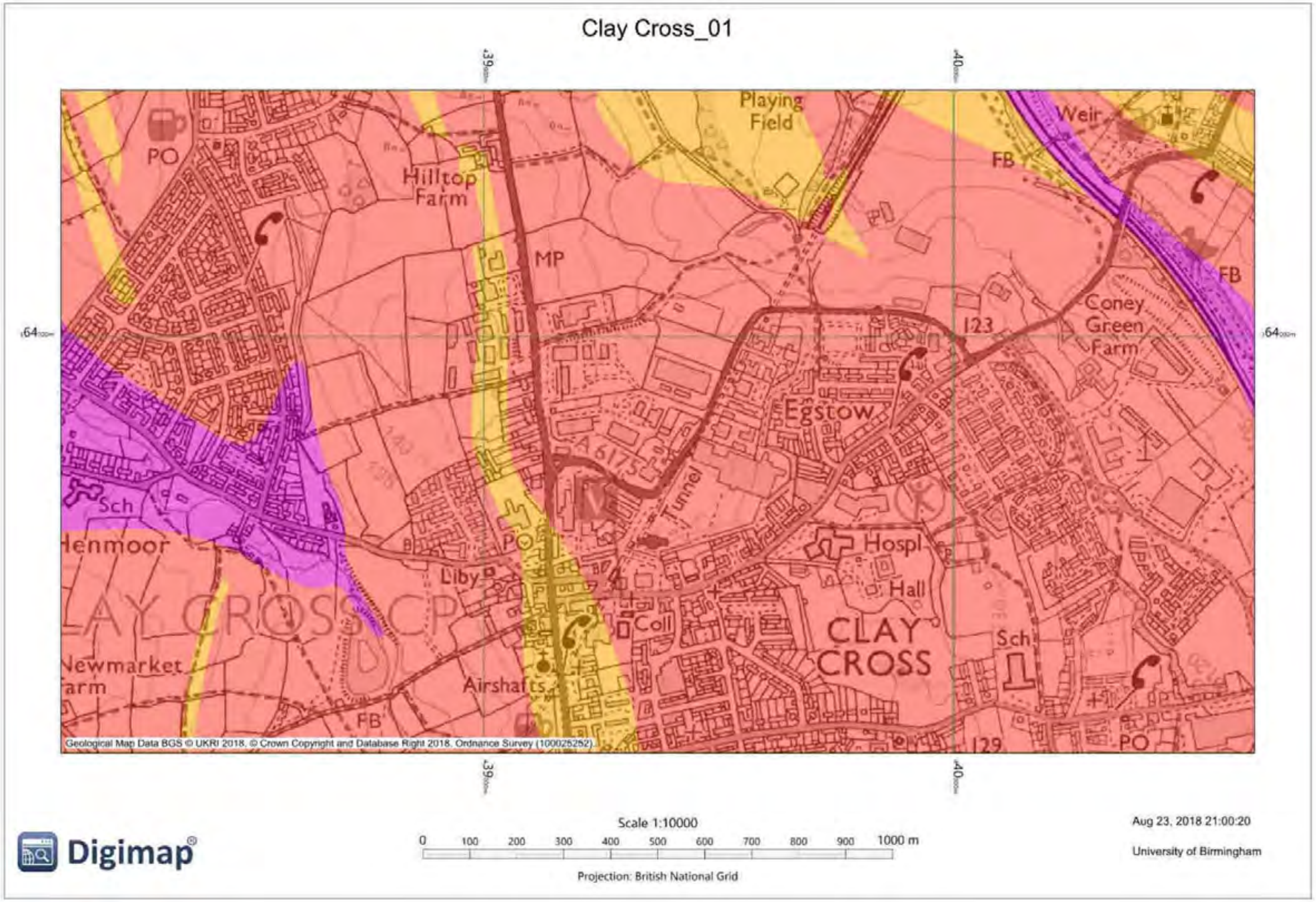


Figure 5.9 Soil strength map of Clay Cross Tunnel site, source Ordnance Survey (2018d)

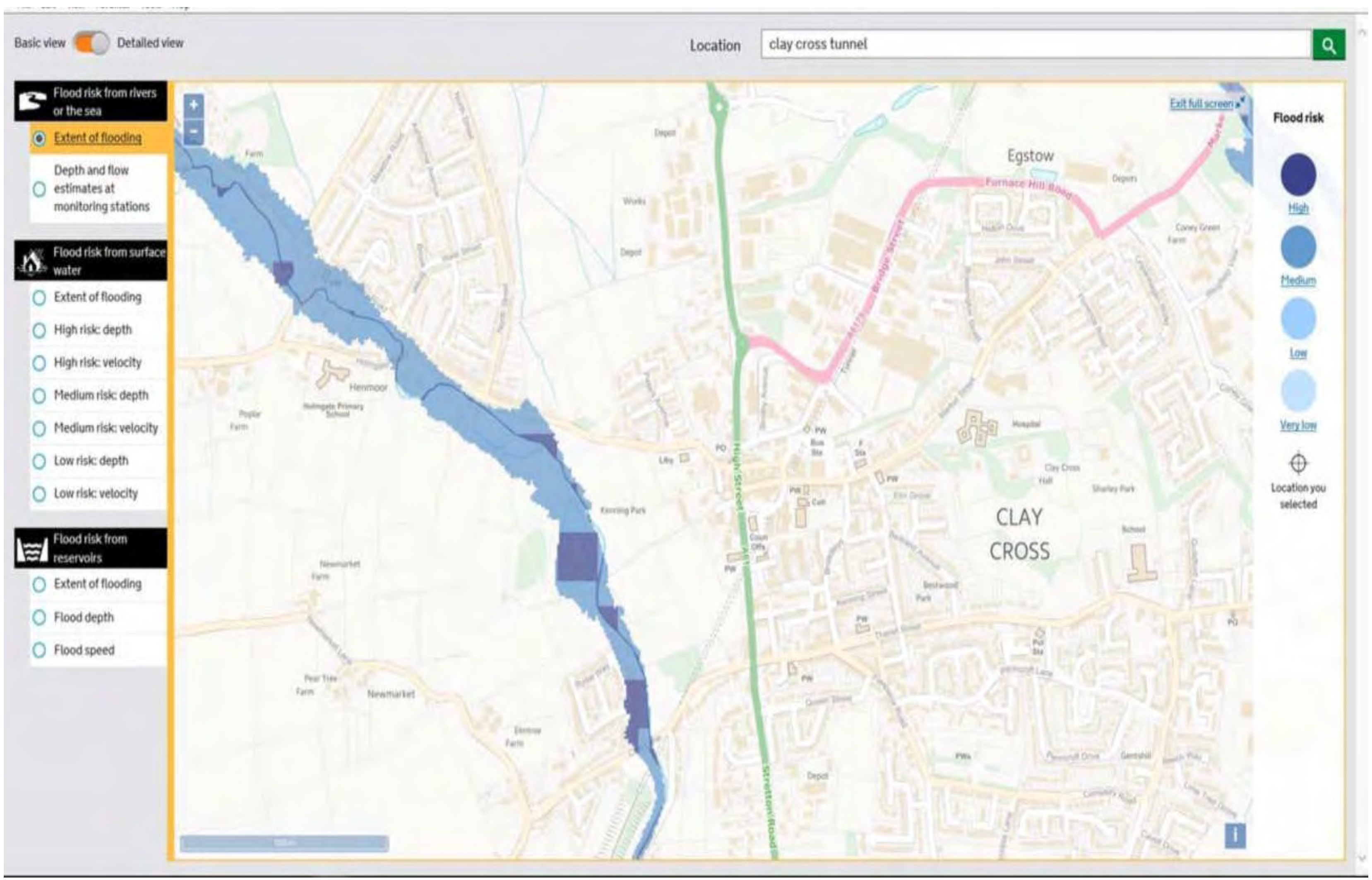


Figure 5.10 Flood risk from rivers at Clay Cross Tunnel site, source the Environment Agency (2018b)

5.2.3 Draycott

The Draycott site is located near Derbyshire. This section was built as part of the Midland railway network, is surrounded by a canal and a highway network and passes relatively to dense residential areas. The length of C3 drainage assets is 3218.69 m for each side of the drain (from miliage 120.0000 to 122.0000). For the case study, the incident data shows that problems are likely to occur at the part of railway network located near to the canal network and the highway fly-over. Therefore, a homogeneous section of track after the intersection of rail line and Erewash canal at Long Eaton towards Draycott was chosen. The track was considered to be homogenous in term sof type of built drainage assets and considerable impacts. For example, the type of the drainage assets are channel drains and ditches and this section is built on the middle of densed residential area. The rationale for choosing this section of site is as follows:

- This section was built in the middle of highway, reservoirs, and canal networks in a residential area, meaning that it is at risk from a variety of sources of flooding, including from the reservoirs. The drainage assets here therefore function as a side (cess) drain.
- The C3 assets pass through dense residential areas and are on an important section of the
- railway network (main line). This means that the impact of ineffective drainage may be high.

Figure 5.11 shows an aerial view of Draycott site, Figure 5.12 shows the homogeneous section and Figure 5.13 shows a map of the drainage assets on this site.

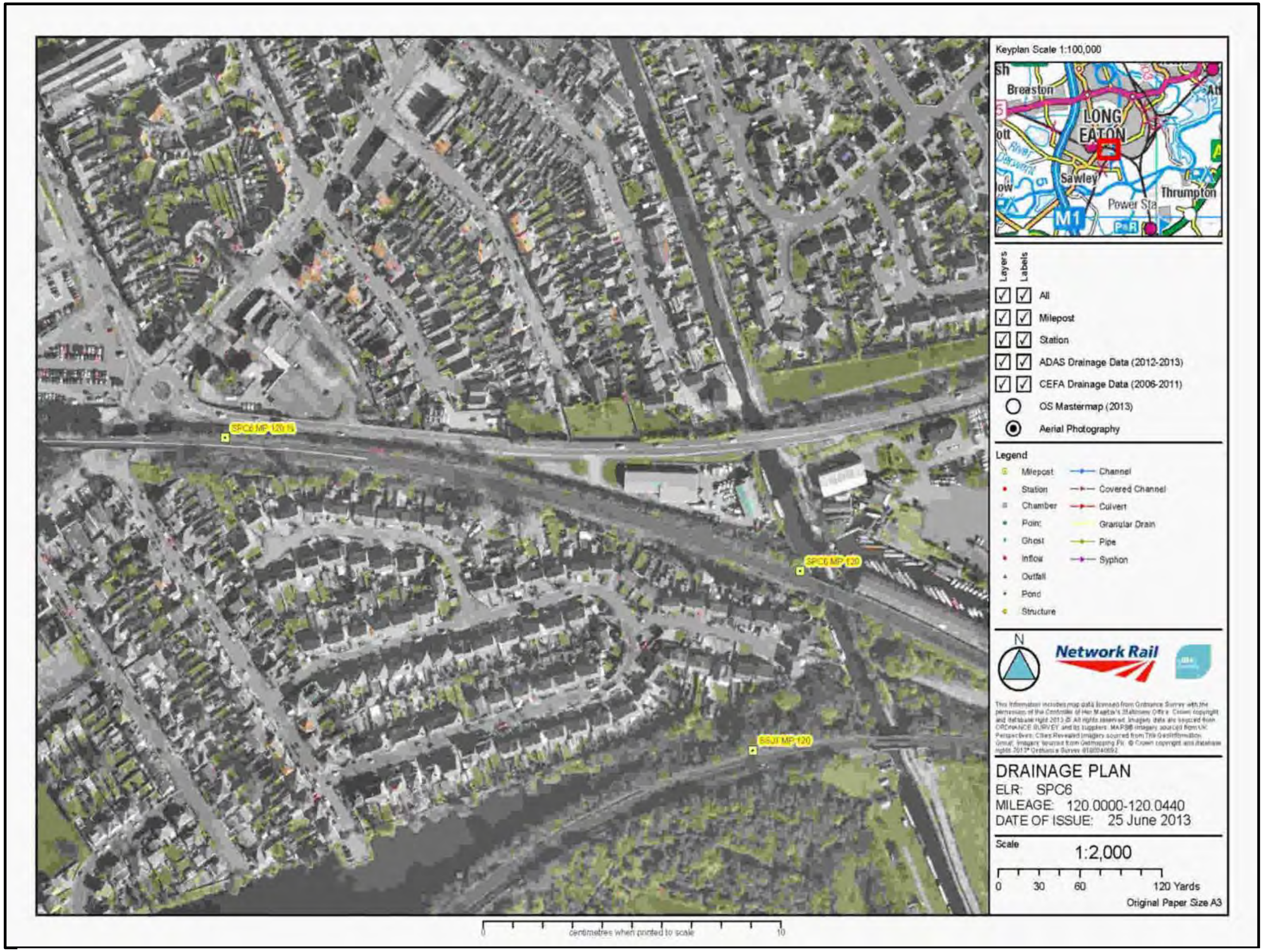


Figure 5.11 Aerial view of Draycott site, source Network Rail (2013e)

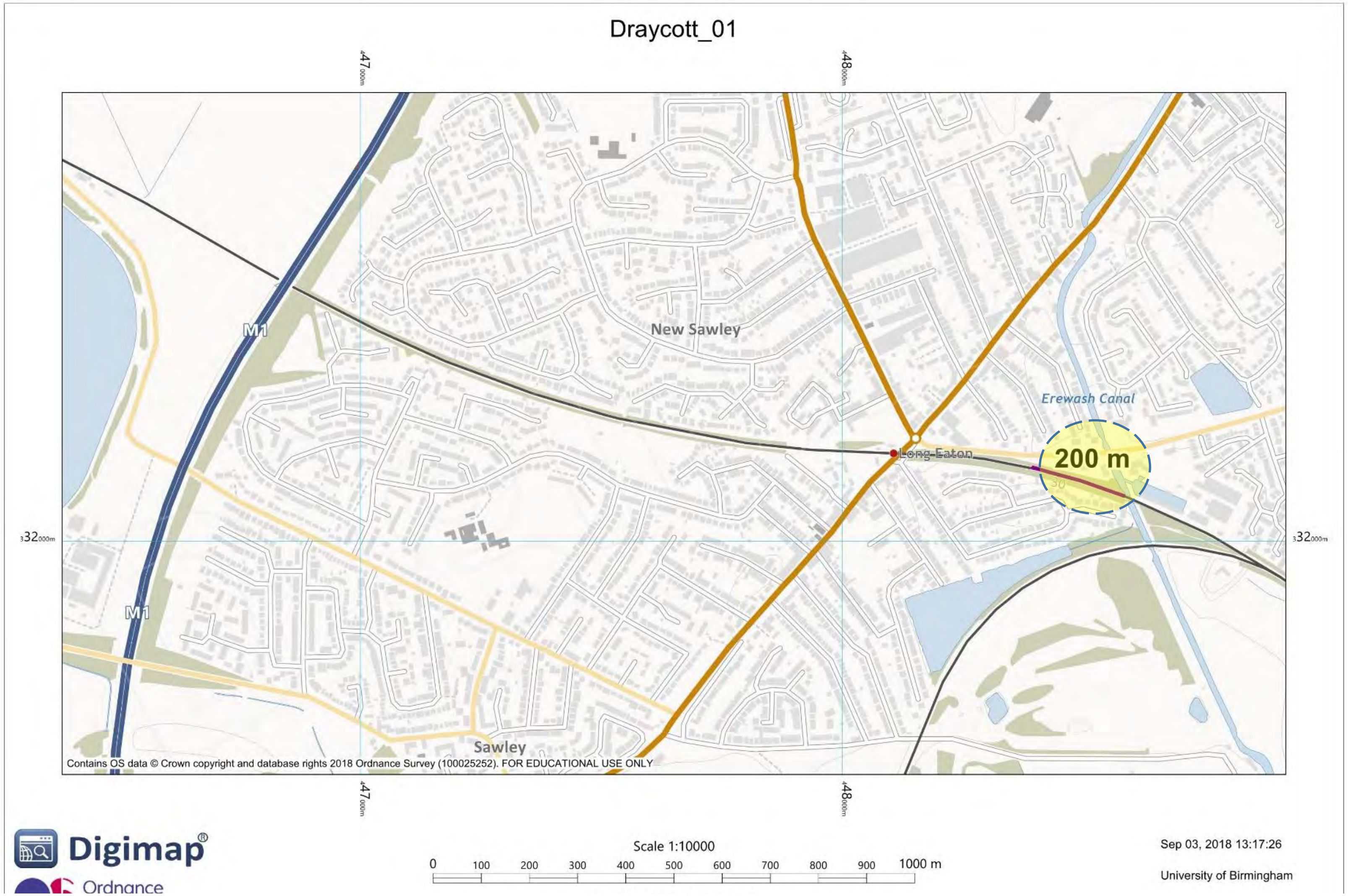


Figure 5.12 Homogeneous section at Draycott site, source after Ordnance Survey (2018e)

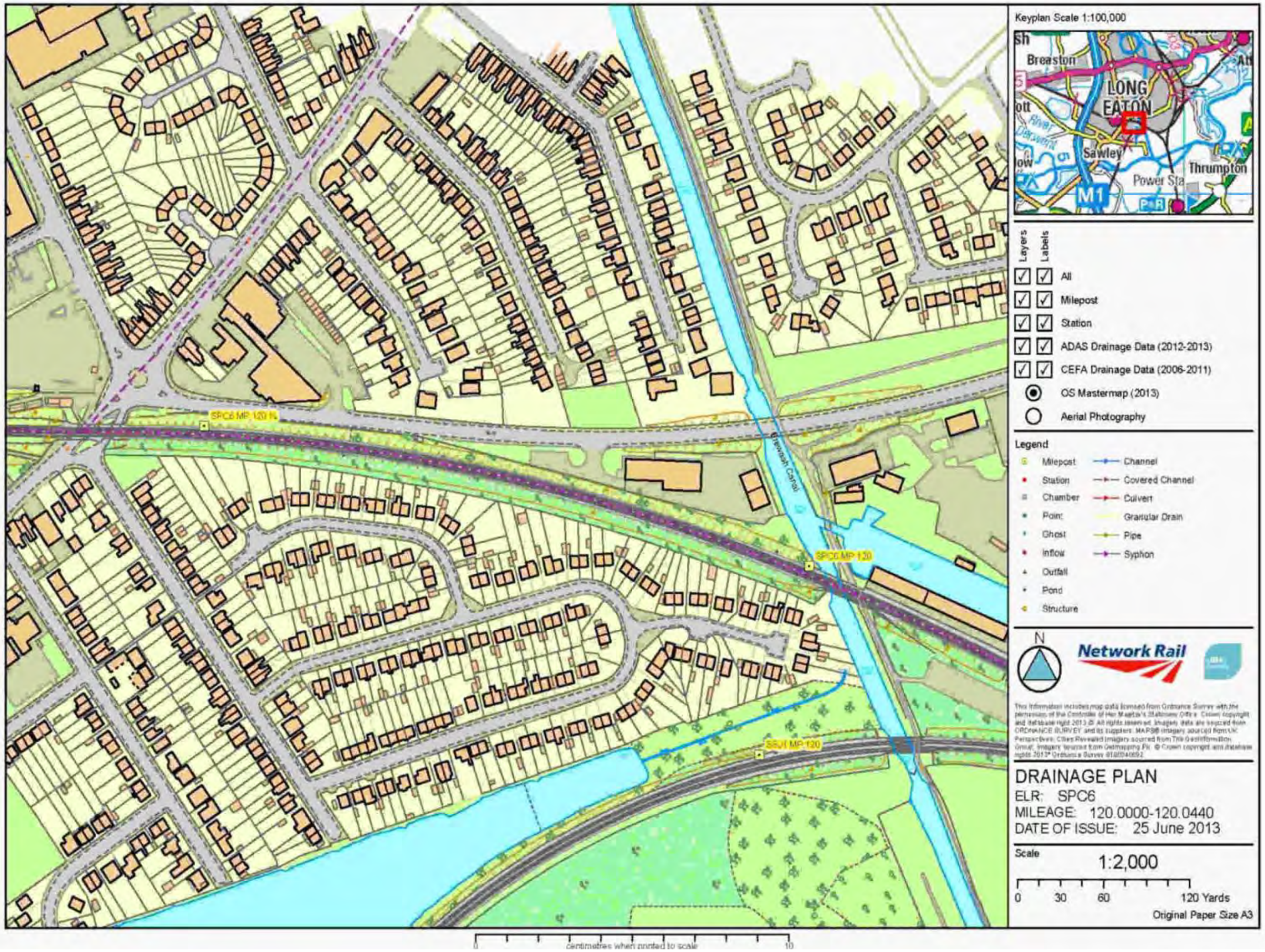


Figure 5.13 Map of drainage assets at Draycott site source Network Rail (2013f)

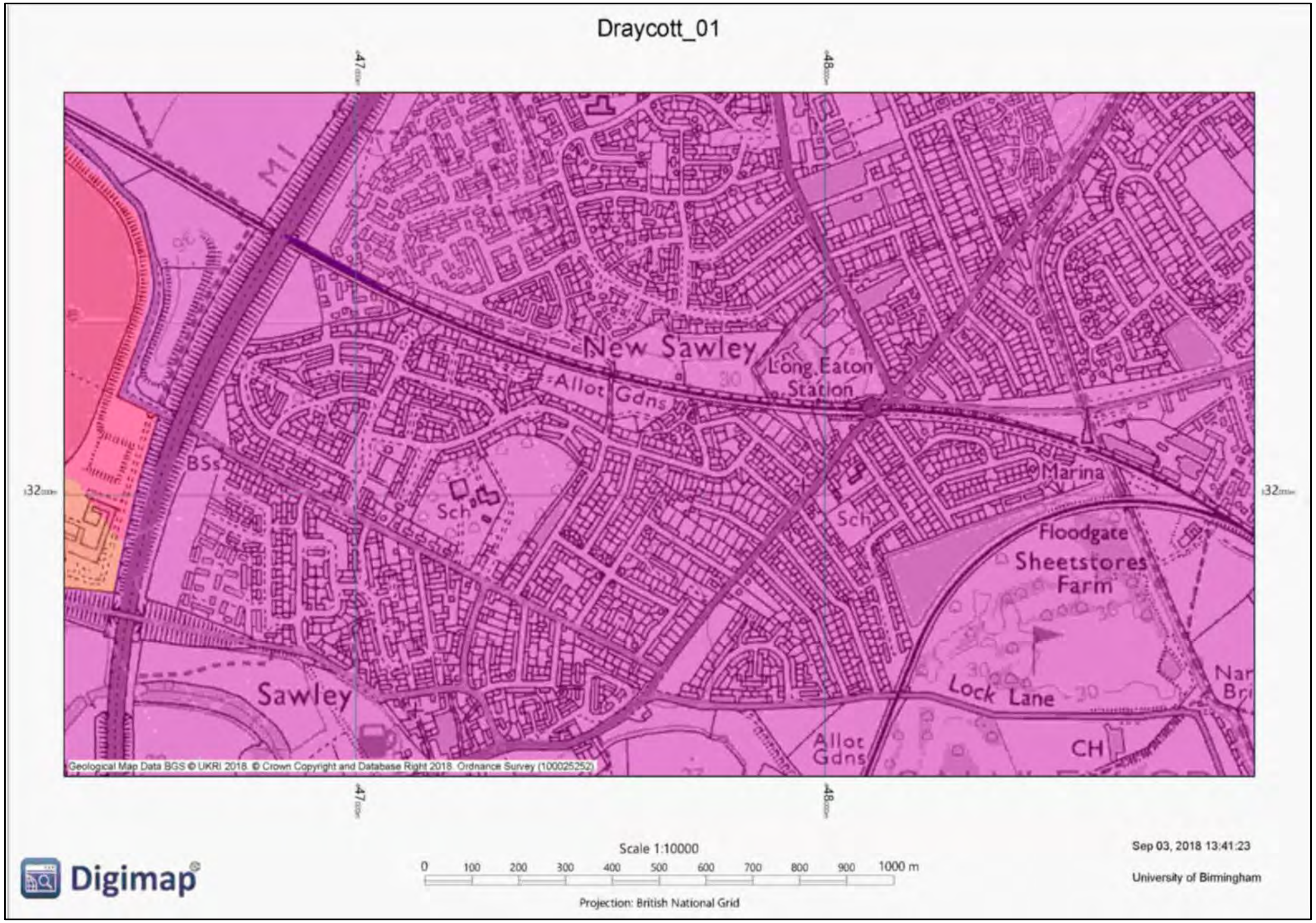


Figure 5.14 Soil strength map of Draycott site, source Ordnance Survey (2018f)

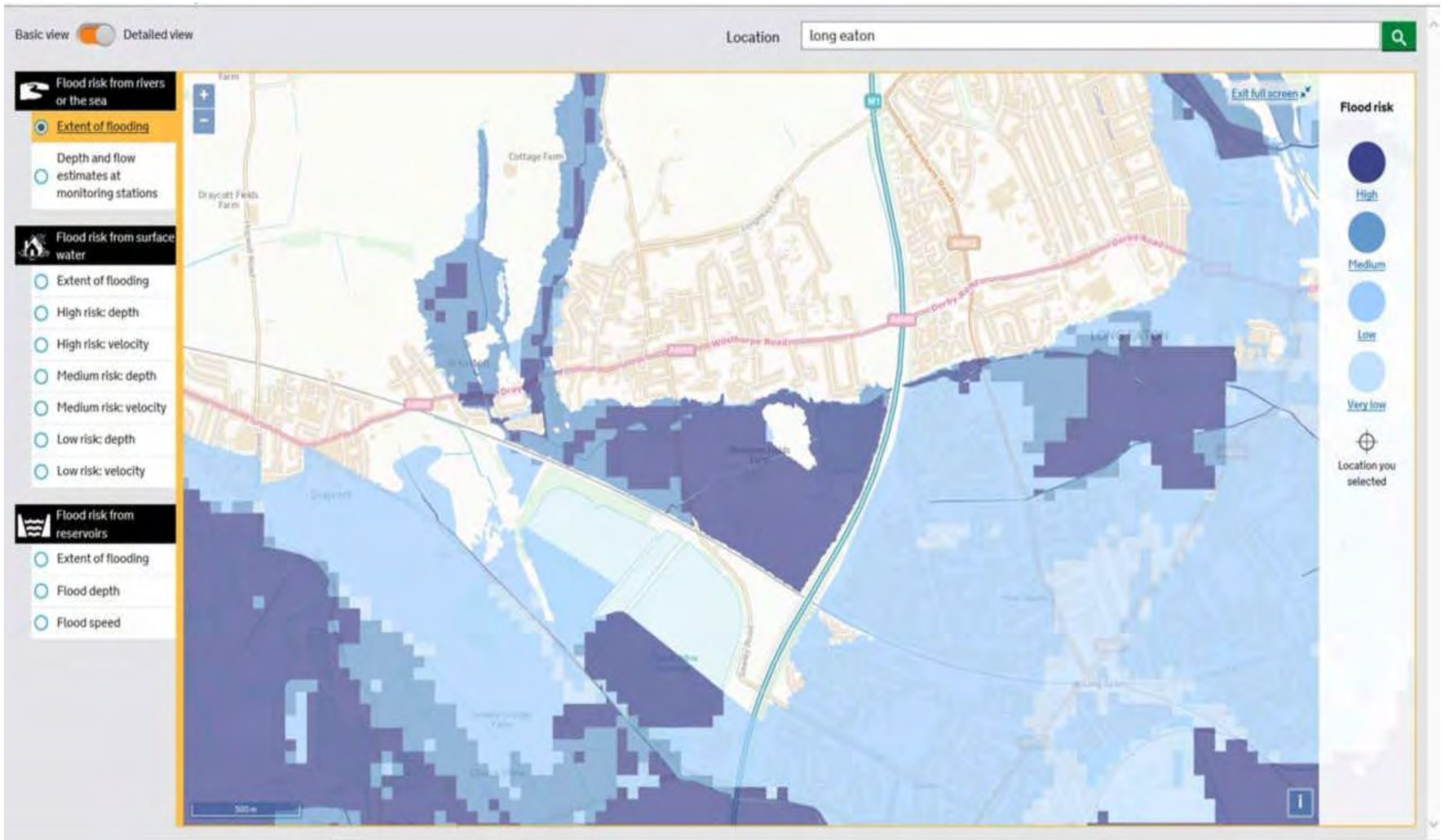


Figure 5.15 Flood risk from rivers at Draycott site, source Environment Agency (2018c)

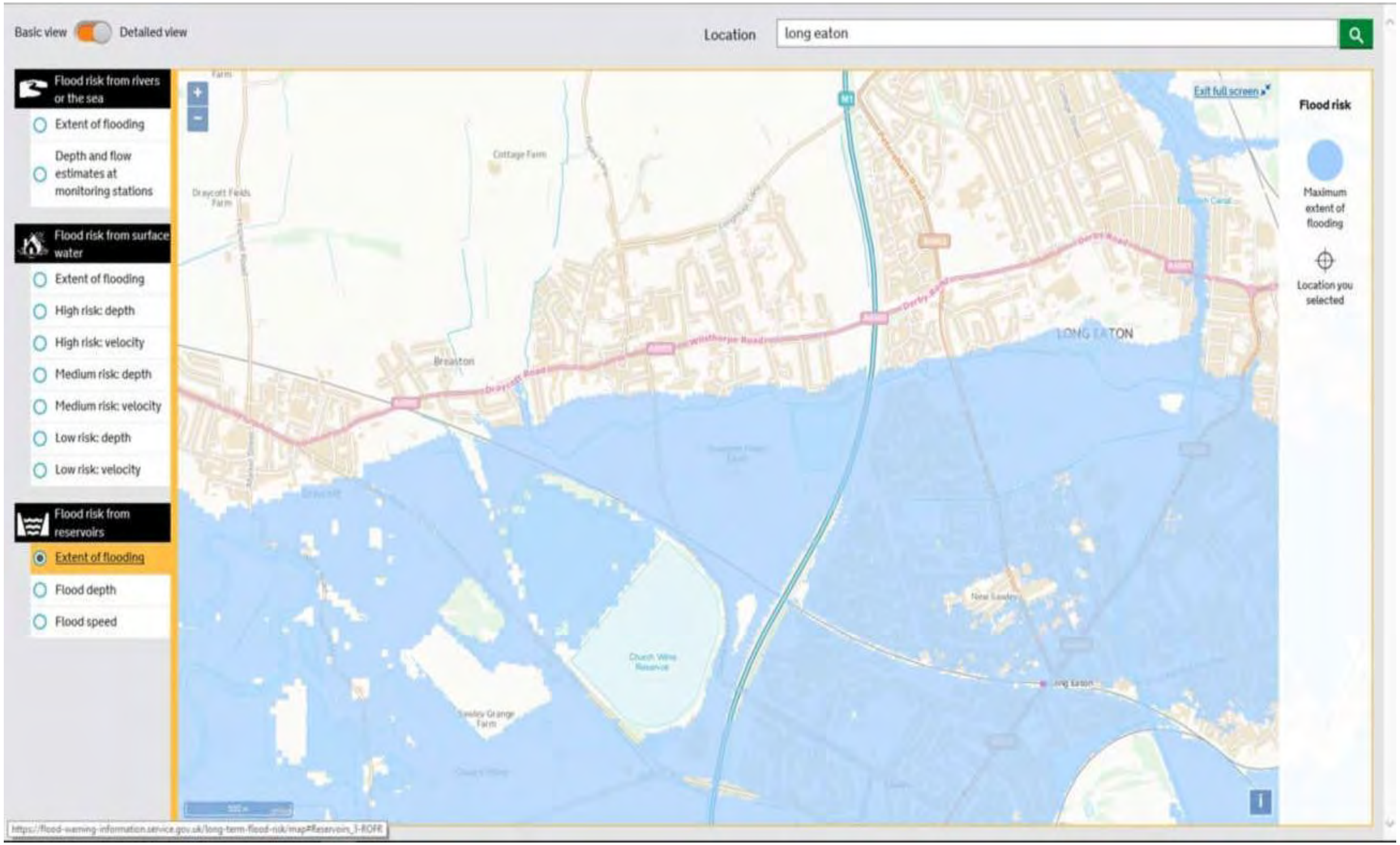


Figure 5.16 Flood risk from reservoirs at Draycott site, source Environment Agency (2018d)

5.3 Risk Identification l

The process describes in 4.4 and 4.5 was used to identify the risks associated with poor drainage for the three sites. These, mainly all possible risks related to C3 assets (see Figure 4.15), are summarised in Tables 5.1-5.3 Table 5.1 and Table 5.2 show that there are twenty-two basic and eleven mid-events associated with a variety of contributing factors, whereas Table 5.3 presents four mid events associated of failure modes

Table 5.1 Causal factors of defective or failed channel drains and ditches (mid events)

Code	Causal Event/ Risk Item	Type	Contributing Factor
X5	Weak soil	Basic event	Subgrade
X6	Flood risk from surface water (heavy rainfall)	Basic event	Environmental
X7a	Flood risk from rivers	Basic event	Environmental
X7b	Flood risk from the sea	Basic event	Environmental
X7c	Flood risk from reservoirs	Basic event	Environmental
X8	Excessive soil pressure	Basic event	Subgrade
X10	Weathering (chemical)	Basic event	Environmental
X11	Change to land use (catchment area)	Basic event	Land use
X12	Changes to drain upstream	Basic event	Land use
X19	Lack of debris clean out	Basic event	Maintenance
X20	Non ballast material infiltration	Basic event	Maintenance
	(waste from the train, spillage from the train, fly tipping)		
X21	Poor ballasting practices	Basic event	Maintenance
X25	Vegetation overgrowth	Basic event	Maintenance
X26	Spoil tipping	Basic event	Maintenance
X28	Aging channel drains and ditches material	Basic event	Component
X29	Scour around channel drains and ditches	Basic event	Environmental
X30	Inadequate gradient of channel drains and ditches	Basic event	Design
X40	Damage caused by other assets/ 3rd party assets	Basic event	Land Use
X41	Damage caused by burrowing animals	Basic event	Maintenance
X42	Lack of silt clean out (channel drains) or excavate (ditches)	Basic event	Maintenance
X43	Damage caused by poor installation	Basic event	Installation
X44	Prolonged extreme hot weather	Basic event	Environmental

Table 5.2 Causal factors of defective or failed channel drains and ditches (basic events)

Code	Causal Event/ Risk Item	Type	Contributing Factor
H1	Excessive water infiltration to track bed	Mid event	Environmental
G1	Softening below drain level	Mid event	Subgrade
F1	Settlement due to change of gradient	Mid event	Subgrade
F4	Erosion	Mid event	Environmental
E11	Bank instability	Mid event	Subgrade
E12	Silting channel drain and ditches	Mid event	Maintenance
E13	Deterioration of channel drains and ditches material	Mid event	Component
DE1	Debris infiltration	Mid event	Maintenance

Table 5.3 Failure modes of defective or failed channel drains and ditches (mid events)

Code	Causal Event/ Risk Item	Type	Failure Mode
D8	Blocked channel drains and ditches	Mid event	Channel drains and ditches failure
D9	Collapsed channel drains and ditches	Mid event	Channel drains and ditches failure
D10	Inadequate capacity of channel drains and ditches	Mid event	Channel drains and ditches failure
C3	Failure/ defective channel drains and ditches	Mid event	Channel drains and ditches failure

A description of the potential risks of C3 assets is provided in Appendix 6.

5.4 Risks specific to the case studies

Following bthe identification of all possible risks, the senior drainage engineer was consultated to identify those risks which could occur at the three sites. Expert advice was captured through discussion and by means of a questionnaire. These questionnaires and a discussion notes from senior drainage engineer are shown in Appendix 3.

5.4.1 Frequency of occurrence of railway drainage risks at the Ardsley Tunnel site

This section and the next two sections present the data obtained concerning the presence of particular risks and the frequency with which they will occur at the case study sites. As mentioned above, the data was obtained via questionnaire and discussion from historical sources and extant literature. These are summarised in Table 5.4 Ardsley Tunnel), Table 5.6 (Clay Cross Tunnel), and Table 5.7 (Draycott). Table 5.4 shows that eleven risks are present, out of the total of twenty-two possible risks. Two risks are related to the environment (X6, X7a), three risks are associated with land-use (X11, X12, X40), five are related to maintenance (X19, X20, X25, X26, and X42) and one is related to components (X28).

Flooding from surface water (X6) occurred eight times between 2009 and 2018. Most of these events occurred in 2012 (there were a total of seven events between April December), whereas only one event occurred in December 2015. Then the risks occurrence data were divided by 10 years (see Section 5.4) to obtain frequency occurrence or occurrence rate of the specific risks, which then used as inputs to quantify the risk likelihood (see Table 5.4). The highest water levels were recorded above the rail head. Although there is no record of X7a (flooding from river) risk, during the questionnaire and discussion session, the senior asset engineer (drainage) confirmed that this risk has occurred. Therefore, instead of relying just on incident records, an online flood map of the UK was used to ascertain the frequency of X7a. This map (see Figure 5.5) shows that the homogeneous section is light blue in colour; and that the likelihood of the risk occurring ranges between 0.1 % (1 in 1000 years) and 1 % (1 in 100 years) (see Table 5.5).

Table 5.4 Availability and frequency of each risk occurring at the ArdsleyTunnel site

Code	Basic Event/ Risk	Availability	Frequency (years)	Source of Data
X5	Weak soil	-		
X6	Flooding from surface water	√	0 - 8 in 10	NR's record
X7a	Flooding from river	√	1 in 1000 - 1 in 100	UK's flood map
X7b	Flooding from sea	-		
X7c	Flooding from reservoirs	-		
X8	Excessive soil pressure	-		
X10	Weathering (chemical)	-		
X11	Change to land use (catchment area)	√	1 in 100 - 1 in 30	Literature
X12	Changes to drain upstream	√	1 in 100 - 1 in 30	Literature
X19	Lack of debris clean out	√	0 - 1 in 10	NR's record
X20	Non ballast material infiltration	√	1 in 100 - 1 in 30	Literature
	(waste from the train, spillage from the train, fly tipping)			
X21	Poor ballasting practices	-		
X25	Vegetation overgrowth	√	0 - 1 in 10	NR's record
X26	Spoil tipping	√	1 in 100 - 1 in 30	Literature
X28	Aging channel drains and ditches material	√	0 - 1 in 50	Literature
X29	Scour around channel drains and ditches	-		
X30	Inadequate gradient of channel drains and ditches	-		
X40	Damage caused by other assets/ 3rd party assets	√	0 - 1 in 10	NR's record
X41	Damage caused by burrowing animals	-		
X42	Lack of silt clean out (channel drains) or excavate (ditches)	√	1 in 30 - 1 in 10	Literature
X43	Damage caused by poor installation	-		
X44	Prolonged hot weather	-		

Table 5.5 Frequency of occurrence for every flood risk category, source after Environment Agency (2018)

Category	Frequency of occurrence per year (%)
Very low risk	0 - 0.1 % (1 in 1000 years)
Low risk	0.1 % (1 in 1000 years) - 1 % (1 in 100 years)
Mediun	1 % (1 in 100 years) - 3.3 % (1 in 30 years)
High risk	3.3 % (1in 30 years) - 10 % (1in 10 years)
Very high risk	> 10 % (1 in 10 years)

Table 5.5 discusses the risk of flooding, using data from the UK's Flood Map. Where there is no historical data, this table can be used to determine the frequency with which a particular risk occurred.

Data held by Network Rail on C3 risks associated with land use is available for the Ardsley Tunnel site. According to NR's data, there has been one instance in which 3rd party assets (X40) caused a failure within the last ten years (2009 – 2018). This involved over running drains due to [a] volume of water running off third party land' (Network Rail, 2018) For the other two risks posed by land use, i.e. change to land use (catchment areas) (X11) and changes to upstream drainage (X12), there are no historical records. For that reason, the frequency of these risk occurring was estimated, using data obtained from Leeds City Council (2018) and Network Rail (2013). Apparently, this section is surrounded by farming land, e.g. Sissons, Lower Street and Dunningley which were likely not change in short period time see Figure 5.2 Considering the lack of historical land use change in the area in the last 30 years and the small likelihood of land use change occurring in the future. it was assumed that the risk might occur within a mid to long-term planning horizon. Therefore, the frequency with which this risk occurs was estimated to be between 1 in 30 years and 1 in 100 years and was therefore considered to be a medium risk (see Table 5.5).

Maintenance has five associated risks (i.e. X19. X20, X25, X26, X42). At the Ardsley Tunnel site, two out of five risks have occurred within the last decade: a failure to clean out debris (X19); and vegetation overgrowth (X25). The former occurred during December 2012, when debris and leaves inhibited water drainage in a couple of drainage channels. X20 risk, namely non-ballast material infiltration (i.e. waste from the train, spillage from the train, fly tipping) can lead to a debris infiltration risk (DE1). Given that this section of track is more frequently used by passenger trains than freight trains, the chances of this risk occurring within a ten-year period are lower and was estimated to be between 1 in 30 years and in 1 in 100 years. It was therefore categorised as a medium risk (see Table 5.5)

Similarly, when it comes to spoil tipping risk (X26), the estimates for this risk occurring were based on type of the assessed site; this risk is more likely to occur when the section of track is built on earthworks. There was an incident in December 2012, where water cascaded through the embankment and cutting without substantial damages. Thus, it is assumed that the frequency of this risk occurring is above 30 years but below 100 years. It is therefore a medium (see Table 5.5).

The remaining two risks associated with (X20) and (X42) are assumed to be medium risk, occurring between 1 in 30 years to 1 in 100 years due to rarely reported problems associated with silt and material infiltration into the C3 drainage asset.

The failure to clean out silt (channel drains) or excavate (ditches) (X42) are maintenance factors. This risk may be elevated when the site is built upon water sensitive layers, for example fine grained soils such as clay (Ghataora and Rushton, 2012). However, for the Ardsley Tunnel site, the geology map from Edina (see Figure 5.4) shows that the surface deposit bedrock type here is Pennine Middle Coal Measures Formation Mudstone, Siltstone and Sandstone (PMCM-MDSS). Thus, the subgrade is likely to contain a coal layer, which is not water sensitive. Therefore, it is assumed that the frequency with which silt in channel drains and ditches (E12) leads to a blockage (D8) is between 1 in 100 years and 1 in 30 years. It is therefore a medium risk (see Table 5.5).

When it comes to aging, deteriorating components, aging channels, drains and ditches (X28), the deterioration rate of a C3 drainage asset increases with the age of the components' planned service life, which is between 30 and 50 years (Skutsch, 1998; Network Rail, 2017b;). Therefore, the frequency with which this risk occurs was assumed to between 1 in 30 years and 1 in 50 years.

5.4.2 Frequency of draining risks occurring at the Clay Cross Tunnel site

In a similar way to the previous section, the probability of each risk occurring at this site was calculated using Boolean algebra and the engineering model Table 5.6 summarises the risks associated with the C3 assets and the frequency with which they occur at the Clay Cross site. It shows that ten risks (of the total of twenty-two) are present at the Clay Cross Tunnel site. Three of these are associated with the environment (X6, X7a, X29), three are associated with land use (X11, X12, X40) and four are related to maintenance (X19, X20, X21, and X25).

Table 5.6 Availability and frequency of each risk occurring at the Clay Cross Tunnel site

Code	Basic Event/ Risk	Availability	Frequency (/ year)	Source of Data
X5	Weak soil	-		
X6	Flooding from surface water	√	0 - 9 in 10	NR's record
X7a	Flooding from river	√	1 in 100 - 1 in 30	UK's flood map
X7b	Flooding from sea	-		
X7c	Flooding from reservoirs	-		
X8	Excessive soil pressure	-	-	-
X10	Weathering (chemical)	-		
X11	Change to land use (catchment area)	√	1 in 100 - 1 in 30	Literature
X12	Changes to drain upstream	√	1 in 100 - 1 in 30	Literature
X19	Lack of debris clean out	√	1 in 30 - 1 in 10	Literature
X20	Non ballast material infiltration	√	1 in 100 - 1 in 30	Literature
	(waste from the train, spillage from the train, fly tipping)			
X21	Poor ballasting practices	√	1in 30 - 1 in 10	Literature
X25	Vegetation overgrowth	√	0 - 1 in 10	NR's record
X26	Spoil tipping			
X28	Aging channel drains and ditches material			
X29	Scour around channel drains and ditches	√	1in 30 - 1 in 10	Literature
X30	Inadequate gradient of channel drains and ditches	-		
X40	Damage caused by other assets/ 3rd party assets	√	1 in 100 - 1 in 30	Literature
X41	Damage caused by burrowing animals	-		
X42	Lack of silt clean out (channel drains) or excavate (ditches)	-		
X43	Damage caused by poor installation	-		
X44	Prolong hot weather	-		

Flooding from surface water (X6) occurred nine times between 2009 and 2018. Four events occurred between June and December 2009 and two in September and November 2012. Thereafter, three events occurred in October 2013, June 2014, and November 2016. The highest the flood water reached was above the rail head. Despite the fact that historical data on river flooding is not provided, the rail sections here may be at elevated risk of flooding due to their position at the inlet of the Clay Cross tunnel, which is located near a river (see Figure 5.10). Estimating the probability with which this risk would occur was only possible through soliciting expert opinion. In terms of the frequency with which an X7a event occurred, the UK flooding map was used. This map showed that the area was at a medium risk of flooding (indicated by a mid-blue colour), which means that the chances of a flood occurring once in 30 years was 3.3% and once in100 years was 1%. It was these figures that were included as the input when calculating the propensity for this risk occurring.

There is no historical record for three of the risks under investigation. These are: change to land use (catchment area) (X11), changes to upstream drainage (X12), and damaged cause by other/3rd party assets (X40). For that reason, planning data from Derbyshire County Council (2017) and Network Rail was used when estimating the probability that these risks would occur. With regards to changing land use in this area, in the short to medium run, the frequency was assumed to be between 1 in 30 years and 1 in 100 years for both risks i.e. these risks might occur within the mid-long-term period of urban planning in this area. For X40, we can see that this section was built near a fly over bridge. Therefore, any unpredicted disruption on that structure may have had an effect on the railway. However, there is no record that this risk occurred over the last ten years. As a result, it was assumed that there is a moderate chance that this risk occurs. The range was assumed to be between 1 in 100 and 1 in 30 years. It was therefore classified as a medium risk (see Table 5.5).

There are four risks associated with maintenance at the site. Vegetation overgrowth risk (X25) has been recorded once within the last ten years. This was in November 2009, where leaves fell onto the main line and caused a blockage. This exacerbated flooding from surface water that was also occurring at the time.

Although there is no historical data concerning the two risks associated with maintenance issues (i.e. a failure to clean out debris (X19) and poor ballasting practice (X21)), these risks are likely to occur from the comparison of records of another site which is facing the same problem (i.e. Ardsley Tunnel); these may occur less frequently that once every ten years.In comparison, the frequent floods at Clay Cross were recorded higher than Ardsley which was assumed to be medium risk (1 in 30 – 1 in 100 years) Therefore, the frequency with which this occurs was assumed to be between 1 in 10 and 1 in 30 years. It is therefore a high risk (see Table 5.5). Another risk related to maintenance, namely non-ballast material infiltration (waste from the train, spillage from the train, fly tipping) associated with (X20) and poor ballasting practice (X21) was considered to occur less frequently than the X19 and X21 risks discussed above. Therefore, the frequency with which these risks occur is assumed between 1 in 30 years and 1 in 100 years. They are therefore a medium risk (see Table 5.5). This assumption is based on the fact that this line is predominately used by passengers train than freight activity which potentially release the above materials to track substructure and drainage assets.

5.4.3 Frequency of drainage risks occurring at the Draycott site

Much like in the previous section, Boolean algebra and the engineering model were used to estimate the probability with which each of the risks will occur at this site. Table 5.7 shows that ten risks are present, out of a total of twenty-two possible risk. Three of these are environmental (X6, X7a, and X7c), two are associated with land use (X11 and X12), three are related to maintenance (X19, X25, and X42), one (X28) is related to components, and one (X43) is related to installation.

Table 5.7 Availability and frequency of risks occurring at the C3 at Draycott site

Code	Basic Event/ Risk	Availability	Frequency (years)	Source of Data
X5	Weak soil	-		
X6	Flooding from surface water	√	0 - 12 in 10	NR's record
X7a	Flooding from river	√	1 in 100 - 1 in 30	UK's flood map
X7b	Flooding from sea	-		
X7c	Flooding from reservoirs	√	1 in 1000- 1 in 100	UK's flood map
X8	Excessive soil pressure	-	-	-
X10	Weathering (chemical)	-		
X11	Change to land use (catchment area)	√	1 in 100 - 1 in 30	Literature
X12	Changes to drain upstream	√	1 in 100 - 1 in 30	Literature
X19	Lack of debris clean out	√	1 in 30 - 1 in 10	Literature
X20	Non ballast material infiltration			
	(waste from the train, spillage from the train, fly tipping)			
X21	Poor ballasting practices			
X25	Vegetation overgrowth	√	1 in 30 - 1 in 10	Literature
X26	Spoil tipping			
X28	Aging channel drains and ditches material	√	1 in 50 - 1 in 30	Literature
X29	Scour around channel drains and ditches			
X30	Inadequate gradient of channel drains and ditches	-		
X40	Damage caused by other assets/ 3rd party assets			
X41	Damage caused by burrowing animals	-		
X42	Lack of silt clean out (channel drains) or excavate (ditches)	√	1 in 100 - 1 in 30	Literature
X43	Damage caused by poor installation	√	1 in 100 - 1 in 30	Literature
X44	Prolonged hot weather	-		

Flooding from surface water (X6) occurred twelve times between 2009 and 2018. Most of these events occurred in 2012 (including seven times from July to December). Two occurred in 2014, one in January and one in February. One event occurred in February 2016 and two occurred in 2018, one in March and one in April of that year. The most affected assets were highway bridges 12 to 17, which flooded nine times, whereas bridge 16 was affected only once and bridges 12 to 13 twice. The water reached a level higher than the rail head. Although there is no record of

X7a (flooding from river) and X7c (flooding from reservoirs) risks, the track engineering confirmed that these risks may occur in the future.

In order to estimate the frequency with which X7a and X7c risks occur, an online UK flood map was used. The map (see Figure 5.15) shows that there is a medium risk of an X7a risk occurring and low risk of an X7c risk occurring (depicted by a mid and light blue colour respectively, see Figure 5.16). This means that the chance of flooding ranges from 1% (1 in 100 years) and 3.3% (1 in 30 years) and from 0.1 % (1 in 1000 years) to 1 % (1 in 100 years) respectively.

C3 risks, i.e. those associated with land use factors, have been recorded at the Draycott site. However, for two risks, i.e. those associated with changes to land use (catchment area) (X11) and changes to upstream drainage (X12), there is no historical record. Therefore, in this case, data was drawn from Erewash Borough Council (2017) and Network Rail (2013) when estimating the probability that these risks would occur. Consider to unsubstantial land use for this area within short and medium period (less than 30 years), the risk might be occurred within mid and long-term planning period. Therefore, the frequency with which this risk occurs is between 1 in 30years and 1 in 100 years. It is therefore a medium risk (see Table 5.5).

There are three risks associated with maintenance at the Draycott site (i.e. X19. X25, and X42). Although historical data for the last decade is not available for X19 (failure to clean out debris) and X25 (vegetation overgrowth), these risks were considered to occur less frequently than one every ten years. Therefore, the frequency with which these risks occur is assumed to be between 1 in 10 years and 1 in 30 years. It is therefore a high risk (see Table 5.5). When it comes to X42 (a failure to clean out silt from drainage channels or ditches), the frequency with which this occurs is assumed to be between 1 in 30 years and 1 in 100 years. This means it is a medium risk. This is because the chances of a silting event at the site are unlikely, given its location (see soil strength map in Figure 5.14).

According to (Skutsch, 1998; Network Rail, 2017) the deterioration of channels is likely to occur within the service life period, which is typically between 30 and 50 years Therefore, the risks associated with component failure and aging channels and ditches (X28) was assumed to be between 1 in 30 to 1 in 50 years.

When it comes to risks associated with installation and damage caused by poor installation (X43), there is no evidence that there has been an incident in the last decade. Therefore, it was assumed that the frequency with which this risk occurs is between 1 in 30 years and 1 and 100 years.

6 CASE STUDIES: LIKELIHOOD OF RAILWAY DRAINAGE RISK

6.1 The likelihood that the Identified Risks Occur

The engineering model was developed to map the relationship between an undesired event (failure risk) and its causal events (identified risks) track using a fault tree (FT). This is discussed in more detail in Chapter 4. For the case study, one sub FT, namely C3 (channel drains and ditches), was selected to demonstrate the approach (see Chapter 5). Thereafter, C3's sub FT is treated as an individual FT in order to quantify the probability of each risk on the C3 drainage asset on the three sections chosen for study (i.e. Ardsley Tunnel, Clay Cross Tunnel, and Draycott).

To quantify C3's FT, Boolean algebra rules were used to transform the FT's structure into a mathematical relationship to show the probability (P) of C3 occurring (PC3) given the above quantified probability of the occurrence of the associated failure modes (i.e. blockage (PD8), collapse (PD9), and inadequate capacity (PD10) and the causal event as a whole (for example X25, vegetation overgrowth). This is described in more detail in Section 6.1.1. Using the developed mathematical expression, the data presented in Table 5.4, Table 5.6, and Table 5.7 was used as an input for the Monte Carlo simulation (MCS). As discussed in Chapter 4, the MCS is used to overcome some of the uncertainty accompanying the data (concerning the frequency of each risk occurring). For the case studies the MCS was iterated 10,000 times to aggregate the inputs and produce the probabilistic results. The results show the range of probability of occurrence of each risk (see Sections 6.1.2-6.1.4).

6.1.1 Boolean algebra for channel drains and ditches

This sub section discusses the process through which C3's FT was transformed into a mathematical expression using Boolean algebra rules. C3's FT was deconstructed into a number of equations, as presented in the formulae 6.1-6.13 below. Figure 4.15 in Chapter 4 shows the structure of C3's FT.

Boolean Algebra rules were used to perform a quantitative analysis of the FT presented in Figure 6.17 The risks are those given in Tables 6.1 – 6.3. The probability of PC3 (i.e. defective or failed channel drain and ditches) occurring can be determined as follows:

PC3 = PD8 U PD9 U PD10 = PD8 + PD9 + PD10 Eq 6.1

PD8 = PDE1 U PX21 U PE12 U PX25 U PX26 =

PDE1 +PX21 + PE12 + PX25 + PX26 Eq 6.2

PD9 = PE13 U PX40 U PX41 U PE11 =

PE13 U PX40 U PX41 U PE11 ……Eq 6.3

PD10 = PH1U PX11 U PX12 U PX30 =

PH1 + PX11 + PX12+ PX30 ……Eq 6.4

PDE1 = PX19 U PX20 = PX19 + PX20 Eq 6.5

PE12 = PX42 U PX43 U PF1 = PX42 + PX43 + PF1 … Eq 6.6

PF1 = PG1 U PX40 U PX44 = PG1+ PX40 + PX44 ……Eq 6.7

PG1 = PH1 U PX5 =PH1 + PX5 ……Eq 6.8

PH1 = PX6 U PX7a U PX7b U PX7c = PX6 + PX7a + PX7b + PX7c Eq 6.9

PD8 – PD10 show the probability of failure occurring in channel drains and ditches (C3)

Where,

PD8 : probability of blocked channel drains and ditches

PD9 : probability of collapsed channel drains and ditches

P10 : probability of inadequate capacity of channel drains and ditches

To uncover the root causes of a specific failure, the above equations, which mostly focus on a combination of mid and basic events, can be presented entirely in terms of basic events (see Tables 3a, 3b, and 3c assigning a causal event or risk item). For example, PD8 consists of five mid events, PDE1, PE12, PF1, PG1, and PH1 (see equations 6 to 10). Thus, PD8 can be determined as follows:

PD8 = PX19 + PX20 + PX21 + PX42 + PX43 +
(PX5 + PX6 + PX7a + PX7b + PX7c + PX40 + PX44) + PX25 + PX26 =
PX5 + PX6 + PX7a + PX7b + PX7c + PX19 + PX20 + PX25 + PX26 + PX40 +
PX42 + PX43 + PX44 Eq 6.10

PDE1, PE12, PF1, PG1, and PH1 shows the probability of various mid events associated with PD8 occurring.

Where:

PDE1 : debris infiltration

PE12 : silting channel drain and ditches

PG1 : softening below drain level

PH1 : excessive water infiltration to track bed

Using a similar analysis, it can be shown that:

PD9 = PX28 + PX10 + PX40 + PX41 + PX6 + PX7a + PX7b + PX7c + PX11 + PX12 +
PX8 + PX29 = PX6 + PX7a + PX7b + PX7c + PX8 + PX10 + PX11 + PX12 +
PX28 + PX29 + PX40 + PX41 Eq 6.11

PD10 = PX6 + PX7a +PX7b + PX7c + PX11 + PX12 + PX30 Eq 6.12

PC3 = PX5 + 3*PX6 + 3*PX7a + 3*PX7b + 3*PX7c + PX10 + 2*PX11 + 2*PX12 +
PX19 + PX20 + PX21+ PX25 + PX26 + PX28 + PX29 + PX30 + 2*PX40 + PX41

$$+ PX42 + PX43 + PX44 \qquad \text{Eq 6.13}$$

6.1.2 Assumptions

The following assumptions were made in developing the quantitative fault tree analysis above (Ayyub, 2014; Veldhuis *et al.,* 2011):

- The occurrence of events is assumed to be a Poisson process; this means that the occurrence of a risk event in any specified short time period is likely to conform with the intended time period. For example, flooding from surface water may occur several times in one year (length of time, period t, is one year).
- The occurrences of risk events are statistically independent of a disjointed time period.

6.1.3 Monte Carlo Simulation

The quantification underpinning the engineering model brings with it uncertainties, particularly concerning the estimation of risks occurring. This can be dealt with by using a Monte Carlo Simulation (MCS) as discussed in chapters 3 and 4. The MCS requires at least three points of input data to obtain a range of risk likelihoods. It was therefore necessary to estimate minimum values (min), maximum values (max) and mid points, based on the range of risk frequencies for each identified risk. This was obtained by extracted historical data (see Appendix 4) and extant literature which then aggregated using @Risk^{TM} software These were used as inputs for the risk likelihood formula associated with C3 drainage assets (Equation 6.15) and to obtain three estimation points (min, mid, and max). Thereafter, these points were modelled as a PERT probability distribution within an MCS, in order to aggregate the likelihood of particular risks (see Section 5.8). In a graphical comparison between PERT and Triangular distribution with the same three points inputs (see Figure 6.1) , a PERT distribution was chosen since… it offers smoother tails that may better represent uncertainty whereas the Triangulat is apparently simplified that parts and tend to more intuitive (Cretu *et al*., 2011).

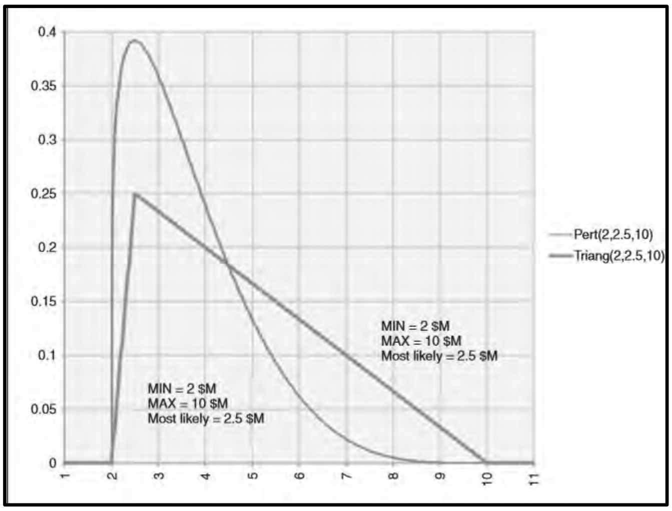


Figure 6.1 Pert Distribution versus Triangular Distribution, source Cretu *et al. (*2011)

The minimum, maximum and mid values were calculated (see Table 5.4-Table 5.6) for each drainage risk at the three sites.

6.1.4 The probability of failed channel drains and ditches occurring at Ardsley Tunnel.

In order to model the uncertainties associated with the estimated likelihood of risks occurring at the Ardsley Tunnel site, the three input points were determined from Table 5.4 and applied to the engineering model using a PERT distribution (see Section 4.11). The engineering model were performed using the following formulae:

a) PD8, likelihood of blockage (see Equation 6.10)
b) PD9, likelihood of collapsed (see Equation 6.11)
c) PD10, likelihood of inadequate capacity (see Equation 6.12)
d) PC3, likelihood of defective or failed channel drains and ditches (see Equation 6.13)

To obtain the likelihood (probability of occurrence) values, an Excel spreadsheet was used to input the required parameters (i.e. frequency of occurrence of the available risks from Table

6.4). Thereafter the @Risk^{TM} software (Palisade Corporation, 2017) was used to carry out the MCS.

There are thirteen columns in the spreadsheet (see Table 6.1). Details for each of these columns are as follows:

a) <u>Column 1-2</u>

   Column 1 and 2 indicate the code and name of the basic events that have been identified by experts, e.g., X6 refers to flooding from surface water

b) <u>Column 3</u>

   Column 3 includes the range of the number of incidents in years. For example, the range of X6 risk is between 0 and 8 in 10 years (see Table 5.4)

c) <u>Column 4 -6</u>

   As mentioned above, the input range is determined as 0 to 8 in 10 years. To provide a three points estimation of the probability of a particular risk occurring, the following was considered:

   The minimum frequency of occurrence (min): this was determined as the lowest number in the range (0)

   - Maximum frequency of occurrence (max): this was determined as the highest number in the range (8 in 10 years). The frequency of occurrence per year can also be written as 8/10, or 8.00E-01
   - Mid frequency of occurrence: this was determined as the mid-point of the minimum and maximum frequency, which was calculated as 0 plus 8.00E-01 divided by 2, resulting 4.00E-01 per year.

d) <u>Column 7 -9</u>

To obtain the rate of occurrence (λ) of a basic event, the above values (column 4-6) were used as an input into the formula in equation 3.9 in Section 3.5):

The formula can be written as:

$$\lambda Xi = \frac{fXi * Lh}{Ls} \qquad \text{Eq 6.14}$$

Where:

λXi : rate of occurrence of basic event Xi

fXi : frequency of occurrence of basic event

Lh : length of the homogeneous section

Ls : lLength of the sections exposed to failure

For λX6 min:

λX6min : rate of occurrence of X6 risk (minimum value)

fX6min : frequency of occurrence of basic event X6 (minimum value) = 0

Lh : length of the homogeneous section = 200 m (200 m length from the end of Ardsley portal towards Leeds)

Ls : length of the sections exposed to failure = 2414.016 m (this length fot left and right (two sides) of C3 drainage assets) drainage assets at Ardsley Tunnel drainage system)

$$\lambda X6min = \frac{0\ (per\ year) * 200\ m}{2414.016\ m} = 0$$

For λX6 max:

fX6max : frequency of occurrence of basic event = 8.00E-01 per year

Lh : length of the homogeneous section = 200 m

Ls : Length of the sections exposed to failure = 2414.016 m

$$\lambda X6min = \frac{8.00E - 01\ (per\ year) * 200\ m}{2414.016\ m} = 6.63E - 02\ per\ year$$

For λX6 mid:

fX6mid : frequency of occurrence of basic event = 4.00E-01 per year

Lh : length of the homogeneous section = 200 m

Ls : Length of the sections exposed to failure = 2414.016 m

$$\lambda X6mid = \frac{4.00E-01\ (per\ year) * 200\ m}{2414.016\ m} = 3.31E-02\ per\ year$$

e) Column 10 - 12

$$px(x) = \frac{(\lambda t)^{x} \exp(-\lambda t)}{x!} \quad (6.15)$$

$$PX6(1) = \frac{(\lambda X6 * 1)^{1} \exp(-\lambda X6 * 1)}{1!}$$

Where:

For PX6min, x=1 occurrence, t = 1 (per year)

It was assumed that the risk occurring one event (x=1) per year (t=1). This likelihood value altogether with impacts value (provides in Chapter 7) for one failure event per year will be used to calculate the risk value for one occurrence per year at the specific site (presents in Chapter 8).

$$PX6min = \frac{(\lambda X6min * 1)^{1} \exp(-\lambda X6min * 1)}{1!} = \frac{(0 * 1)^{1} \exp(-0 * 1)}{1!} = 0$$

$$PX6mid = \frac{(\lambda X6mid*1)^{1} \exp(-\lambda X6mid*1)}{1!} = \frac{(3.31E-02*1)^{1} \exp(-3.31E-02*1)}{1!} = 3.21\%$$

$$PX6max = \frac{(\lambda X6max*1)^{1} \exp(-\lambda X6max*1)}{1!} = \frac{(6.63E-02*1)^{1} \exp(-6.63E-02*1)}{1!} = 6.20\%$$

f) Column 13

According to Vose (2008), Monte Carlo simulation (MCS) requires inputs with specific distribution; one type of the most common distribution is PERT which is less intuitive compare to the Triangle distribution, The PERT distribution can be performed by using three points estimates (i.e. minimum, mid, and maximum). As selected distribution to model the risk likelihood in this research, these three points were obtained from minimum, mid, and maximum costs of a risk impact In this column, the three point estimates from columns 10 – 12 (see Table 6.8).were used as input to obtain a PERT distribution using the @Risk™ software.

For example, the three point estimation of the likelihood of flooding from surface water (PX6) at Ardsley Tunnel were 0, 3.21%, and 6.20%.Then, these values were used as inputs of RiskPert function in @Risk™ software. In the input cell for this distribution (column 13), these values were written as '=RiskPert(cell in column 10 for PX6min (0), cell in column 11 for PX6mid (3.21%), and cell in column 12 for PX6max (6.20%)'. Thereafter, the function produced a mean (modus) value of this PERT distribution; this was 3.17% (cell in column 13) as can be seen in Figure 6.18. The similar process was conducted for another risks likelihood which then contributed to the likelihood of three failure modes comprise blocked (PD8), collapsed (PD9), and inadequate capacity (PD10) and one undesired event, defective or failed channel drains and ditches (PC3).

As a result, the likelihood of defective or failed channel drains and ditches (PC3) at Ardsley Tunnel without considering uncertainty are equal to sum of all likelihoods (mean or modus values in column 13) as formulated by Boolean rule (see Equation 6.10 – 6.13) was 13.14%. After the Monte Carlo simulation with 10,000 iterations, the @Risk™ software produced the likelihood value of C3 drainage assets with 90% confidence level was 15.77%.

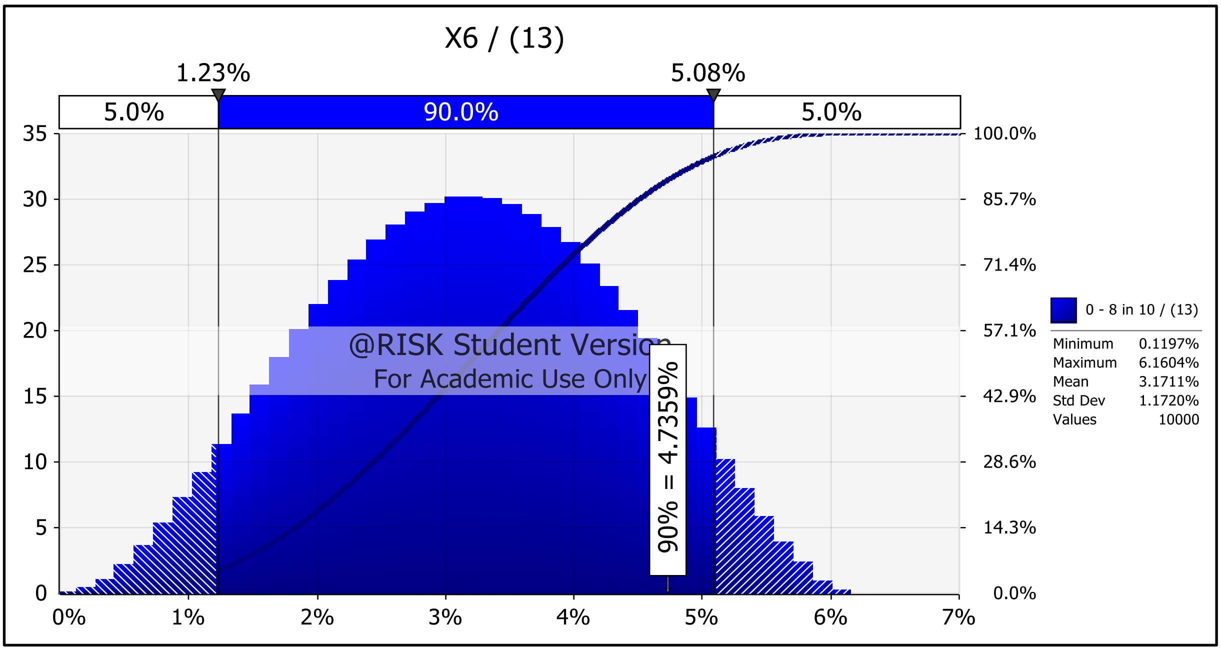


Figure 6.2 PERT distribution for X6 (flood from surface water) at the Ardsley Tunnel site as input for Monte Carlo simulation (MCS) using @Risk^{TM} software

Figure 6.2 shows, the likelihood of a range of rates of occurrence (λ) of occurring using a PERT distribution.

The MCS, calculated using @Risk^{TM}, with 10,000 iterations, produced the following outputs (see Figure 6.19):

a) There is a 90 per cent chance of of the likelihood of the failure mode PD8 being between 3.00% and 6.96%, 2.24% and 6.13% for collapsed (PD9) and 1.63% and 5.50% for inadequate capacity (PD10) respectively.

b) There is a 90 per cent chance of achieving the occurrence of defective or failed channel drains and ditches (PC3) of between 9.33% and 16.14%

Table 6.1 summarises the probability of the basic and mid events occurring at the Ardsley Tunnel. From the table it may be seen that:

a) The probability of occurrence, with a 90 % confidence level, for a blocked (PD8_90) is 6.59%, for collapsed (PD9_90) 5.79% and for inadequate capacity (PD10_90) 5.14% respectively. These are higher than their likelihoods without considering uncertainty which would have been obtained using Boolean algebra formula and modus values of the selected distribution. PERT which are valued 4.99%, 4.21% and 3.57% respectively.

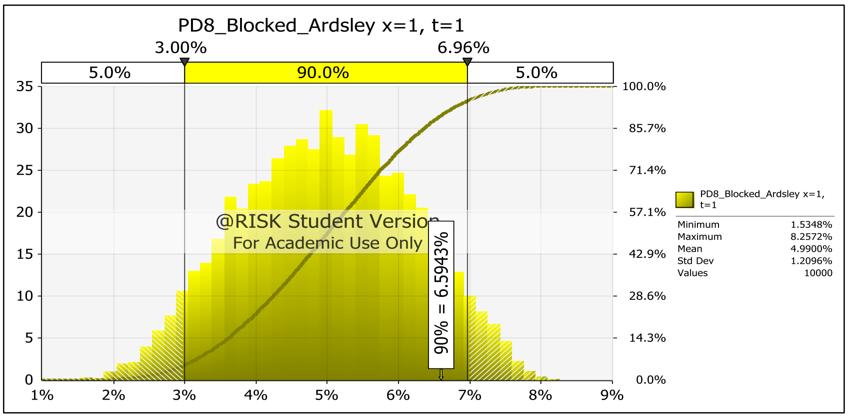
b) The probability of occurrence of a defective or failed channel drains and ditches with a 90 % confidence (PC3_90 =P D8_90 + PD9_90 + PD10_90), is 15.47%, whereas its deterministic (value without condidering uncertainty) value is 12.77%

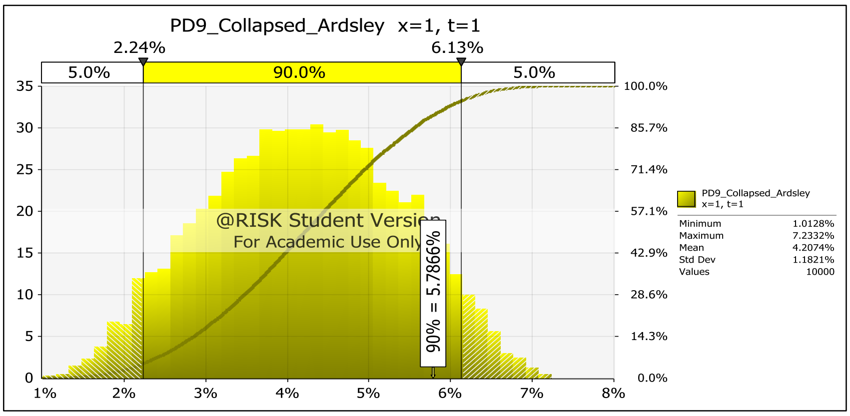
Table 6.1 Spreadsheet for estimating the lrisk likelihood of C3 drainage assets at Ardsley Tunnel site using @Risk ™ software

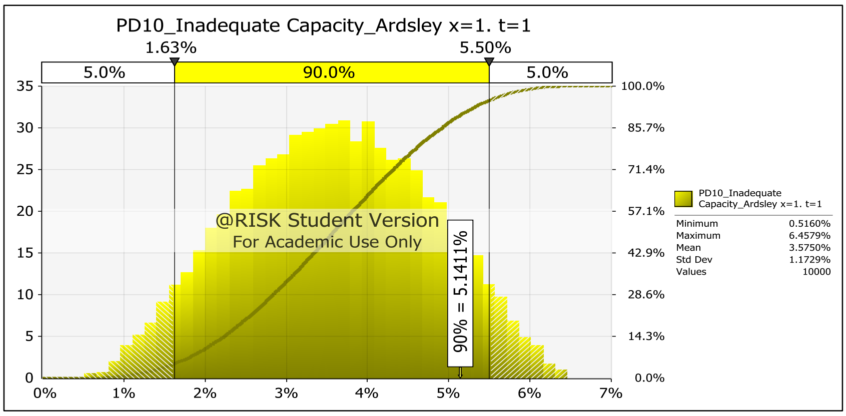
Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 8 in 10	0.00E+00	4.00E-01	8.00E-01	0.00E+00	3.31E-02	6.63E-02	0.00%	3.21%	6.20%	3.17%
X7a	Flooding from river	1 in 1000 - 1 in 100	1.00E-03	5.50E-03	1.00E-02	8.28E-05	4.56E-04	8.28E-04	0.01%	0.05%	0.08%	0.05%
X19	Lack of debris clean out	0 - 1 in 10	0.00E+00	5.00E-02	1.00E-01	0.00E+00	4.14E-03	8.28E-03	0.00%	0.41%	0.82%	0.41%
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	8.28E-04	1.80E-03	2.76E-03	0.08%	0.18%	0.28%	0.18%
X25	Vegetation overgrowth	0 - 1 in 10	0.00E+00	5.00E-02	1.00E-01	0.00E+00	4.14E-03	8.28E-03	0.00%	0.41%	0.82%	0.41%
X26	Spoil tipping	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	8.28E-04	1.80E-03	2.76E-03	0.08%	0.18%	0.28%	0.18%
X40	Damage caused by other assets/ 3rd party assets	0 - 1 in 10	0.00E+00	5.00E-02	1.00E-01	0.00E+00	4.14E-03	8.28E-03	0.00%	0.41%	0.82%	0.41%
X42	Lack of silt clean out (channel drains) or excavate (ditches)	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	8.28E-04	1.80E-03	2.76E-03	0.08%	0.18%	0.28%	0.18%
											PD8_Blocked	4.99%
											PD8_Blocked_90	6.59%

Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 8 in 10	0.00E+00	4.00E-01	8.00E-01	0.00E+00	3.31E-02	6.63E-02	0.00%	3.21%	6.20%	3.17%
X7a	Flooding from river	1 in 1000 - 1 in 100	1.00E-03	5.50E-03	1.00E-02	8.28E-05	4.56E-04	8.28E-04	0.01%	0.05%	0.08%	0.05%
X11	Change to land use (catchment area)	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	8.28E-04	1.80E-03	2.76E-03	0.08%	0.18%	0.28%	0.18%
X12	Changes to drain upstream	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	8.28E-04	1.80E-03	2.76E-03	0.08%	0.18%	0.28%	0.18%
X28	Aging channel drains and ditches material	1 in 50 - 1 in 30	2.00E-02	2.67E-02	3.33E-02	1.66E-03	2.21E-03	2.76E-03	0.17%	0.22%	0.28%	0.22%
X40	Damage caused by other assets/ 3rd party assets	0 - 1 in 10	0.00E+00	5.00E-02	1.00E-01	0.00E+00	4.14E-03	8.28E-03	0.00%	0.41%	0.82%	0.41%
											PD9_Collapse	4.21%
											PD9_Collapse_90	5.79%

Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 8 in 10	0.00E+00	4.00E-01	8.00E-01	0.00E+00	3.31E-02	6.63E-02	0.0000%	3.2060%	6.2029%	3.1711%
X7a	Flooding from river	1 in 1000 - 1 in 100	1.00E-03	5.50E-03	1.00E-02	8.28E-05	4.56E-04	8.28E-04	0.0083%	0.0455%	0.0828%	0.0455%
X11	Change to land use (catchment area)	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	8.28E-04	1.80E-03	2.76E-03	0.0828%	0.1792%	0.2754%	0.1792%
X12	Changes to drain upstream	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	8.28E-04	1.80E-03	2.76E-03	0.0828%	0.1792%	0.2754%	0.1792%
									PD10_Inadequate Capacity			3.57%
									PD10_Inadequate Capacity_90			5.14%
											P(C3)	12.77%
											P(C3)_90	15.47%







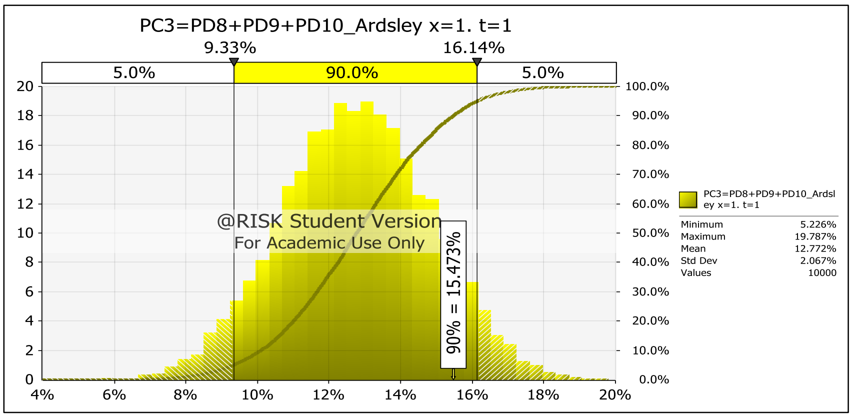


Figure 6.3 The range of likelihood of C3 drainage assets(PC3) at Ardsley Tunnel comprising three failure modes : blocked (PD8), collapsed (PD9), and inadequate capacity (PD10)

6.1.5 Probability of defective of failed channel drains and ditches (C3) at The Clay Cross Tunnel

For the Clay Cross Tunnel site a similar calculation procedure as that presented in Section 6.1.4 was conducted, resulting in the Figure 6.4. It is noteworthy that there is:

a) A 90 per cent chance of the occurrence of the failure mode being between 3.30% and 8.58% for blocked (PD8), 2.65% and 7.83% for collapsed (PD9) and 2.27% and 7.41% for inadequate capacity (PD10) respectively.
b) A 90 per cent chance of the occurrence of defective or failed channel drains and ditches (PC3) being between 11.50% and 20.63%.

Table 6.2 summarises the probability of the basic and mid events occurring at the Clay Cross Tunnel site. The results are as follows:

a) The probability of occurrence, with a 90 % confidence, for blocked (PD8_90) is 8.09%, 7.35% for collapsed drains (PD9_90) and 6.96% for inadequate capacity (PD10_90). These are relatively higher than their likelihoods in deterministic results which are valued 5.98%, 5.27%, 4,87% respectively.
b) The probability of occurrence of defective or failed channel drains and ditches with a 90 % confidence (PC3_90 =P D8_90 + PD9_90 + PD10_90), is 19.70%, whereas its deterministic value is 16.11%

Table 6.2 Spreadsheet for estimating the lrisk likelihood of C3 drainage assets at Clay Cross Tunnel site using @Risk TM software

Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 9 in 10	0.00E+00	4.50E-01	9.00E-01	0.00E+00	4.53E-02	9.05E-02	0.00%	4.33%	8.27%	4.26%
X7a	Flooding from river	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X19	Lack of debris clean out	1 in 30 - 1 in 10	3.33E-02	6.67E-02	1.00E-01	0.00E+00	6.71E-03	1.01E-02	0.00%	0.67%	1.00%	0.61%
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X25	Vegetation overgrowth	0 - 1 in 10	0.00E+00	5.00E-02	1.00E-01	0.00E+00	5.03E-03	1.01E-02	0.00%	0.50%	1.00%	0.50%
X40	Damage caused by other assets/ 3rd party assets	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
											PD8_Block Blocked	5.98%
											PD8_Blocked_90	8.09%

Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 9 in 10	0.00E+00	4.50E-01	9.00E-01	0.00E+00	4.53E-02	9.05E-02	0.00%	4.33%	8.27%	4.26%
X7a	Flooding from river	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X11	Change to land use (catchment area)	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X12	Changes to drain upstream	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X29	Scour around channel drains and ditches	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X40	Damage caused by other assets/ 3rd party assets	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
											PD9_Collapse	5.27%
											PD9_Collapse_90	7.35%

Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 9 in 10	0.00E+00	4.50E-01	9.00E-01	0.00E+00	4.53E-02	9.05E-02	0.00%	4.33%	8.27%	4.26%
X7a	Flooding from river	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X11	Change to land use (catchment area)	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
X12	Changes to drain upstream	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	0.00E+00	2.18E-03	3.35E-03	0.00%	0.22%	0.33%	0.20%
											PD10_Inadequate Capacity	4.87%
											PD10_Inadequate Capacity_90	6.95%
											P(C3)	16.11%
											P(C3)_90	19.70%

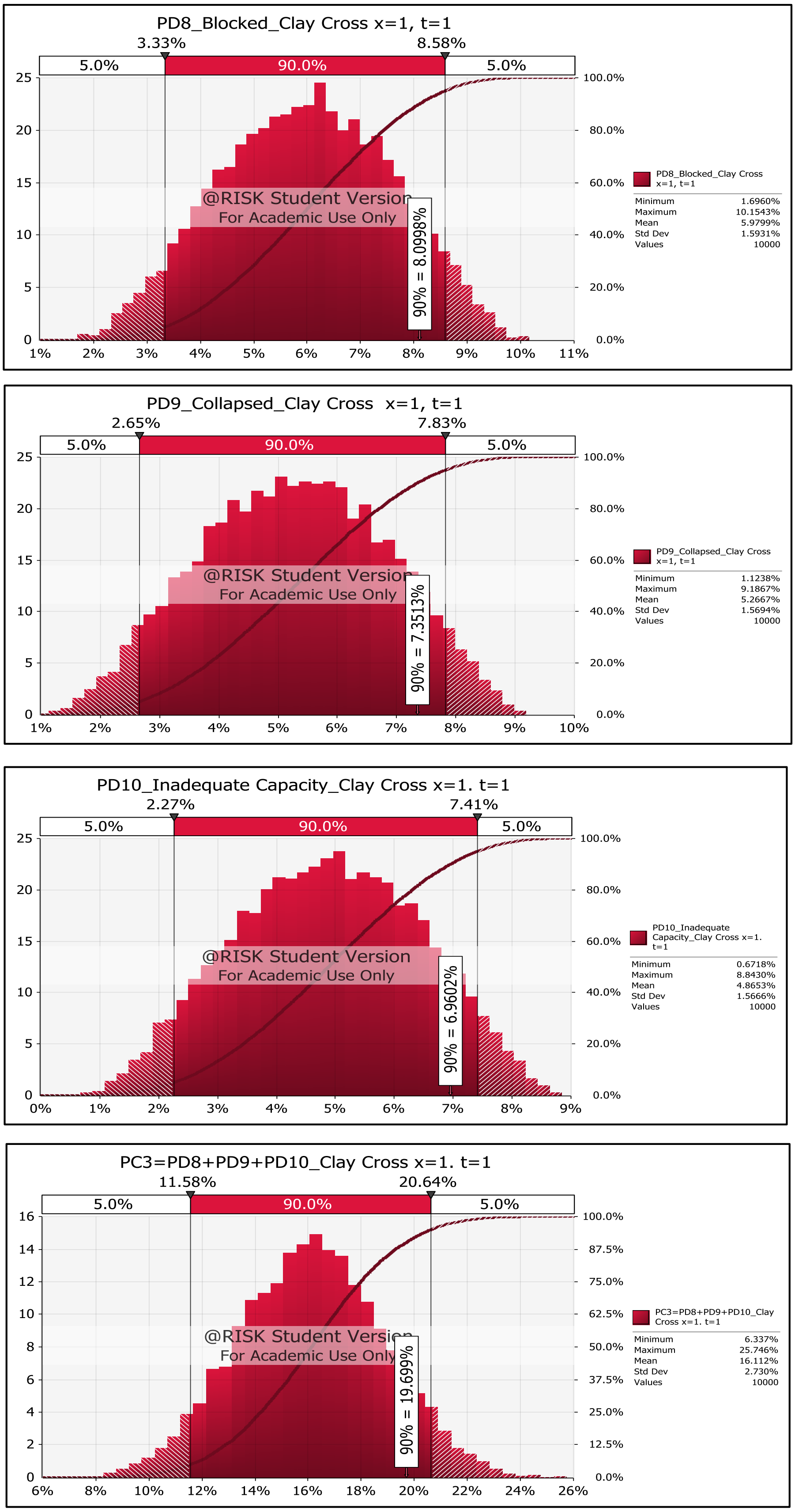


Figure 6.4 The range of likelihood of C3 drainage assets (PC3) at Clay Cross Tunnel comprising three failure modes: blocked (PD8), collapsed (PD9), and inadequate capacity (PD10)

6.1.6 Probability of defective of failed channel drains and ditches (C3) occurring at the Draycott Site

For the Draycott site, a similar calculation procedure as presented in Section 6.1.4 and 6.1.5 were adopted. The resulting probability distribution is shown in Figure 6.5. A summary of the results is as follows:

a) There is a 90 per cent chance of the occurrence of the failure mode being between 1.47% and 3.72% for blocked (PD8), 1.20% and 3.44% for collapsed (PD9) and 1.09% and 3.33% for inadequate capacity (PD10) respectively.

b) There is a 90 per cent chance of the occurrence of defective or failed channel drains and ditches (PC3) being between 5.25% and 9.07%

Table 6.3 summarises the probability of basic and mid events occurring at the Draycott site. It is worth noting that:

(a) The probability of occurrence, with 90 % confidence, for blocked (PD8_90) is 3.50%, 3.24% for collapsed (PD9_90) and 3.12% for inadequate capacity (PD10_90). These are relatively higher than their likelihoods in deterministic results which are valued 2.59%, 2.33% and 2.21% respectively.

(b) The probability of occurrence of defective or failed channel drains and ditches, with 90 % confidence, (PC3_90 =P D8_90 + PD9_90 + PD10_90), is 8.66%, whereas its deterministic value is 7.13%.

Table 6.3 Spreadsheet for estimating the lrisk likelihood of C3 drainage assets at Draycott Tunnel site using @Risk ™ software

Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 12 in 10	0.00E+00	6.00E-01	1.20E+00	0.00E+00	1.86E-02	3.73E-02	0.00%	1.83%	3.59%	1.82%
X7a	Flooding from river	1 in 100 - 1 in 30	3.33E-02	6.67E-02	1.00E-01	1.04E-03	2.07E-03	3.11E-03	0.10%	0.21%	0.31%	0.21%
X7c	Flooding from reservoirs	1 in 1000- 1 in 100	1.00E-03	5.50E-03	1.00E-02	3.11E-05	1.71E-04	3.11E-04	0.00%	0.02%	0.03%	0.02%
X19	Lack of debris clean out	1 in 30 - 1 in 10	3.33E-02	6.67E-02	1.00E-01	1.04E-03	2.07E-03	3.11E-03	0.10%	0.21%	0.31%	0.21%
X25	Vegetation overgrowth	1 in 30 - 1 in 10	3.33E-02	6.67E-02	1.00E-01	1.04E-03	2.07E-03	3.11E-03	0.10%	0.21%	0.31%	0.21%
X42	Lack of silt clean out (channel drains) or excavate (ditches)	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	3.11E-04	6.73E-04	1.04E-03	0.03%	0.07%	0.10%	0.07%
X43	Damage caused by poor installation	1 in 100 - 1 in 30	1.00E-02	2.17E-02	3.33E-02	3.11E-04	6.73E-04	1.04E-03	0.03%	0.07%	0.10%	0.07%
										PD8_Blocked		2.59%
										PD8_Blocked_90		3.50%
Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 12 in 10	0.00E+00	6.00E-01	1.20E+00	0.00E+00	1.86E-02	3.73E-02	0.00%	1.83%	3.59%	1.82%
X7a	Flooding from river	1 in 100 - 1 in 30	3.33E-02	6.67E-02	1.00E-01	1.04E-03	2.07E-03	3.11E-03	0.10%	0.21%	0.31%	0.21%
X7c	Flooding from reservoirs	1 in 1000- 1 in 100	1.00E-03	5.50E-03	1.00E-02	3.11E-05	1.71E-04	3.11E-04	0.00%	0.02%	0.03%	0.02%
X11	Change to land use (catchment area)	1 in 100 - 1 in 30	1.00E-02	1.00E-02	1.00E-02	3.11E-04	3.11E-04	3.11E-04	0.03%	0.03%	0.03%	0.03%
X12	Changes to drain upstream	1 in 100 - 1 in 30	1.00E-02	5.50E-02	1.00E-01	3.11E-04	1.71E-03	3.11E-03	0.03%	0.17%	0.31%	0.17%
X28	Aging channel drains and ditches material	1 in 50 - 1 in 30	2.00E-02	2.67E-02	3.33E-02	6.21E-04	8.28E-04	1.04E-03	0.06%	0.08%	0.10%	0.08%
										PD9_Collapse		2.327%
										PD9_Collapse_90		3.24%
Code	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Range of number of incidents for basic event	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
		(years)	min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
X6	Flooding from surface water	0 - 12 in 10	0.00E+00	6.00E-01	1.20E+00	0.00E+00	1.86E-02	3.73E-02	0.00%	1.83%	3.59%	1.82%
X7a	Flooding from river	1 in 100 - 1 in 30	3.33E-02	6.67E-02	1.00E-01	1.04E-03	2.07E-03	3.11E-03	0.10%	0.21%	0.31%	0.21%
X7c	Flooding from reservoirs	1 in 1000- 1 in 100	1.00E-03	5.50E-03	1.00E-02	3.11E-05	1.71E-04	3.11E-04	0.00%	0.02%	0.03%	0.02%
X11	Change to land use (catchment area)	1 in 100 - 1 in 30	0.00E+00	5.00E-03	1.00E-02	0.00E+00	1.55E-04	3.11E-04	0.00%	0.02%	0.03%	0.02%
X12	Changes to drain upstream	1 in 100 - 1 in 30	0.00E+00	5.00E-02	1.00E-01	0.00E+00	1.55E-03	3.11E-03	0.00%	0.16%	0.31%	0.16%
									PD10_Inadequate Capacity			2.21%
									PD10_Inadequate Capacity_90			3.13%
											P(C3)	7.13%
											P(C3)_90	8.66%

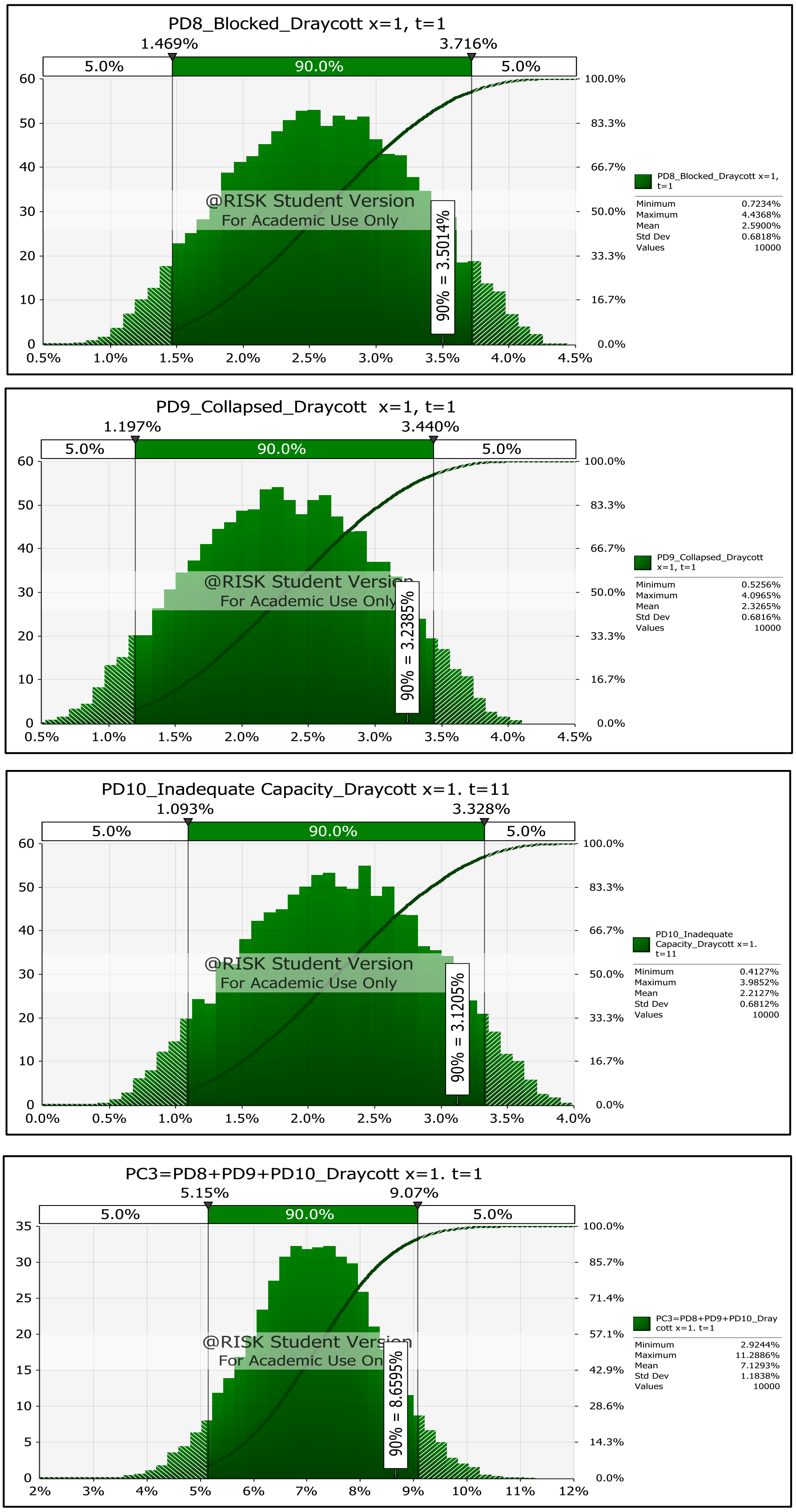


Figure 6.5 The range of likelihood of C3 drainage assets (PC3) at Draycott Tunnel comprising three failure modes: blocked (PD8), collapsed (PD9), and inadequate capacity (PD10)

6.2 Tornado Graph

To identify parameters that have the most influential influence on the likelihood of a risk occurring, a sensitivity analysis was conducted. To facilitate this, the 'Tornado graphs' feature of @Risk^{TM} was used. A Tornado graph can be used to display a ranking of the input variables that have an influence on the likelihood values produced by the simulation as shown in Figure 6.6.

The tornado graph chart in Figure 6.6 shows that the main contributor for this type of failure at the Clay Cross Tunnel site is flooding from surface water (X6), whereas the least influential factor is damage caused by other/3rd party assets (X40). For the Ardsley site, X40 is only the third most important causal event; the least important is X20 risk (i.e. non-ballast material infiltration - waste from the train, spillage from the train, fly tipping). This suggests that the type of the assessed site (e.g. earthworks (cutting slope)) and the land use of its surrounding area (e.g. there was an incident involving water from adjacent field (golf course)) may influence the chances of a failure or defection occurring.

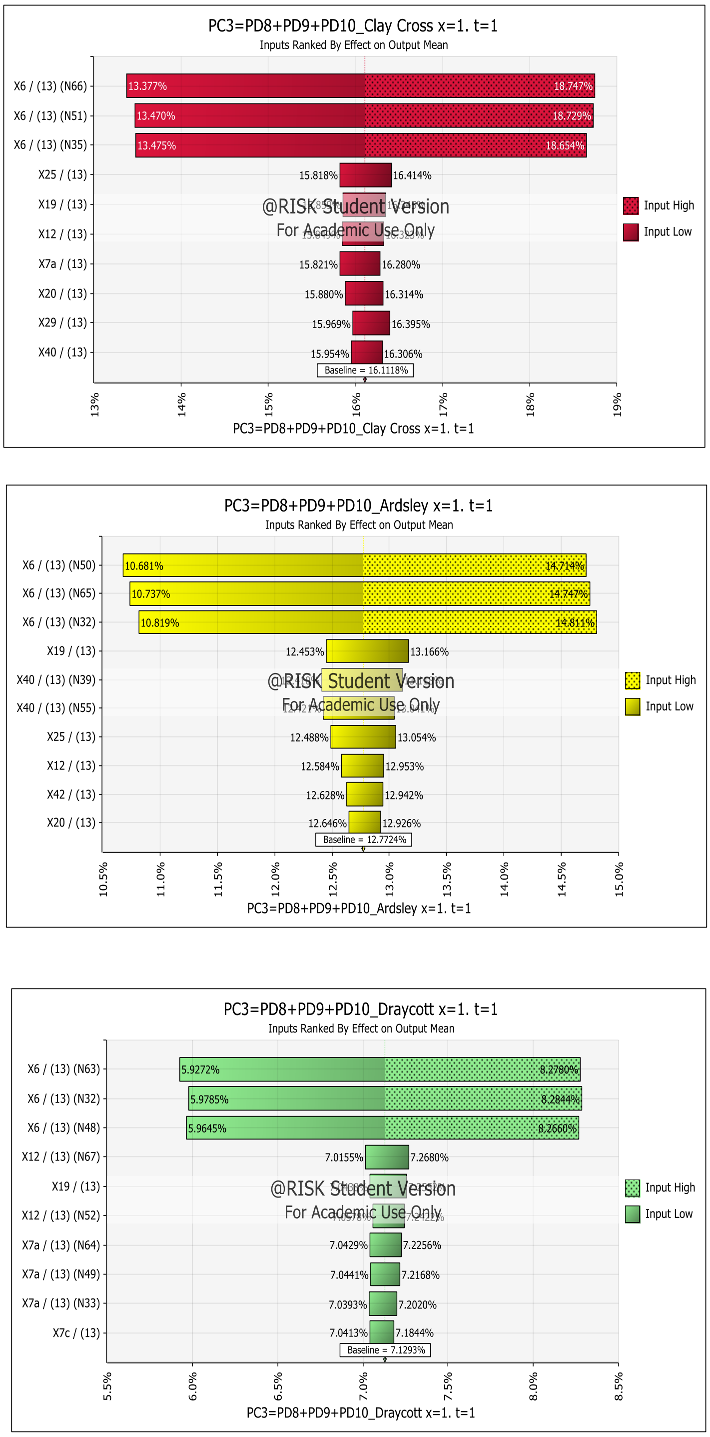


Figure 6.6 Tornado graph as sensitivity analysis of input-output of MCS for three sites (i.e., Ardsley Tunnel, Clay Cross, and Draycott

6.3 Summary

An engineering model, which and embodied a fault tree (FT), together with the expert consultation and advice, was used to determine the presence of various risks. This helped to provide an understanding of the underlying problems and failure mechanisms associated with drainage assets.

The fault tree and Monte Carlo simulation (FT-MCS) part of the engineering model was used to quantify the likelihood (i.e. the probability of occurrence) of defective or failed drainage assets, in terms of a range of likely values. Thereby offering a range of potential likelihood, rather than a single value allowing decision makers to diagnose drainage asset problems quantitatively when there is uncertainty associated with the available data.

The results have shown that the likelihood of defective or failed channel drains and ditches (C3) at Clay Cross Tunnel is higher than at both the Ardsley Tunnel and Draycott sites (see Figure 6.3, Figure 6.4, Figure 6.5). The analysis has shown that the chances of each of the three types of failure (i.e., blockage, collapse and inadequate capacity) are different for each of the sites and are therefore likely to occur at different rates at each site.

The results show that blockages (D8) are more likely to occur than collapses (D9) and inadequate capacity (D10) at all three sites. The likelihood of defective or failed C3 is also affected by the rate of occurrence of basic events at the site. This can be seen if we look at the likelihood values at the Draycott site. Although the frequency that X6 occurs is higher than in other sites (12 times in 10 years), the overall length of C3 exposed to failure is the longest of all three

7 CASE STUDIES: THE IMPACTS OF RAILWAY DRAINAGE RISK

7.1 Introduction

The case study described in this chapter involves quantifying the impact of railway drainage risk at three selected sites on the UK rail network (see Section 5.2) using the risk cost model described in Chapter 4 and Chapter 5. As discussed in Chapter 6, for the task in hand the case study focuses on channel drains and ditches. In order to quantify the potential impact of failed channel drains and ditches, the cost model uses a Monte Carlo simulation performed using the @RISK™ (see Section 6.1.3). Section 7.2 presents the model used to quantify the cost-risks associated with a range of socio-economic impacts. The results of this quantification are presented in Sections 7.4-7.6..

7.2 Impact quantification using the cost model

The cost model was developed in order to determine the risk associated with the drainage of a section of ballasted railway track in monetary terms (see Section 5.5). The total cost impact, *It*, can be determined from:

$$It = \sum_{j=1}^{m}\sum_{i=1}^{n} I_{i=} \sum_{j=1}^{m}\sum_{i=1}^{6} I_{i=} \sum_{j=1}^{m}(I1j + I2j + I3j + I4j + I5j + I6j)$$

Eq 7.1

where I_i is the cost impact of the i^{th} impact of drainage failure, and

i=1,………, n = 1,………..,6

j=1,……….,m

I_1: unplanned maintenance costs; this impact can be divided into some potential impacts as follows:

I_{11}: damage to track substructure (wet bed)

I_{12}: clearing drainage asset and pumping floodwater

$I_{12'}$: pumping floodwater

I_{13}: damage to drainage component

I_{14}: damage to signalling

I_2: delay costs; this impact can be associated to a variety of delay as follows:

I_{21}: delay costs without speed restrictions and cancelations

I_{22}: delay costs with speed restrictions (5 MPH)

I_{23}: delay costs with cancellations

I_3: additional passenger travel costs

I_4: alternative travel mode (usually bus) costs

I_5: property (other than farming) damage costs; this impact can be assigned to two types of property as follows:

I_{51}: residential damage cost

I_{52}: non residential damage cost

I_6: farming land damage costs

In terms of the homogenous sections that are the focus of this research, it was assumed that the impacts to the track substructure occurred along the length of the section under assessment. The base year to which all costs have been discounted or escalated is 2015; the discount rate was assumed as 3.5% (ORR, 2018). The year 2015 was selected as the base year since it can be used to cover the current control period (CP) 5 from 2014 to 2019, and the following CP6 from 2019 to 2024. The future value interest factor (FVIF) and discount factor (DF) used (ORR, 2018) in the total impact calculation in Chapter 7 is summarised in Table 7.3.

7.3 Total impact of failed channel drains and ditches

The next three sections present data on the impact of particular risks for each of the three case study sites. As mentioned in Section 5.6, the data was obtained via interviews, from historical sources and with reference to extant literature. The findings are summarised in Table 7.1 and Appendixes 7.1-7.2 (for Ardsley Tunnel), Table 7.4 and Appendixes 7.3-7.4 (for Clay Cross Tunnel), and Table 7.6 and Appendixes 7.5-7.6 (for Draycott).

7.4 Total impact (costs) of failed channel drains and ditches (C3) at ArdsleyTunnel

7.4.1 Ardsley Tunnel

Table 7.1 shows that four impacts out of a possible twelve identified in Section 5.5 were found to be present. Two impacts (costs) are related to unplanned maintenance (remediation of wet beds (I_{11}), clearing drainage assets and pumping floodwater (I_{12})); and two impacts are associated with delay costs (delay costs without speed restrictions or cancellations (I_{21}), delay costs with speed restrictions (I_{22})). According to Network Rail (Appendix 4), it was not evident that additional passenger travel costs (I_3) and alternative travel mode (usually bus) costs (I_4) were available for this site due to its spatial condition.

The failure of drainage assets (i.e. channel drains and ditches (C3)), which was likely to have been caused by frequent flooding at Ardsley Tunnel, may have led to excessive water infiltration in the track substructure; as a consequence, water cannot dissipate adequately and therefore remains on the track. This is known as a wet bed (Network Rail, 2018) and may reduce the performance of ballasted railway track. In this research, the remediation of wet beds (code I_{11}), clearing drainage assets and pumping floodwater (code I_{12}) are categorised as unplanned maintenance (code I_1). The resulting delay costs (code I_2) comprise delay costs without speed restrictions and cancellations (I_{21}), delay costs with speed restrictions (I_{22}), and delay costs with cancellations (I_{23}).

The impacts that emerge are related to the condition of the site. For example, damage to property due to flooding from surface water was not present at this site due to its urban spatial condition. As mentioned in Chapter 6, the homogeneous section at the Ardsley Tunnel was built on a cutting of earthworks, which is prone to water flowing from or dissipating from the top of the cutting. In the previous chapter, a flood risk from the surface water was the main factor contributing to the failure of channel drains and ditches (C3). However, this was considered not to affect non-residential property (i.e. at Thorpefields and Clydesdale) and farmland (at Low Street and Sissons Farm respectively) since these are located at the top of the cutting, when the section subject to flooding is at the bottom of the cutting (see Figure 7.1).

Figure 7.1 Flood risk from surface water (extent of flooding) at Ardsley Tunnel (Environment Agency, 2018e)

Table 7.1 Summary of the impact of risks associated with blocked channel drains and ditches at Ardsley Tunnel

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Cost (min) (£)	Cost (mid) (£)	Cost (max) (£)	Cost (mean) (£)	Data Source
1	2	3	4	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (i.e. wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12	Incident	1	Clearing drainage asset and pumping floodwater. 5%*(I11+I21+I22)				5,742.06	6,420.00	9,230.89	£6,775	Environment Agency (2018)
I13	m	200	Damage to drainage component								
I14	m	200	Damage to signalling								
I2			Delay costs								
I21	minutes	574.88	Delay costs without speed restrictions and cancela	27.57	40.26	90.11	15,850.82	23,142.00	51,801.51	£26,703	NR's record (Appendix 4)
I22	minutes	422	Delay costs with speed restrictions (5 MPH)	42.86	47.62	52.38	18,085.76	20,095.29	22,104.82	£20,095	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		0	Residential cost								
I52		0	Non residential cost								
I6		0	Farming land damage costs								
It			Total Costs Impact							£142,285	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impact with 90% confidence (It90)							£152,984	

Table 7.2 Summary of average delay (in minutes) at Ardsley Tunnel from 2009 to 2018. Source: Network Rail (see Appendix 4)

Date	**Delay minutes (I3a)**	**Cost (£)**	**Delay minutes with speed restriction (I3b)**	**Cost (£)**
1	**2**	**3**	**4**	**5**
22 June 2012	-	-	422	£20,095
27 April 2012	404	£36,404		
06 July 2012	904	£33,145		
05 August 2012	283	£10,911		
24 September 2012	1068	£29,448		
24 September 2012	672	£19,159		
22 December 2012	272	£8,061		
12 December 2015	994	£48,005		
Sum	4597	£185,133.01	422	£20,095.29
Average (per incident-year)	574.88	23,142.00	422.00	20,095.29
Unit cost (perminute)_minimum	1	27.57		£42.86
(minimum value of column (3)/column (2))				
Unit cost (perminute)_mid	1	40.26		£47.62
(average value of column (3)/ column (2))				
Unit cost (perminute)_maximum	1	90.11		£52.38
(maximum value of column (3)/ column (2))				

7.4.2 Quantification of the total impact (costs) of failed channel drains and ditches at Ardsley Tunnel

To obtain the total impact (costs) values, an Excel^{TM} spreadsheet was used to input the required parameters (i.e. the three-point estimates of the impacts identified in Figure 7.1). Thereafter the @Risk^{TM} software (Palisade Corporation, 2017) was used to carry out the MCS.

Table 7.3 FVIF and DF from 2009 to 2018 with i=3.5% and 2015 as a reference year (after ORR, 2018)

Year	**n**	**Factor**		**i**
		FVIF*	**DF***	
		(1+i)^n	**1/((1+i)^n)**	
2009	6	1.23		3.50%
2010	5	1.19		3.50%
2011	4	1.15		3.50%
2012	3	1.11		3.50%
2013	2	1.07		3.50%
2014	1	1.04		3.50%
2015	0	1.00		3.50%
2016	1		0.97	3.50%
2017	2		0.93	3.50%
2018	3		0.90	3.50%

***FVIF** : Future Value Interest Factor
***DF** : Discounted Factor

There are ten columns in the spreadsheet (see Table 7.1). Details of how the data was arrived at for each of these columns are as follows:

a) Columns 1-2

Column 1 and 2 indicate the code and name of the potential impacts that have been identified by experts in the FGD session (see Chapter 4), e.g., I2 refers to costs associated with delays (I_{21}).

b) Column 3

Column 3 shows the quantity of unplanned maintenance taken to repair damage to track substructure when the drainage assets fail, e.g, wet bed, clearing drainage assets and pumping flood-water. The adverse outcomes of these failures is presented in terms of the number of minutes of delay. In terms of impacts to the rail service, e.g. delays the calculation of average delay per year (in minutes) was obtained using data from the last decade (i.e. 2009 to 2018). The associated calculations are presented in Table 7.1.

c) Column 4

Column 4 hows the assessment unit for a specific impact (cost), e.g. meters of damaged track substructure or minutes of delay.

d) Columns 5-7

Column 6 provides the average unit cost, which was obtained using historical data or with reference to extant literature. For example, a wet bed is likely to occur due to the failure of drainage assets (Network Rail, 2018; 2010). According to ORR (2013), 1,534 wet beds occurred between 2011 and 2012 across the UK rail network. The total cost of dealing with these was £1,709,303, with £1,239,785 associated with manual treatment and £469,518 with mechanical treatament. Accordingly, an average cost of dealing with a wet bed was assumed to be x/y = £/ wet bed. It was assumed that the length of one wet bed is equal to 2 sleepers (2 x 0.7 m = 1.4 m) as point out by Powrie *et al (*2016) and Ghataora *et al.* (2014). Thus, the average cost of repairing a wet bed per metre was calculated by dividing the wet bed cost with the number of wet bed incidents in a particular year. The result in this case £557.14 per wet bed incident, or £397.96 (£425.81 in 2015 price) per metre of railway track (see column 6 in Table 7.1),

Columns 5 and 7 indicate the minimum and maximum unit cost respectively. These have been determined from the costs given in column 6. According to Ahiaga-Dagbui and Smith (2014), in the UK construction industry the variance between predicted and actual costs ranged from ±5% to 15.85% (rounded to 16%). Flyvbjerg *et al.* (2004) shows that the costs of mantaining conventional rail in 25 rail projects escalated by around 29.6% (rounded to

30%). Therefore, to address uncertainty in cost estimation associated with unplanned maintenance (i.e. wet bed), it was assummed that the minimum cost is 95% of the average unit cost (column 5); this felt suitable due to complex efforts to reduce cost more than 5% Meanwhile, the maximum cost value was estimated to be 30% higher than the average value (see column 5 and 7 in Table 7.1)

In terms of the number of minutes of delay, the average at Ardsley Tunnel between 2009 and 2018 was calculated using historical data from Network Rail recorded for Ardsley Tunnel (see Appendix 4). The data was extracted and categorised based on the date of the incident and and the cause of the delay (see Table 7.5). We can see that there were on average 574.88 mintues of delay , with a cost per incident per year of £23,142, resulting in an average cost per delay minute of £40.26. Meanhwile, delays with a speed restriction of 5 mph were 422 delay minutes, with a cost per incident per year of £20,095.29, with an average cost per delay minute of £47.62. The unit cost per delay was obtained by dividing the average cost with the average delay time per incident (see Table 7.5). With this in mind, we can also determine the minimum and maximum cost of delay minues without speed restrictions and cancellations (i.e. £27.57, £90.11), and delay with a speed restriciton cost (i.e. £42.86, £52.38) perminute respectively (see Table 7.5 column 3 and 5).

e) Column 8 -10

The minimum, mid, and maximum cost (column 8, 9, and 10) values were obtained by multiplying the unit costs (column 5, 6, and 7) with the quantity (column 3). For example, for unplanned maintenance (i.e. wet bed) on 200m of a homogeneous section (column 3), the multiplication of this length with the minimum, average, and maximum unit costs (£404.52/m, £425.81/m, and £553.56/m respectively) results in figures of £80,904.57, £ 85,162.70, and £110,711.51 as minimum, average, and maximum costs respectively.

When it comes to clearing drainage assets and the costs associated with pumping floodwater there was a lack of data available to estimate costs. Therefore, it was assumed that 5% of the total costs faced by a rail operator was allocated for this type of unplanned maintenance. This assumption was made on the basis of the burden faced by water companies when dealing with the same issue (Environment Agency, 2018). Based on this assumption, the costs were calculated as 5% of the total wet bed and delay costs (I_{11} + I_{21} + I_{22}). The minimum, average and maximum costs were calculated by multiply 5% with three-point points estimation of the above delay parameters.

f) Column 11

According to Vose (1996), the Monte Carlo simulation (MCS) requires the probability distribution of the inputs to be defined (cf. Section 3.5.4). For the case study the PERT distribution was used because it can suitably model the uncertainty (Cretu, 2012). The three three values igven in columns 8-10 in Table 7.1 were used to specify the three point estimates of the PERT distribution (i(i.e. minimum, average and maximum values). These were used to obtain a PERT distribution using the @Risk™ software.

For example, the three point estimation costs associated with wet bed at Ardsley Tunnel were £80,904.57, £85,162.70, and £110,711.51. These values were used as inputs in a RiskPert function, perfromed using the @Risk™ software. In the input cell for this distribution (column 13), these values were written as '=RiskPert (column 8 (£80,904.57), column 9 (85,162.70), and column 10 (£110,711.51))'. Thereafter, the function produced a modus (mean) value of the PERT distribution; this was £88,711 (column 11), as can be seen in Figure 7.2 and Figure 7.3 . A similar process was used for the other impacts.

For example, the total impact cost associated with blocked C3 at Ardsley Tunnel without considering uncertainty is equal to the sum of all the costs asscoiated with the various impacts (i.e. the various mean values in column 11). It was calculated using equation 7.1 and was equal to £142,285

In order to take into account the distributions of cost uncertainty calcuated using the PERT distributions as calculated above, a Monte Carlo simulation, which used 10,000 iterations was performed the @RiskT^{M} software using Equation 7.1. The resulting distribution of costs is given in Figure 7.4.

@RISK Model Inputs

Name	Cell	Graph	Function	Min	Mean	Max
e_Table_01_Risk Item_Faut Tree_Poor Track_Drainage_Ardsley Tunnel_Impact_06AA.xlsx						
Category: Wet bed						
Wet bed / 11	S12	80,000 115,000	RiskPert(P12,Q12,R12)	£80,904.57	£88,711.15	£110,711.50

Figure 7.2 Input for the PERT distribution for unplanned maintenance (i.e. wet bed) at the Ardsley Tunnel site as an input for the Monte Carlo simulation (MCS) using @Risk^{TM}

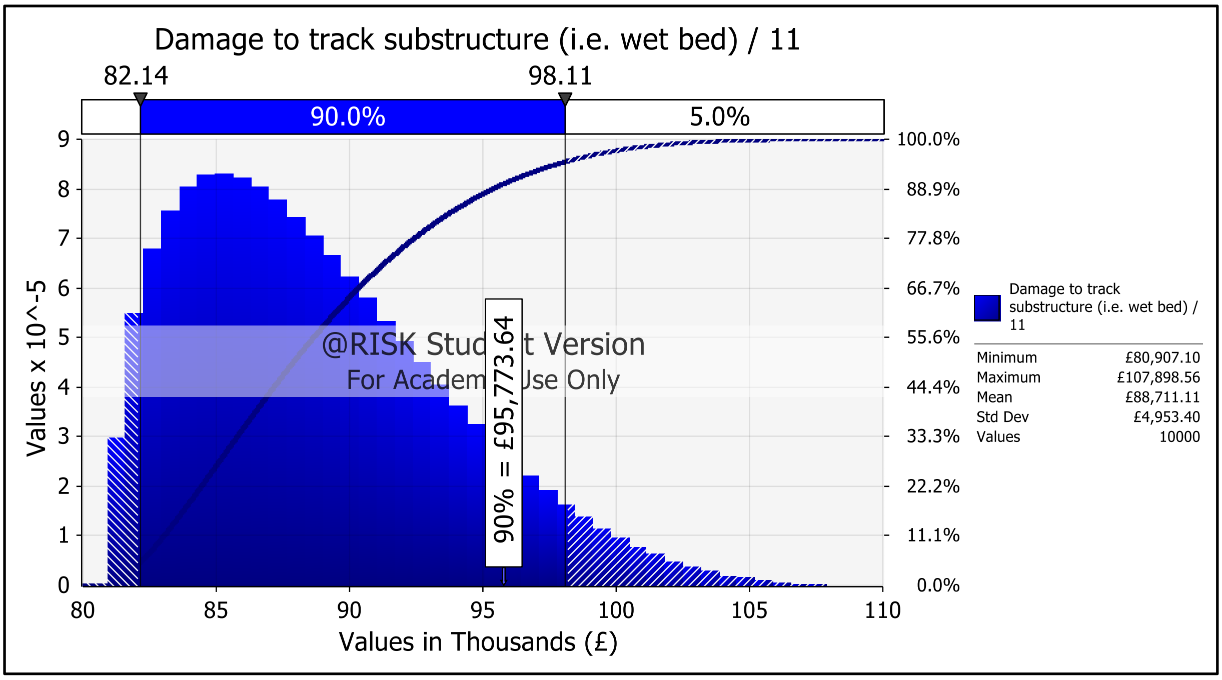


Figure 7.3 PERT distribution graph for unplanned maintenance (i.e. wet bed) at the Ardsley Tunnel site as an input for the Monte Carlo simulation (MCS) using @Risk^{TM}

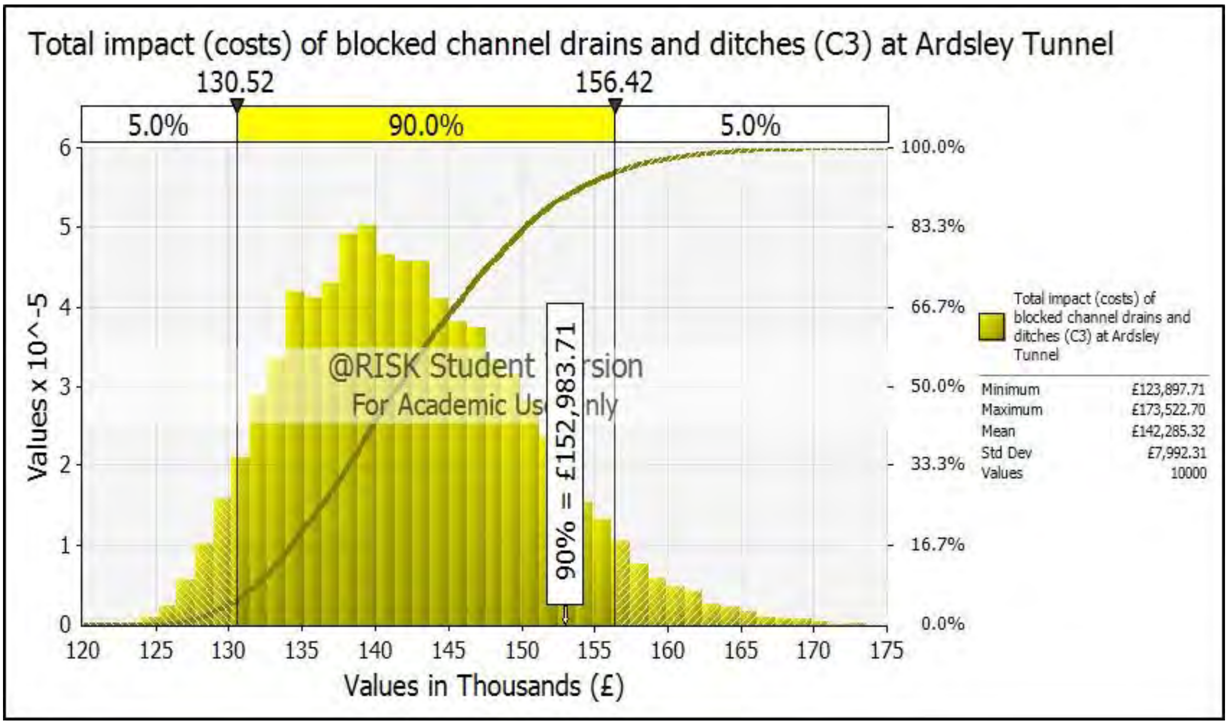


Figure 7.4 The range of total impact (costs) of blocked channel drains and ditches (C3) at Ardsley Tunnel

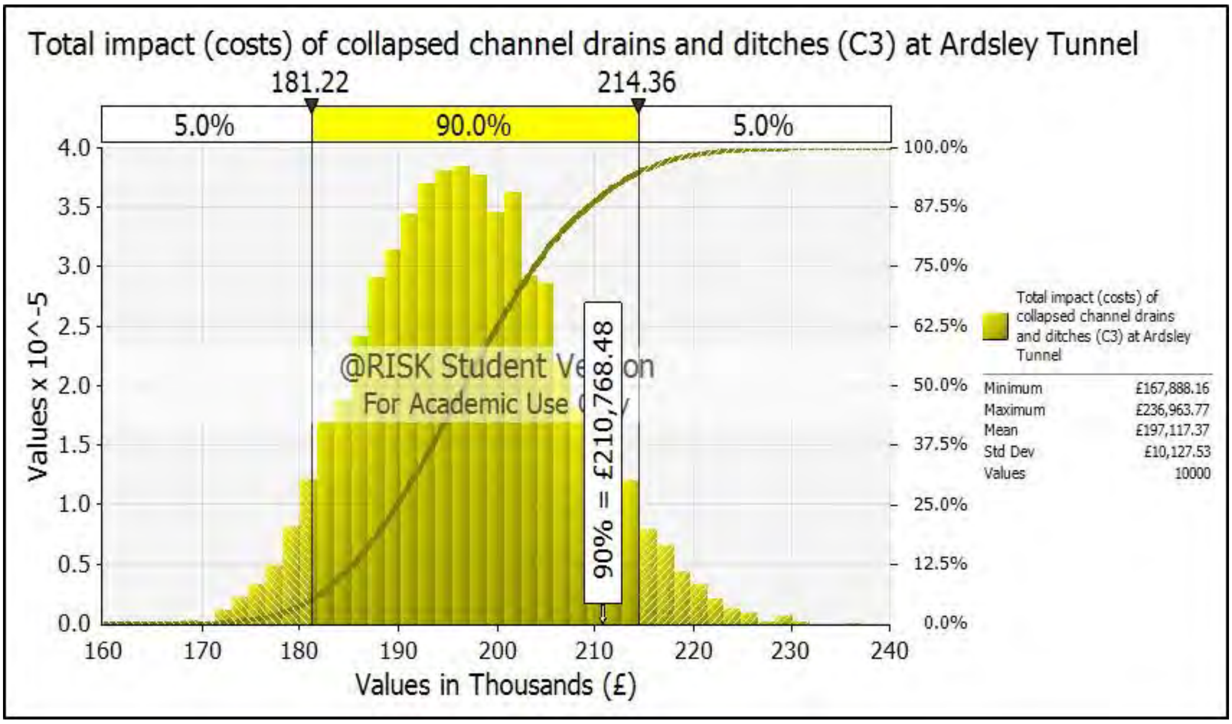


Figure 7.5 The range of total impact (costs) of collapsed channel drains and ditches (C3) at Ardsley Tunnel

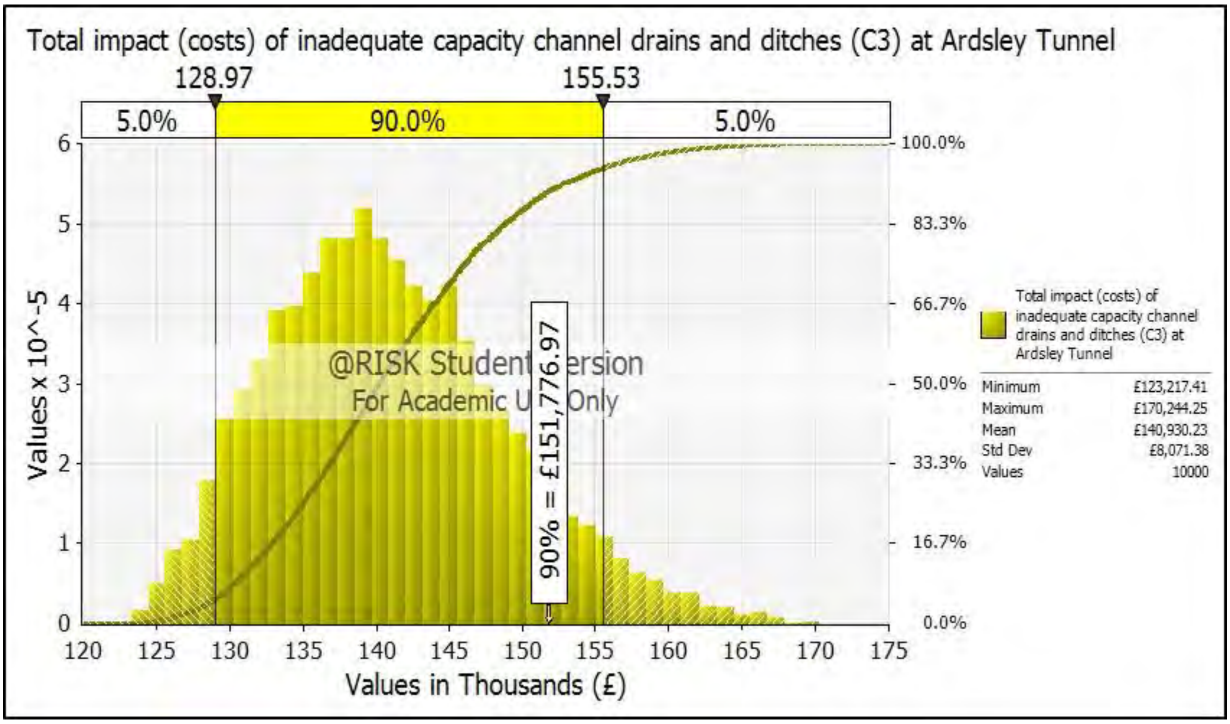


Figure 7.6 The range of total impact (costs) of inadequate capacity of channel drains and ditches (C3) at Ardsley Tunnel

Figures 7.4-7.6 and Tables 7.1-7.3 summarise the total impact associated with the failure modes events occurring at the Ardsley Tunnel site. The results are as follows:

a) There is a 90 per cent chance of the total impact (costs) at Ardsley Tunnel being between £130,520 and £156,420 for blocked, £181,220 and £214,360 for collapsed, and £128,970 and £155,530 for inadequate capacity respectively.

b) The total impact (It), with a 90 % confidence, for blocked (ItD8_90) is £152,984, £210,769 for collapsed drains (ItD9_90), and £151,777 for inadequate capacity (ItD10_90). These are relatively higher than their total impact results without considering uncertainty which are valued £142,285; £197,117; £140,930 respectively. These were obtained using Equation 7.1, i.e. the sum of all available impact values (e.g. I1 (unplanned maintenance costs), I2 (delay costs)).

7.5 Total impact (costs) of failed channel drains and ditches (C3) at Clay Cross Tunnel

7.5.1 The impacts (costs) of defective or failed channel drains and ditches at the Clay Cross Tunnel

As in the previous section, the impact of each risk occurring at this site was calculated on the basis of data obtained via interview, from historical sources and with reference to extant literature. This is summarised in Table 7.4 .

Table 7.4 shows that six out of total of twelve possible impacts are present. Two impacts (costs) are related to unplanned maintenance costs, remediation of wet bed (I_{11}) and clearing drainage asset and pumping floodwater (I_{12})), two impacts are associated with delay costs (delay costs without speed restrictions or cancellations (I_{21}), delay costs with speed restrictions (I_{22})), and two impacts are associated with damage to non-residential property (damage to electricity substations (I_{52}) and damage to depot buildings (I_{53})).

Much like with the Ardsley Tunnel, a wet bed may emerge at the Clay Cross Tunnel as a consequence of a failing drainage assets (C3). The costs associated with this and other types of impact (e.g. clearing drainage assets and pumping floodwater, delay costs and damage to property) are shown in Table 7.4 .

In terms of the cost of damage to non-residential property, property that was considered to be at risk of inundation from surface water was considered (see flood map in Figure 7.7.). Although other types of property (e.g. a business centre) and farmland (at Coney Green Farm) were built next to the property, these are protected by a flood lagoon and a pumping station, which were built to prevent surface water build-up and river flooding (see Figure 7.7, Figure 7.8, and Figure

7.9). Therefore, it was assumed that the only damage cost was to the electricity substation (I_{52}) and a depot building (I_{53}). In Figure 7.7, these buildings are close to the assessed drainage assets (C3).

7.5.2 Quantification of the total impact (costs) of failed channel drains and ditches at the Clay Cross Tunnel

To obtain the total impacts (costs) values, an Excel spreadsheet was used to input the required parameters (i.e. three-point estimates of the available impacts from Table 7.4). Thereafter, the @Risk^{TM} software (Palisade Corporation, 2017) was used to carry out the MCS.

Overall, the procedure adopted was similar to that used for Section 7.4.2. However, because there was also non-residential property nearby, Ordinance Survey maps accessed online through Edina Digimap were used to estimate the affected area. The process can be seen in Figure 7.8 and Figure 7.9. The results are shown in column 3 of Table 7.4 . For the unit cost of damage to non-residential property, a standard costing developed by Penning-Roswell (2013) was used (see Table 2.8 in Chapter 2).

Ahiaga-Dagbui and Smith's work (2014) was used as a reference to calculate the three-point costs. With this in mind, it was assumed that the minimum cost is 95% of the average value, the average cost is equal to the average value and that the maximum cost is 116% of the average value.

Figure 7.7 Flood risk from surface flooding (extent of flooding) at Clay Cross Tunnel (Environment Agency, 2018f)

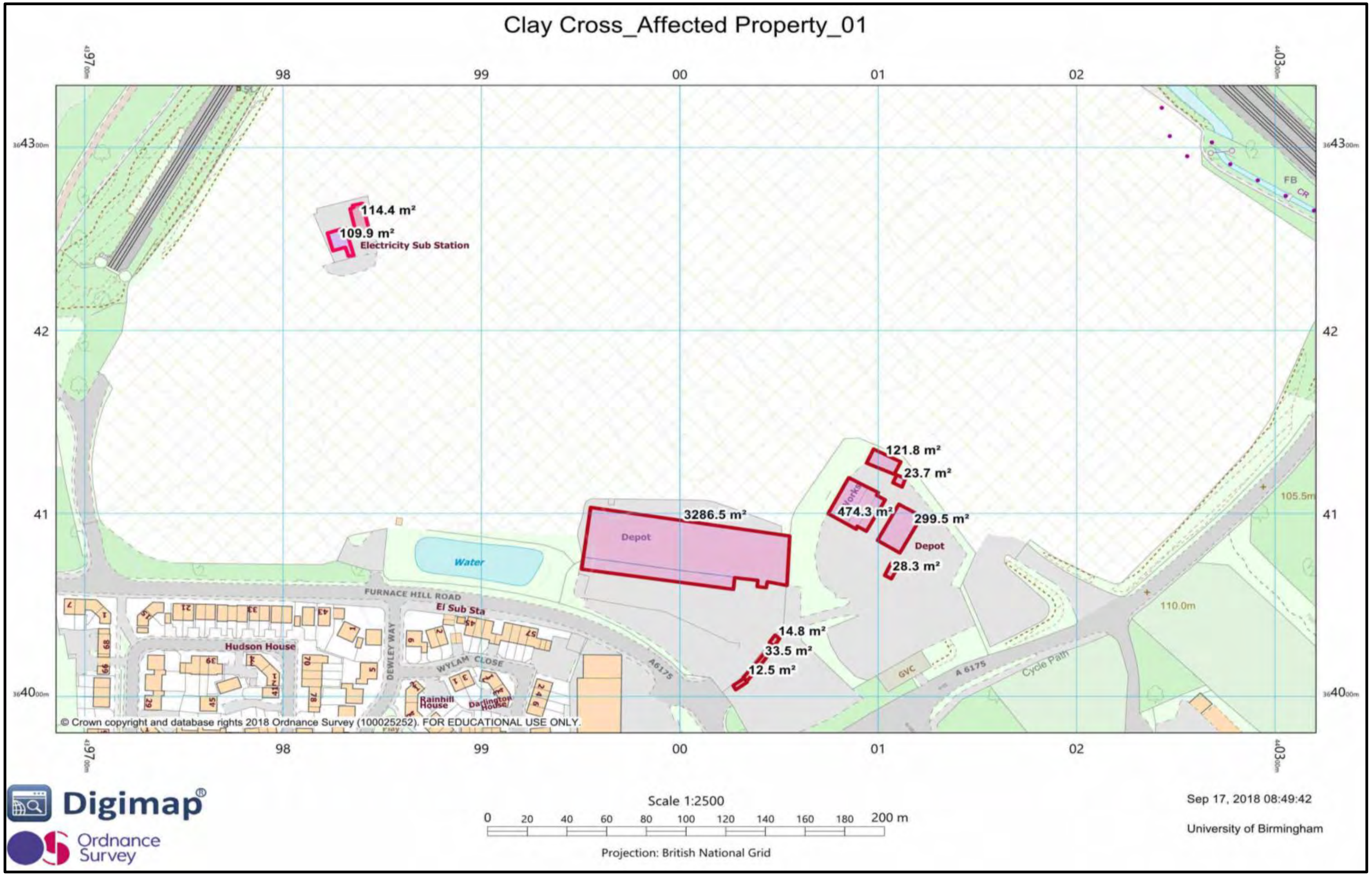


Figure 7.8 Affected property at Clay Cross Tunnel due to failed channel drains and ditches (C3) scale 1:2500, after Ordnance Survey (2018g)

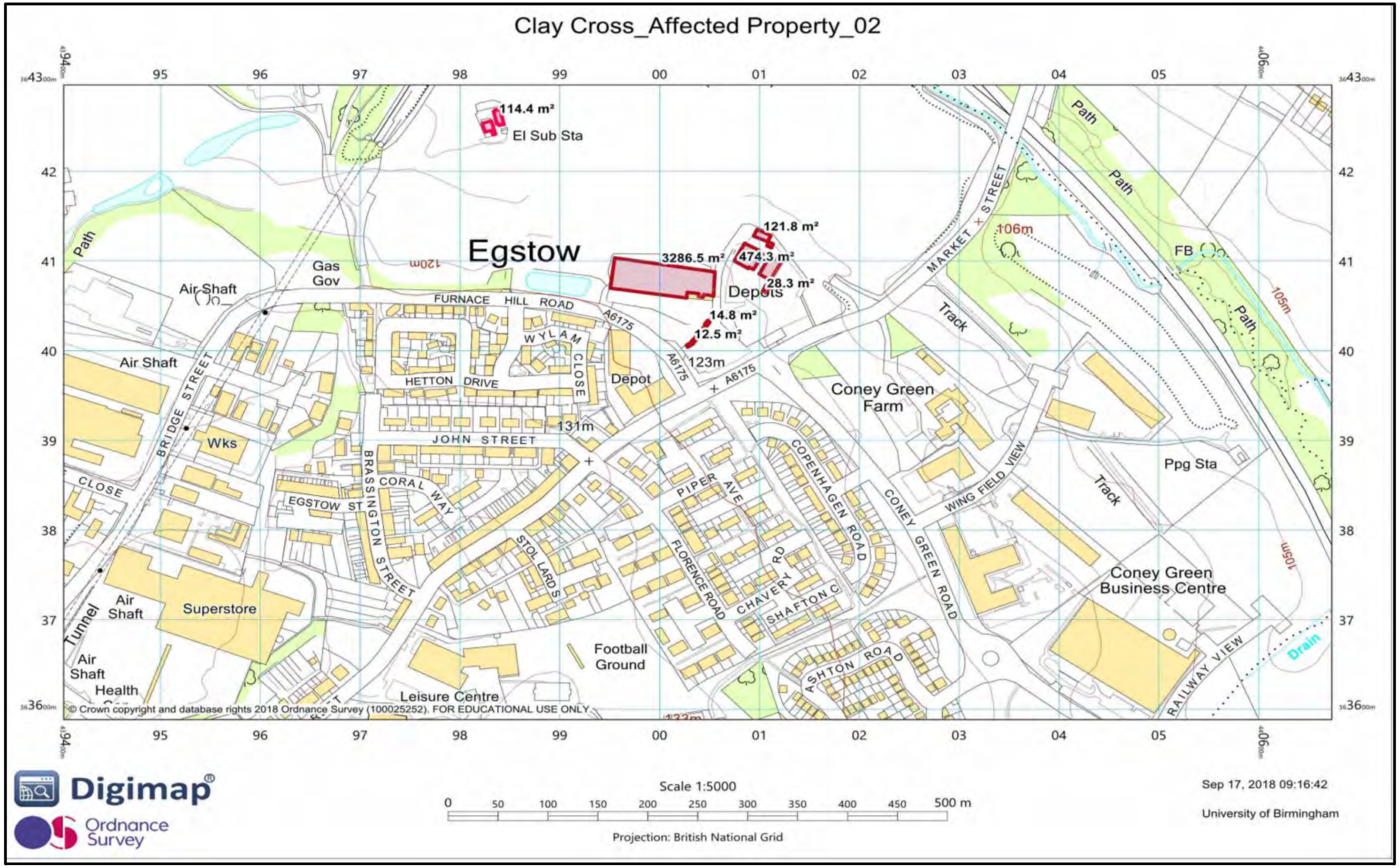


Figure 7.9 Affected property at Clay Cross Tunnel due to failed channel drains and ditches (C3) scale 1:5000, after Ordnance Survey (2018h)

Table 7.4 Summary of the impact of risks associated with blocked channel drains and ditches at Clay Cross Tunnel

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Cost (min) (£)	Cost (mid) (£)	Cost (max) (£)	Cost (mean) (£)	Data Source
1	2	3	4	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (i.e. wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12	Incident	1	Clearing draiange asset and pumping floodwater.				6,672.59	7,595.88	9,853.53	£7,818	Environment Agency (2018)
			5% *(I111 + I21 + I22)								
I13	m	200	Damage to drainage component								
I14	m	200	Damage to signalling								
I2			Delay costs								
I21	minutes	603.29	Delay costs without speed restrictions or cancellations	40.15	70.64	102.61	24,222.31	42,617.03	61,901.47	£42,765	NR's record (Appendix 4)
I22	minutes	643	Delay costs with speed restrictions (5 MPH)	37.46	37.57	38.07	24,066.77	24,137.95	24,457.67	£24,179	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		0	Residential cost								
	m2	4,537.20	Non residential cost								
I52	m2	224.30	Electricity sub station		193.9268		44,215.49	46,542.63	53,989.45	£47,396	Penning-Rowsell *et al.*(2013)
I53	m2	4,312.90	Depot		87.4404		383,344.21	403,520.22	468,083.46	£410,918	
I6		0	Farming land damage costs								
It			Total Costs Impact							£621,788	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impacts with 90% confidence (It90)							£645,507	

Table 7.5 Summary of average delay (minutes) at Clay Cross Tunnel from 2009 to 2018, source Network Rail (Appendix 4)

Date	**Delay Minutes (I3a)**	**Cost (£)**	**Delay minutes with speed restriction (I3b)**	**Cost (£)**
1	**2**	**3**	**4**	**5**
10 June 2009	506	£21,979.43	-	-
01 November 2009	-	-	234	£8,908
23 November 2009	-	-	1051	£39,368
06 December 2009	72	£3,085	-	-
24 September 2012	1305	£52,397	-	-
25 November 2012	129	£7,020	-	-
21 October 2013	156	£10,822	-	-
09 June 2014	357	£28,788.44	-	-
21 November 2016	1,698	£174,227	-	-
Sum	4223	298,319.18	1285	48,275.91
Average (per incident-year)	603.29	42,617.03	642.50	24,137.95
Unit cost (perminute)_minimum	1	40.15		£37.46
(minimum value of column (3)/column (2))				
Unit cost (perminute)_mid	1	70.64		£37.57
(average value of column (3)/ column (2))				
Unit cost (perminute)_maximum	1	102.61		£38.07
(maximum value of column (3)/ column (2))				

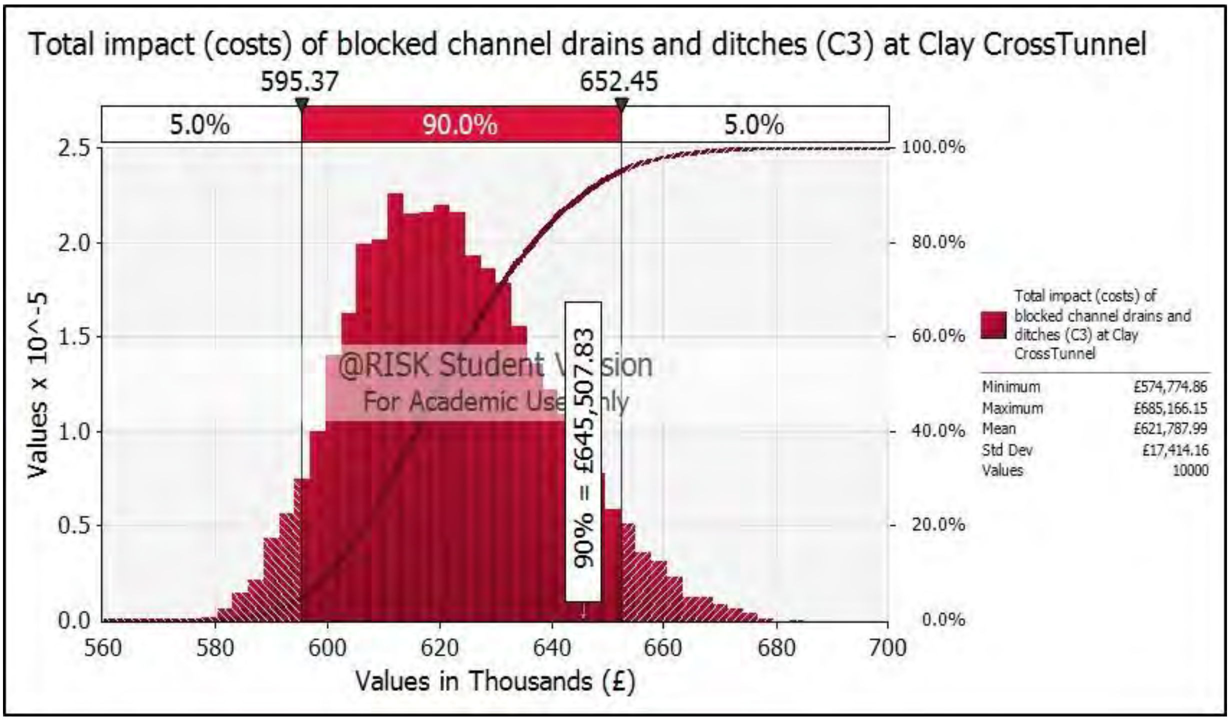


Figure 7.11 The range of total impact (costs) of blocked channel drains and ditches (C3) at Clay Cross Tunnel

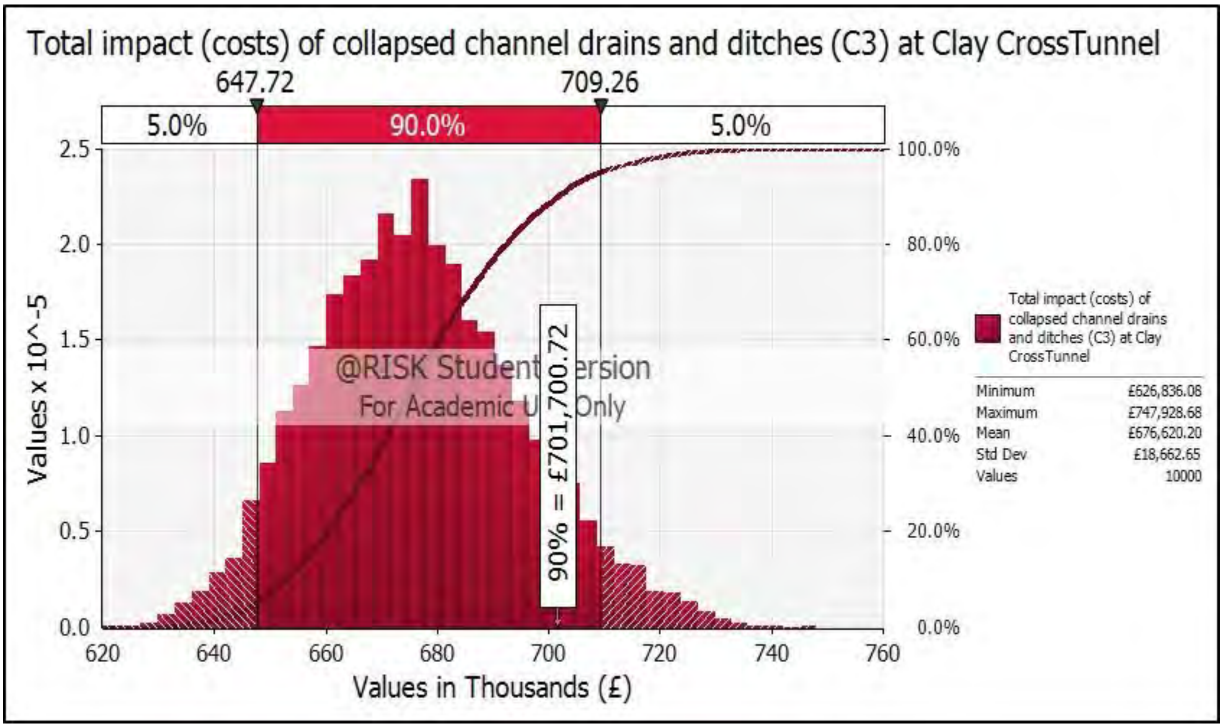


Figure 7.10 The range of total impact (costs) of collapse channel drains and ditches (C3) at Clay Cross Tunnel

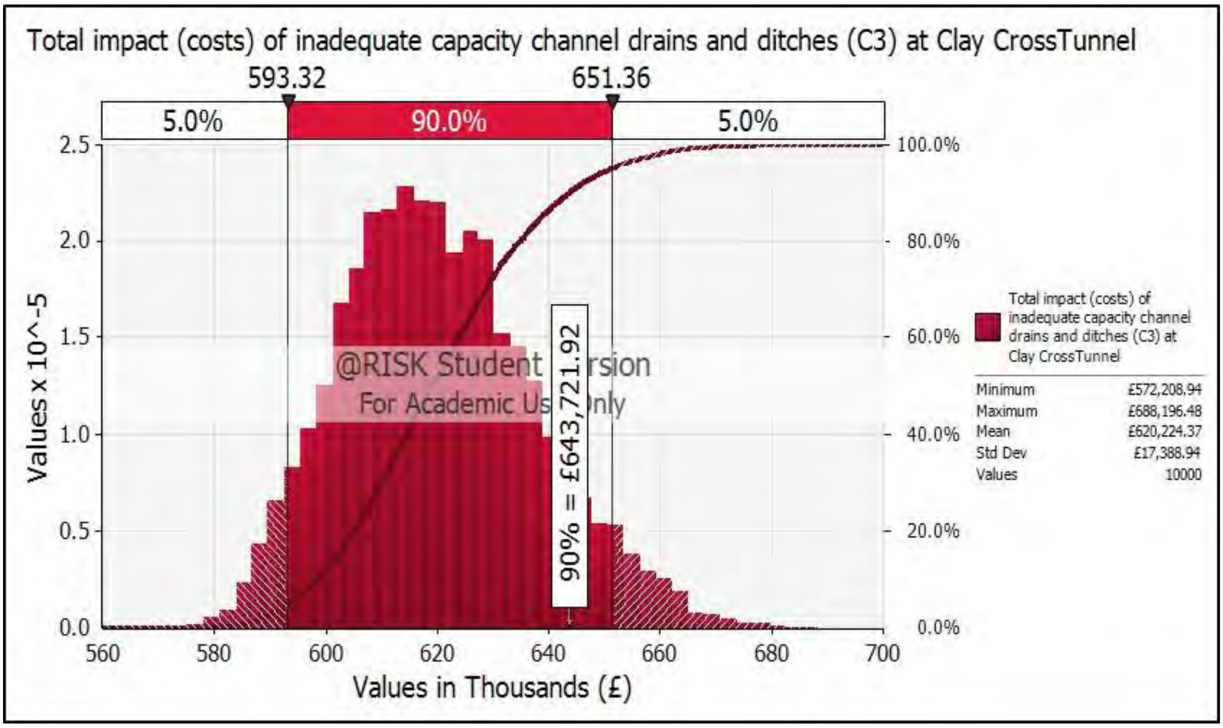


Figure 7.12 The range of total impact (costs) of collapsed channel drains and ditches (C3) at Clay Cross Tunnel

Figure 7.11-Figure 7.12 and Table Table 7.5 and Appendixes 7.3-7.4 summarise the total impact associated with the failuremodes events occurring at the Clay Cross Tunnel site. The results are as follows:

a) There is a 90 per cent chance of the total impact (costs) at Clay Cross Tunnel being between £595,370 and £652,450 for blocked, £647,720 and £709,260 for collapsed, and £593,320 and £651,360 for inadequate capacity respectively.

b) The total impact (It), with a 90 % confidence, for blocked (ItD8_90) is £645,508, £701,700 for collapsed drains (ItD9_90), and £643,722 for inadequate capacity (ItD10_90). These are relatively higher than their total impact results without considering uncertainty which are valued £621,785; £676,620; £620,224 respectively.

7.6 Total impact (costs) of failed channel drains and ditches (C3) at Draycott

7.6.1 Availability of the impacts (costs) of failed channel drains and ditches at the Draycott

As in section 7.3 and 7.5, data on the impact of each risk occurring at this site was obtained via interview, from historical sources and with reference to extant literature. The data is summarised in Table 7.6, Appendixes 7.5, and 7.6.

Table 7.6, Appendixes 7.5, and 7.6. show that five out of a total of twelve possible impacts are present. Two impacts (costs) are related to unplanned maintenance costs (remediation of wet bed (I_{11})), clearing drainage assets and pumping floodwater (I_{12})). Two impacts are associated with delay costs (delay costs without speed restrictions or cancellations (I_{21}), delay costs with speed restrictions (I_{22})), and two impacts are associated with damage to property (damage to residential property (I_{52})).

As with the Ardsley and Clay Cross Tunnel sites, a wet bed may emerge at the Draycott site as an adverse outcome of the failure of drainage assets (C3). The cost implications of this and other impacts (e.g. clearing drainage assets and pumping floodwater, delay costs and damage to property) are presented in . Table 7.6, Appendixes 7.5, and 7.6.

In terms of damage to residential property, the calculation for this type of impact is based on the assumption that flooding from surface water is likely to occur at this site (see Figure 7.14).

7.6.2 Quantification of the total impacts (costs)of failed channel drains and ditches at Draycott

To obtain the total impact (costs) values, an Excel spreadsheet was used to input the required parameters (i.e. the three-point estimates of the available impacts in Table 7.6, Appendixes 7.5, and 7.6.). Thereafter the @Risk^{TM} software (Palisade Corporation, 2017) was used to carry out the MCS.

Overall, a similar procedure was adopted to that used in Sections 7.4.2 and 7.5.2. However, as mentioned above because we were also dealing with residential property, Ordinance Survey maps were also used to measure the affected area (see Figure 7.14). The results of this measurement are presented in column 3 in Table 7.6 ; it was also assumed that the calculation of the area is uncertain. For the unit cost associated with damage of residential property, a standard cost given by Penning-Rowsell (2013) for costs to residential areas to flooding was used (see Appendix 5).

For the three point cost, using insight from Ahiaga-Dagbui and Smith (2014), it was assumed that the minimum cost is 95% of the average value (see column 8 in Table 7.6, Appendixes 7.5, and 7.6), the average cost is equal to the average value (see column 9 in Table 7.6, Appendixes 7.5, and 7.6), and the maximum cost was 116% of the average value (see column 10 in Table 7.6, Appendixes 7.5, and 7.6).

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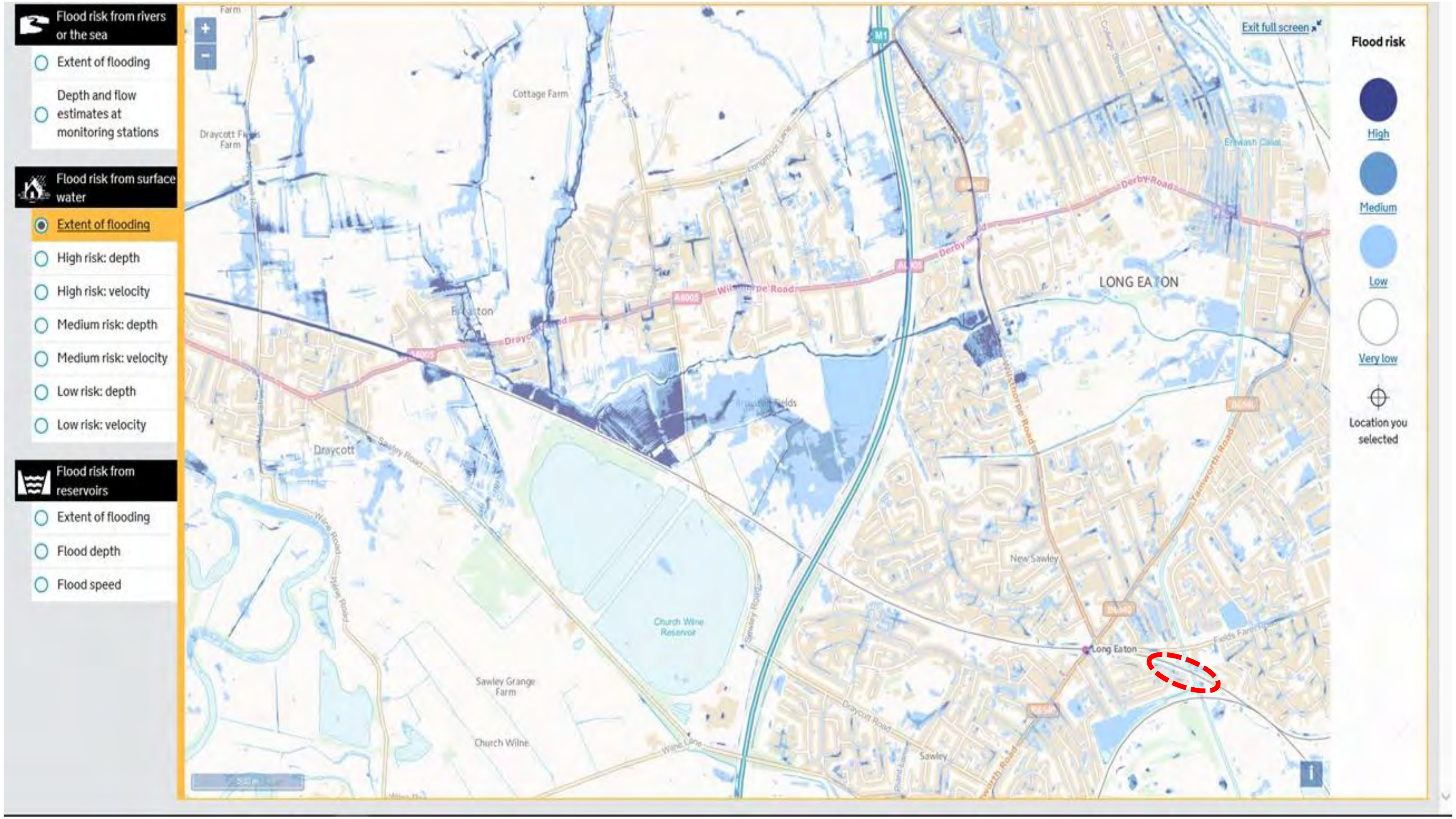

Figure 7.13 Flood risk from surface flooding (extent of flooding) at Draycott, source Environment Agency (2018i)

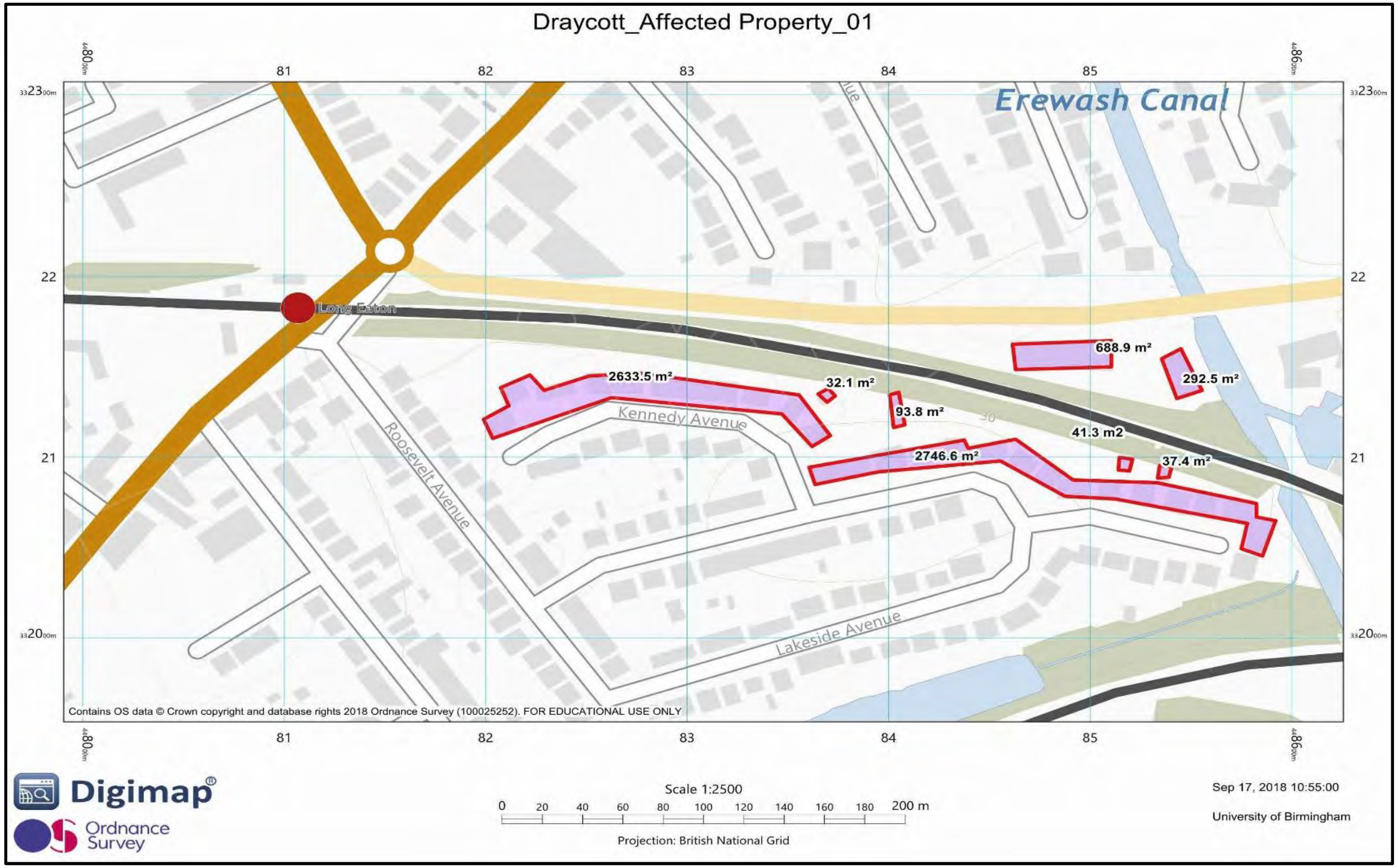

Figure 7.14 Affected property at Draycott due to failed channel drains and ditches (C3), source Ordnance Survey (2018j)

Table 7.6 Summary of impact of risks associated with blocked channel drains and ditches at Draycott

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Min (min) (£)	Mid (mid) (£)	Max (max) (£)	Cost (mean) (£)	Data Source
1	2	3	4	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (i.e. wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12	Incident	1	Clearing drainage asset and pumping floodwater. 5%*(I1a1+I2a+I2b)				7,627.15	9,024.74	11,061.09	£9,131	Environment Agency (2018
I13	m	200	Damage to drainage component								
I14	m	200	Damage to signalling								
I2			Total Delay costs								
I21	minutes	87.29	Delay costs	27.46	52.53	63.15	2,397.19	4,585.06	5,512.32	£4,375	NR's record (Appendix 4)
I22	minutes	1652	Delay costs with speed restrictions (5 MPH)	41.90	54.92	63.54	69,241.30	90,747.07	104,997.95	£89,538	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		6566.1	Residential cost		69.55		433,838.64	456,672.26	529,739.82	£465,045	
I52		0	Non residential cost								
I6		0	Farming land damage costs								
It			Total Costs Impact							£656,800	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impacts with 90% confidence (It90)							£682,288	

Table 7.7 Summary of average delay (minutes) at Draycott from 2009 to 2018, source Network Rail (Appendix 4)

Date	Delay minutes (I3a)	Cost (£)	Delay minutes with speed restriction (I3b)	Cost (£)
1	2	3	4	5
06 July 2012	£239.00	£13,098.33		
25 November 2012			2657	£111,336
20 December 2012			5610	£253,059
20 December 2012			604	£38,379
20 December 2012	5	£316		
22 December 2012			2286	£123,298
22 December 2012	200	£9,087		
27 January 2014			0	£0
01 February 2014	8	£220		
09 February 2016	9	£478		
12 March 2018			406	£18,411
02 April 2018	148	£8,894		
Sum	370	£18,994.11	11563	£544,482.43
Average (per incident-year)	87.29	4,585.06	1652.43	90,747.07
Unit cost (perminute)_minimum	1	27.46		£41.90
(minimum value of column (3)/column (2))				
Unit cost (perminute)_mid	1	52.53		£54.92
(average value of column (3)/ column (2))				
Unit cost (perminute)_maximum	1	63.15		£63.54
(maximum value of column (3)/ column (2))				

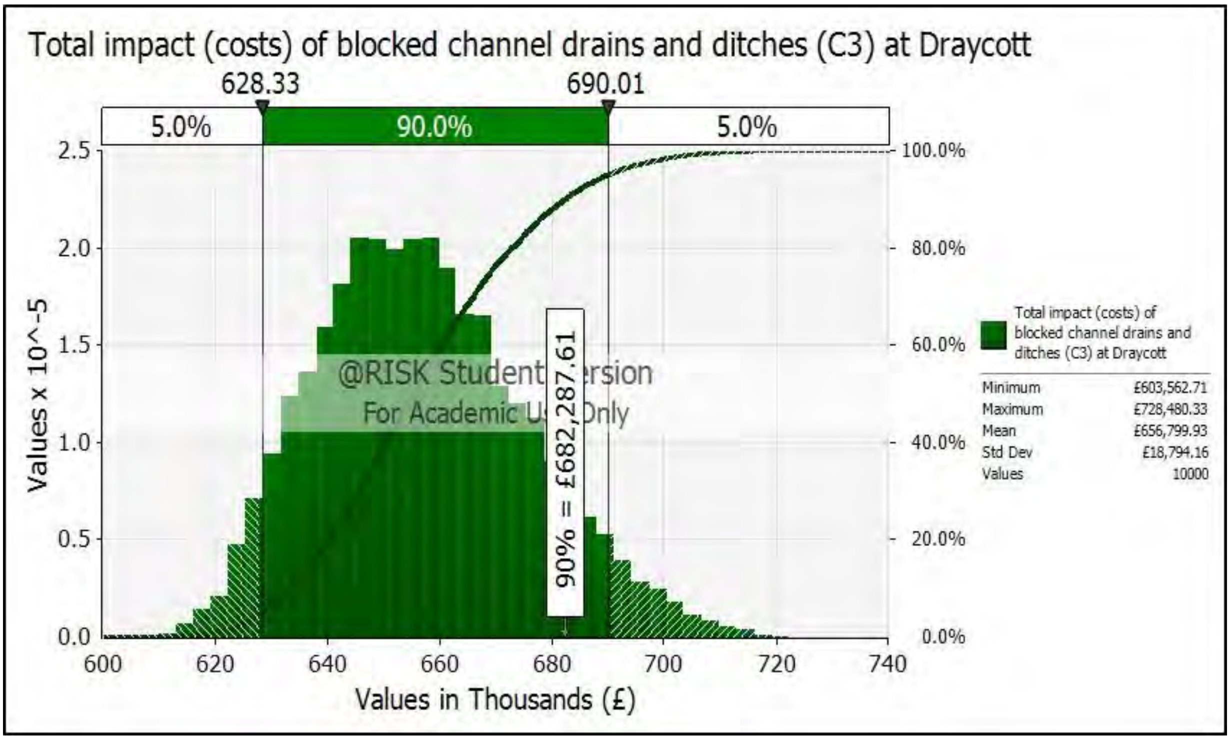

Figure 7.15 The range of total impact (costs) of blocked channel drains and ditches (C3) at Draycott

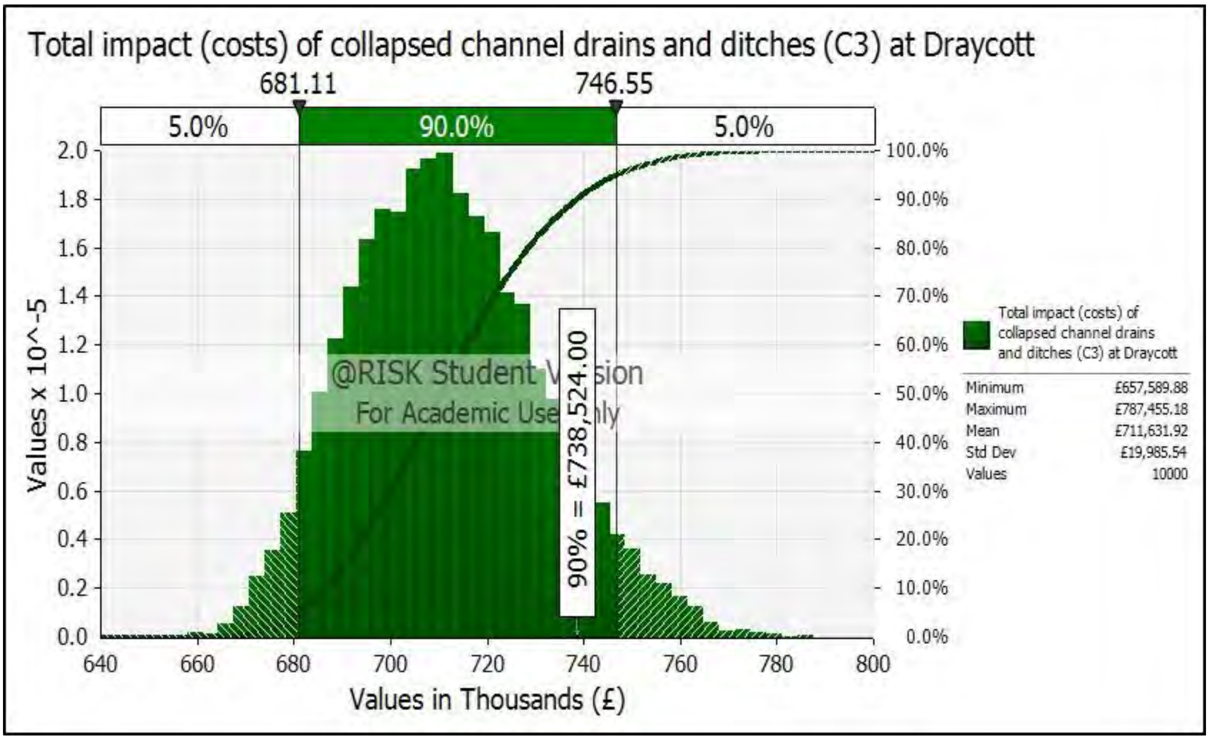

Figure 7.17 The range of total impact (costs) of collapsed channel drains and ditches (C3) at Draycott

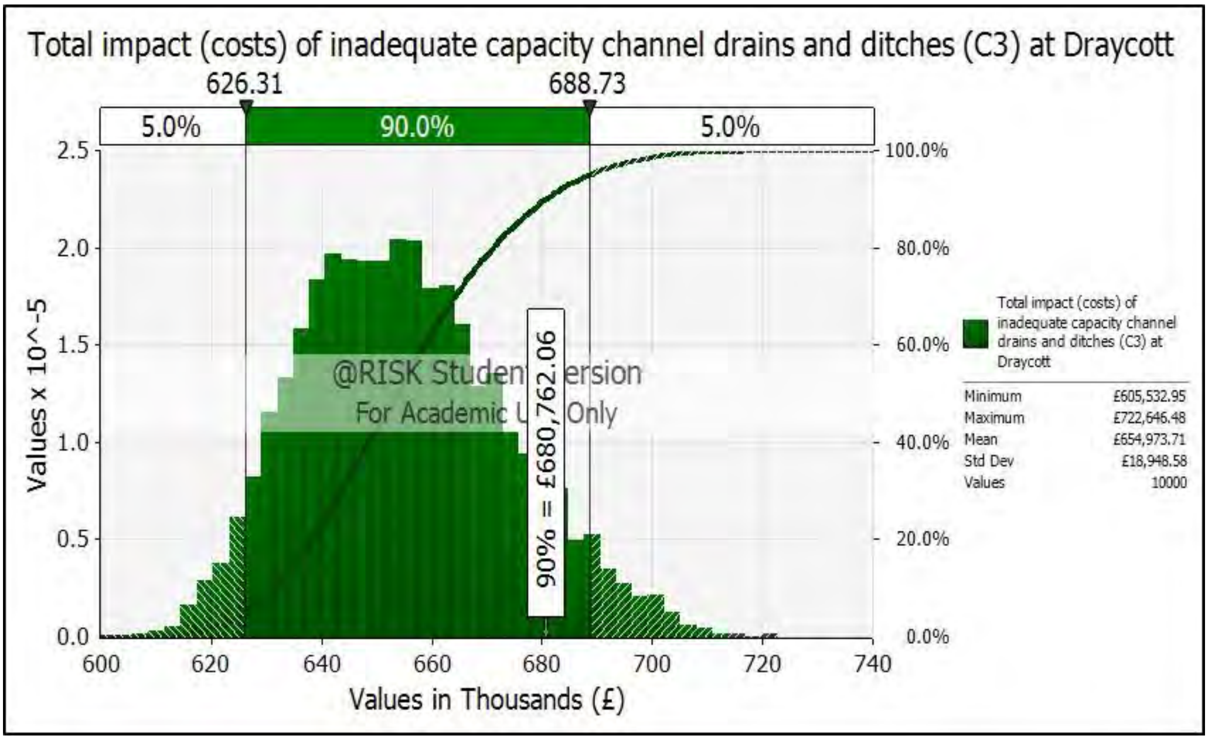

Figure 7.16 The range of total impact (costs) of inadequate capacity channel drains and ditches (C3) at Draycott

The Monte Carlo simulation (MCS), calculated using @Risk™ with 10,000 iterations were utilised to quantify the total impact. Figure 7.15-Figure 7.16 and Table 7.6 and Appendixes 7.5-7.6 summarise the total impact associated with the failure modes events occurring at the Draycott site.. The results are as follows:

a) There is a 90 per cent chance of the total impact (costs) at Draycott being between £628,330 and £690,010 for blocked, £681,110 and £746,550 for collapsed, and £626,310 and £688,730 for inadequate capacity respectively.

b) The total impact (It), with a 90 % confidence, for blocked (ItD8_90) is £682,288, £738,524 for collapsed drains (ItD9_90), and £680,762 for inadequate capacity (ItD10_90). These are relatively higher than their total impact results without considering uncertainty which are valued £656,800; £711,622; £654,974 respectively.

7.7 Summary

A cost model, together with expert elicitation, was used to determine the presence of various impacts associated with failed channel drains and ditches (C3) at three sites on the UK railway network (Ardsley Tunnel, Clay Cross Tunnel, Draycott). This helped to provide an understanding of the impacts (costs) associated with drainage asset failures (C3).

The Monte Carlo simulation (MCS), which formed part of the cost model, was used to quantify the total impacts (costs) associated with failing drainage assets with reference to a range of cost values. Thus, it offered a range of potential costs, rather than a single value. This allows decision-makers to estimate the impact of drainage asset problems in monetary terms, even when there is uncertainty because of a lack of available data.

The quantified impacts indicate the underlying problems that need to be considered by decision-makers when allocating resources. The total impact (costs) can be used as a parameter to evaluate how severe the losses are for the rail operator when a failure occurs at a specific site.

The results have shown that the total impact (costs) of blocked, collapsed, inadequate capacity channel drains and ditches (C3) at Draycott is higher than at both the Clay Cross and Ardsley Tunnel sites (see Figure 7.5-Figure 7.6 for blocked, Figure 7.11-Figure 7.12 for collapsed and Figure 7.15-Figure 7.16 for inadequate capacity respectively). The analysis has shown that the type of impacts are different at each site.

The results of the impact quantification presented in this chapter together with the likelihood of occurrence of the risk as determined in Chapter 6 are together to quantify failure risk in Chapter 8.

8 CASE STUDIES: RISK AND COST BENEFIT ANALYSIS (CBA) OF RAILWAY DRAINAGE FAILURE

8.1 Introduction

The process determined in this research for calculating the likelihood and impact of the risks associated with defective or failed channel drains and ditches was illustrated by three case studies at Ardsley Tunnel, Clay Cross Tunnel, and Draycott and was described in Chapters 6 and 7 respectively. This chapter illustrates by means of case studies of the same three sites, the process devised in the research to analyse the associated risks of these drainage assets. The devised risk analysis process consists of three stages, namely: risk semi-quantification, risk quantification, and cost benefit analysis (CBA). Section 0 describes the process utilised for obtaining risk scores through the semi quantification stage; while Section 0 presents the risk quantification stage which combines into an integrated model the probability of occurrence (i.e. the engineering model illustrated in Chapter 6) and the impact (i.e. the cost model shown in Chapter 7) of the identified risks. The resulting risk values are used to prioritize sites for drainage remediation work. Thereafter, a cost benefit analysis (CBA) is adopted to justify the planned (preventive) maintenance.

8.2 Risk Semi-quantification

There are potentially a large number of risks for any of the three sites considered. Quantifying all of these risks using the approach advocated would be time and would be impractical for a system used in practice. Therefore, the theoretical framework presented in Section 4.3 proposed a process of risk semi-quantification to identify the most significant risks (i.e. failure modes) at the three selected sites and to exclude those less significant from further quantitative analysis.

As described in Section 4.3, the approach for semi-quantifying the identified risks was based on advice provided in BS EN 31010: 2010 (BSI, 2010). The approach utilised a semi-qualitative method that included mapping identified risks to the failure modes associated with inadequate drainage of a section of ballasted railway track. Risk semi-quantification involved obtaining the probability of occurrence (P) and impact (I) of the identified risks. The process adopted involved values of risk parameters comprise P and I in a semi-quantitative scale (see Chapters 4 and 5). An integer scale of 1 to 5 was used to rate the probability of occurrence and impact of each failure mode (risk), where 1 indicates a very low probability of occurrence or very low impact, and 5 a very high probability of occurrence or impact (see Chapter 5). The associated risk scores were calculated by using Equation 5.8. As far as the case studies are concerned, the results of the risk likelihood exercise carried out in Chapter 6 were used to ascertain a range of probabilities and impacts associated with each integer score (e.g. very low probability ≤ 1%; very low impact ≤ £0.2m, see Figure 8.1). By taking the average of the risk scores for each failure mode, the score for a specific failure mode can be compared to other modes that are likely to occur at each site. This enables to determine the riskiest site based on its score.

Risk Matrix			Risk Probability				
			Very Low (<0.1%)	Low (0.1%-1%)	Medium (1%-3.3%)	High (3.3%-10%)	Very High (>10%)
			1	2	3	4	5
Risk Impact	Very High	5 (higher than £0.5m)	5	10	High riisk 15	20	25
	High	4 (£0.4m to £0.5m)	4	8	12	16	20
	Medium	3 (£0.3m to £0.4m)	3	6	Medium risk 9	12	15
	Low	2 (£0.2m to £0.3m)	2	4	6	8	10
	Very Low	1 (less than £0.2m)	1	Low riisk 2	3	4	5

Figure 8.1 Risk matrix developed for the three case study sites

A risk matrix (see Figure 8.1) was developed to enable the risks to be categorised as low, medium and high. A risk score of 15 or greater was considered to be ‘high risk’ (red); and those equal to or greater than 5 but less than 14 were considered to be of ‘medium risk’ (green); whilst risk scores of less than 5 were categorised as having ‘low risk’ (yellow). As mentioned above, those events considered to be of high risk were thereafter quantified following the process described in Section 4.3.

8.2.1 Results

The risk scores obtained for the three sites considered are presented in Table 8.1in terms of risk associated with ‘blocked drain’ (i), ‘collapsed drain’(ii), and ‘inadequate capacity’(iii). The probability of occurrence (P) and impact (I) scores were obtained by transforming the P and I values obtained for each risk in Chapters 6 and 7 respectively to integer values using the scale shown in Figure 8.1. The P and I values used for this purpose were the 90 percentile values (i.e P90 and It90) obtained from the Monte Carlo simulations carried out in Chapters 6 and 7 respectively. Thereafter, the probability of occurrence (P) (see Chapter 6) was multiplied by the perceived impact (I) (see Chapter 7) value, to obtain a risk value (R) (see Equation 5.8). For example, the P90 and It90 for blocked (D8) failure mode were estimated as 8.09% and £645,820 respectively. Transforming these to an integer scale using the ranges given in Figures 8.1, yielded a probability score of 4 (high) and an impact of 5(very high). The resulting risk value, which was calculated by multiplying these values (R = P x I; see Equation 5.8) resulted in a score of 20 (i.e. a high-risk).

Table 8.1 Results of semi-quantification analysis of drainage risk (failure mode) at the selected sites

Identified Risk	Ardsley Tunnel			Clay Cross Tunnel			Draycott			Average risk score
	P	I	R	P	I	R	P	I	R	
i. Blocked (D8)	4	2	8	4	5	20	4	5	20	16
ii. Collapsed (D9)	4	2	8	4	5	20	3	5	15	14
iii. Inadequate capacity (D10)	4	2	8	4	5	20	3	5	15	14
Sum			24			60			50	

Low risk Medium risk High risk

P = Probability of occurrence I= Total impact (costs) R=Risk R=P x I

For the three sites, of the nine identified failure mode (risk) combinations, around 67% were found to have high risk scores and 33% have medium risk scores. The highest individual risk scores in Table 8.1 are associated with the blocked (i), collapsed (ii), and inadequate capacity (iii) at the Clay Cross Tunnel and Draycott sites respectively. In the case study it was assumed that risks had an equal weighting. Summing the risk scores for each risk for each site yielded the total risk for each site (Section 8.2.1.1). Averaging the scores by risk type yields a measure of risk for each failure mode (risk) (Section 8.4.1.2).

8.2.1.1 Risk by site

Figure 2.2 shows the total risks obtained for each site ranked in order from the highest to lowest. From Figure 8.2 it may be seen that the Clay Cross Tunnel site has the highest risk score (i.e. sum for column = 60), whilst Ardsley Tunnel has the lowest total risk score of 24. Although

Ardsley Tunnel site has a high likelihood of the blocked C3 failure mode with a score 4, the impact is relatively low (score 2), as it was believed that flooding damage to adjacent properties was low. Similarly, the analysis found that the impacts for the collapsed drain and inadequate capacity C3 failure modes were also similarly low (i.e. 2), which combined with their high likelihood (4) resulted in risk scores of 8 (i.e. medium). As a result the total risk score for those failure modes at this site was 24 (see Table 8.1).

In contrast, the combination of high probability of occurrence and high impacts of the drainage risks at the Clay Cross Tunnel yielded high risk scores at this site (score 60, see Table 8.1). The potential losses were found to be mainly attributed to the potential impacts on non-residential property at this site and in particular potential damage to an electrical substation and a depot building (see Section 7.4).

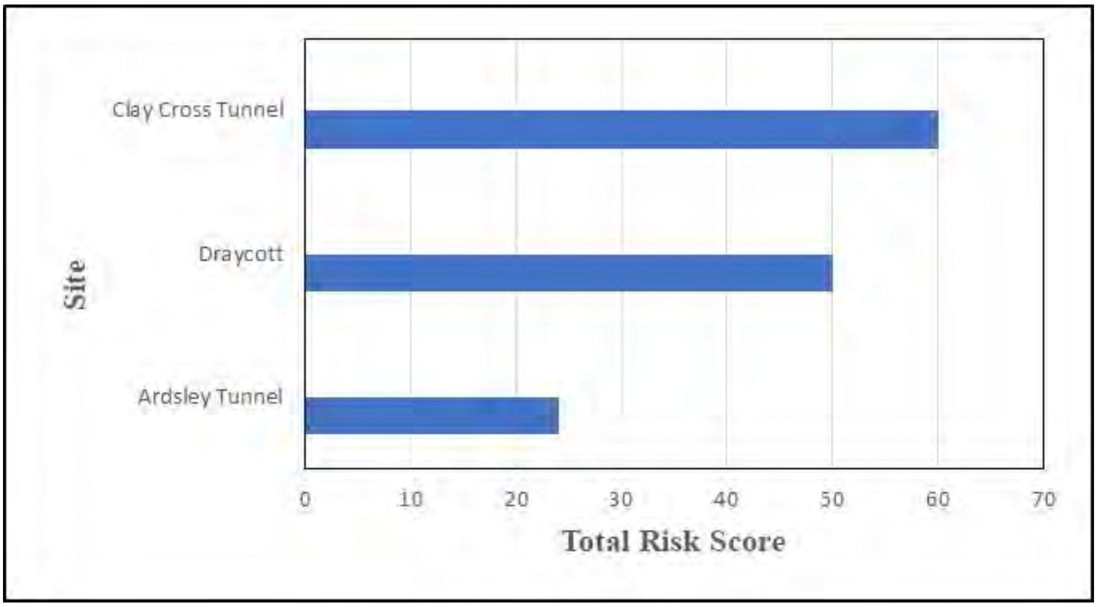

Figure 8.2 Total risk score at the three selected sites

8.2.1.2 Risk by failure mode

Average risks (by failure mode) ranked in order from the highest to the lowest are presented in Figure 8.3. The highest average risk score (i.e. 16 - high risk) was found to be blocked channel drains and ditches (D8). The remaining risks were collapsed drains (D9) and inadequate capacity (D10); both had the same scores (i.e. 14 - medium risk). These scores confirmed that the blocked failure mode was assessed as the highest risk at the Clay Cross Tunnel compared to the others failure modes. This finding can be used to prioritise the risks within selected sites and enable interventions to focus on either reducing their likelihood of occurrence or impact, or both.

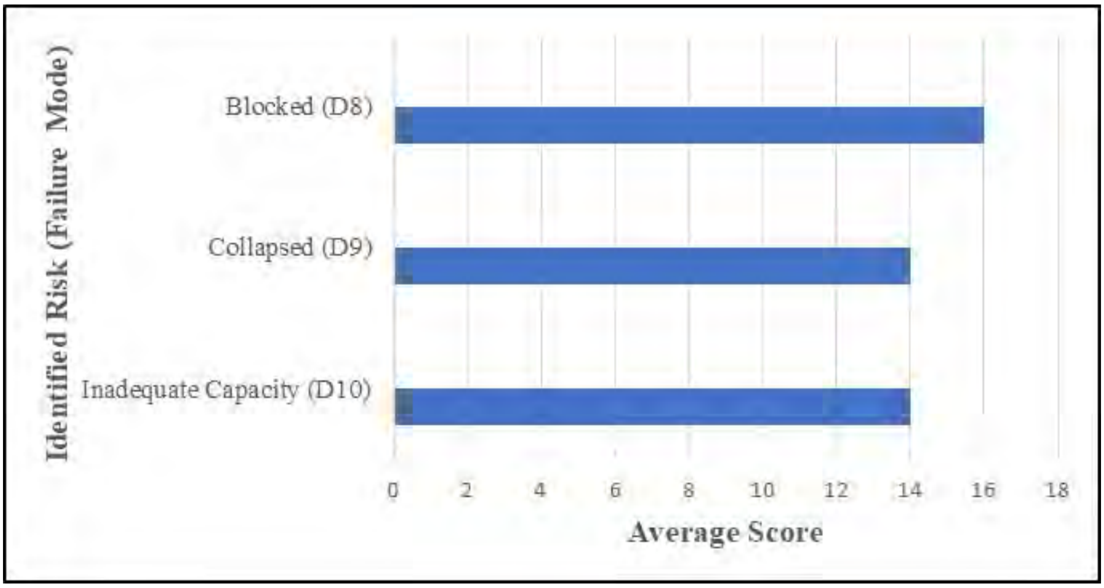

Figure 8.3 Average risk score of various failure modes at the Clay Cross Tunnel

8.3 Risk Quantification (Integrated Model)

In terms of risk assessment, risk quantification estimates precise values resulting from the multiplication of probabilities and their consequences (impacts). The resulting risk is presented in monetary terms, whereas probabilities are in percentages and consequences are in same unit as the risk.. For the three case study sites, the probabilities and impacts of the identified risks associated with poor drainage of ballasted railway track subject to channel drains and ditches (C3) were obtained using a Monte Carlo simulation (see Chapters 6 and 7). Thereafter, costs and benefits of preventive (planned) maintenance to undertake the risks were calculated by means of a cost benefit analysis (CBA) as described in section 8.6.

8.4 Results

8.4.1 Risk assessment results

The @Risk™ software (Palisade Corporation, 2017) was utilised to carry out the Monte Carlo simulation (MCS) and thereby model the probability and cost uncertainties associated with the identified risks.

8.4.1.1 Uncertainties in risk likelihood (probability of occurrence) and impact (cost) estimations

To model the uncertainties associated in the likelihood of occurrence estimations, the three-point estimate procedure described in the literature and discussed in Section 6.4.5 was used. A PERT distribution was used to this end. illustrates the resulting Monte Carlo determined PERT distribution for the annual probability of occurrence of flooding from the surface (X6). In terms of the case study, this risk may lead to various failure modes (i.e. blocked drain, collapsed drain and inadequate capacity) which would then lead to an undesired event, namely defective or failed channel drains and ditches (C3). As shown in Figure 8.4 , the probability of X6 has three estimations: minimum 0, most likely 4.33%, and maximum 8.27%; and there is a 90 per cent chance according to the distribution to obtain annual probability of occurrence of between 1.67% and 6.81%; this was obtained using ten years data period (see Chapter 6 and Appendix 4).

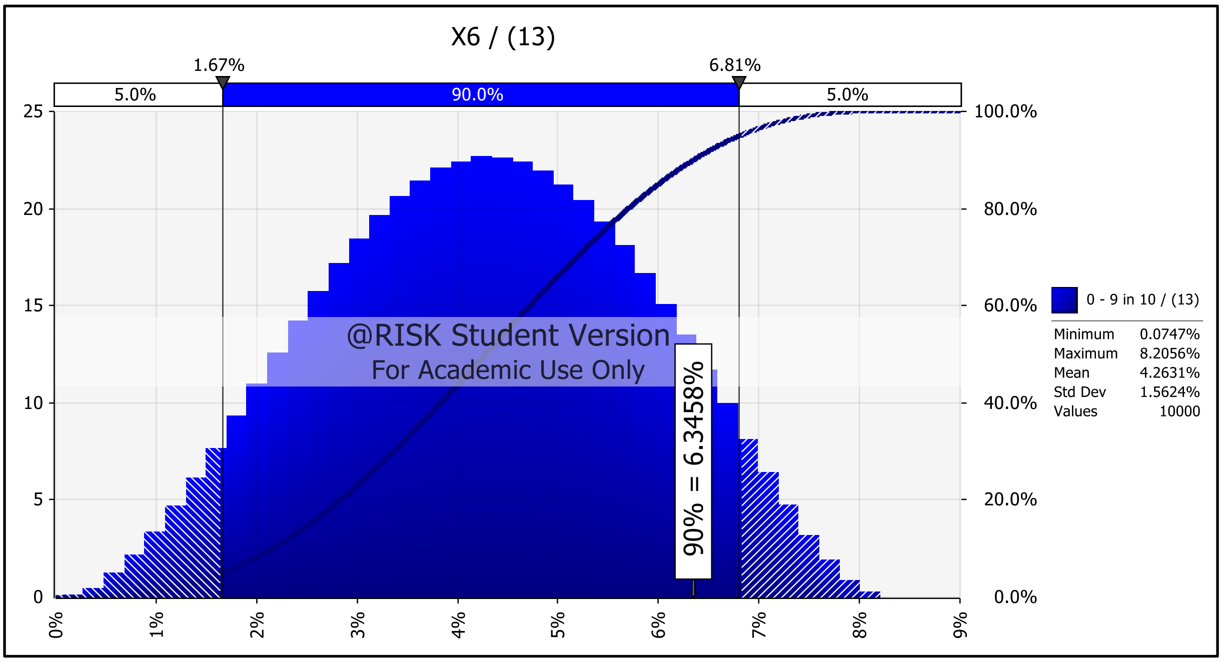

Figure 8.4 PERT distribution as input for likelihood of flooding from the surface flooding (X6) risk per year.

The uncertainty in impact (cost) was also modelled using a PERT distribution (see Chapter 7 for a fuller description). Ahiaga-Dagbui and Smith (2014) found that the variance between predicted and actual cost in the UK construction industry ranged from 5% below the average predicted cost and around above 16% of the average predicted cost. These findings were used to develop the PERT distribution of costs (see Section 7.4.2 for a fuller treatment). Accordingly, to model cost impact of flooded depot at Clay Cross Tunnel, he resulting PERT distribution was generated using 95% of average (£383,344) as minimum value, the average value (£403,520) as mid value , and 116% of the average value (£468,083) as maximum value respectively as shown in Figure 8.5. The distribution of the damage cost to a depot at Clay Cross Tunnel is shown as an example in Figure 8.5. From Figure 8.5 it may be seen that there is a 90 per cent chance of achieving impact values (i.e. costs) of between £389,455 and £438,339.

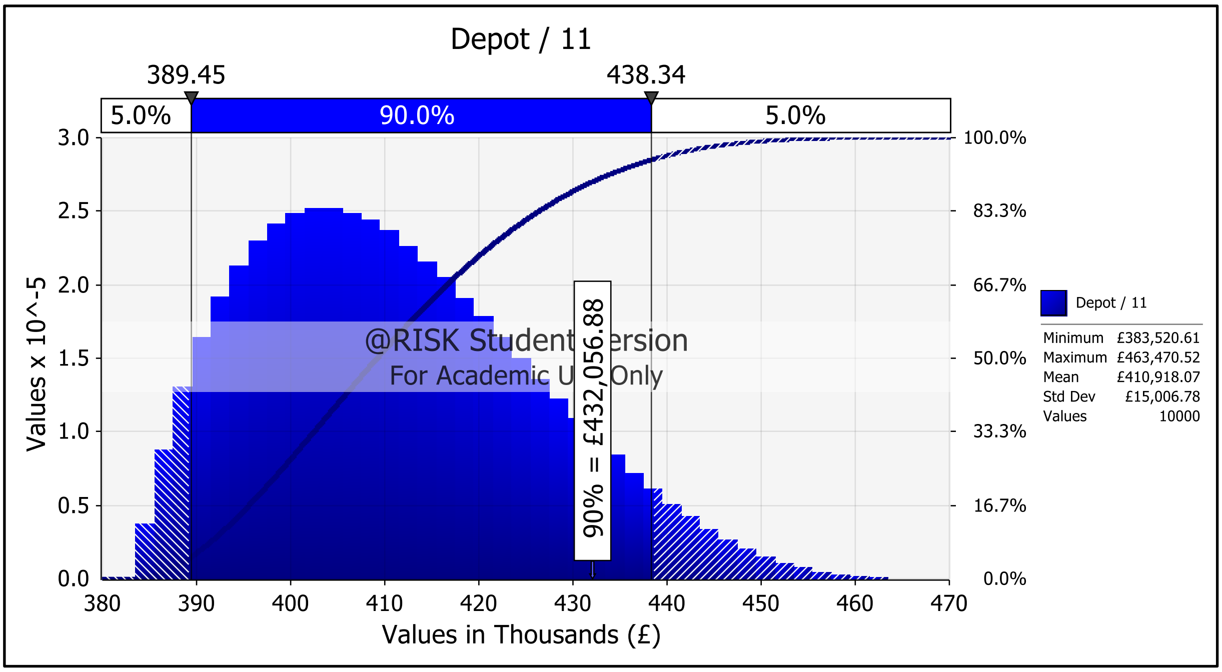

Figure 8.5 PERT distribution as input for property damage cost, i.e. depot (I_{53})

In terms of risk likelihood and impact values as inputs for estimating risk values using @Risk™ software, the above procedures were adopted and calculated (see Sections 6.1.5 and 7.5.2). Following the semi-quantification screening process presented in Section 8.2.1 , the risk quantification, for the purposes of illustrating the approach developed in this research, focused on Clay Cross Tunnel.

8.4.1.2 Risk assessment - results of risk quantification (Integrated model)

As described above, the semi-quantitative analysis confirmed that the Clay Cross Tunnel obtained the highest score of the three sites considered (see Table 8.1). Thereafter, the likelihood distributions obtained in Section 6.1.5 and impact distribution in Sections and 7.5.2 were combined using a Monte Carlo Simulation (MCS). The simulation was performed as follows:

1. Using the determining three-point estimations of the likelihood and cost impact for each failure mode separately (see Sections 6.1.5 and 7.5.2).
2. Determing PERT frequency distributions, using the @Risk™ software to obtain the

distribution of risk values for D8, D9, and D10 risks respectively (see see Sections 6.1.5 and 7.5.2).

3. Multiplying the frequency distributions determined in Step 2 above using a Monte Carlo Simulation 10,000 iterations performed using the @Risk^{TM} software for the whole failure mode simultaneously, to obtain the range of risk values for a C3 failure.
4. Performing a MCS using the @Risk^{TM} to combine all failure modes using the 'OR' relationship to determine the defective or failed C3 as the top event.

The results of the simulation are given in Figure 8.6 and Table 8.2.The results can be summarised as follows:

1. There is a 90 per cent chance of the risk value being between £24,240 and £56,930 for blocked (RD8), £18,570and £53,510 for collapsed (RD9), and £-14.390 and £46,500 for inadequate capacity (RD10) respectively .
2. There is a 90 per cent chance of the risk values of defective or failed channel drains and ditches (RC3) being between approximately £78,830 and £135,740. As illustrated in Figure 8.6 and , the highest risk (R90) value of a failure mode is blocked drains (cost of approximately £53,822) whereas the second and third highest modes are collapsed drains (approximately £50,406) and inadequate capacity respectively (approximately £43,439).
3. For the RC3, the risk value of defective or failed channel drains and ditches was obtained by running @Risk^{TM} for all failure modes was found to be approximately £129,545 at the 90% confidence level.

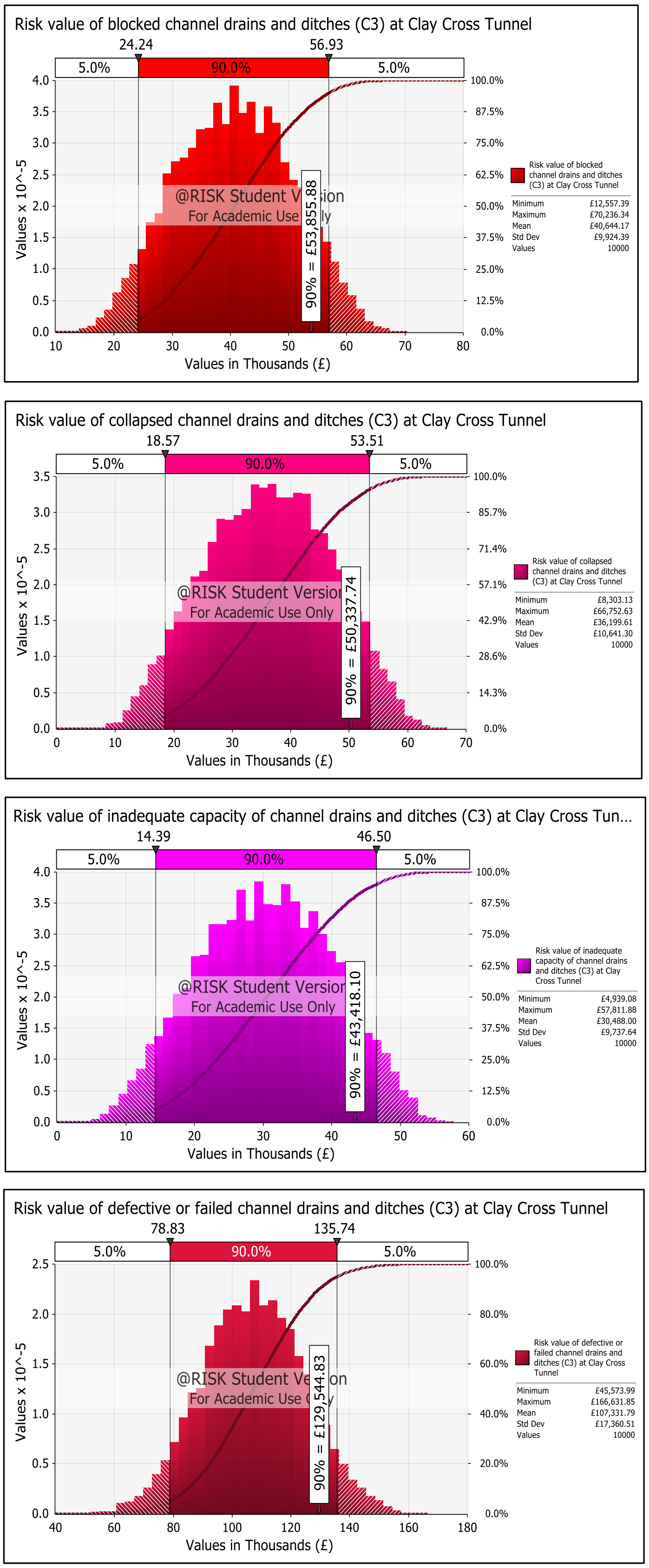

Figure 8.6 Risk values of failure modes of defective or failed channel drains and ditches (C3) at Clay Cross Tunnel

Table 8.2 Summary of risk parameters value (i.e. probability of occurrence (P), total impact (It), and risk value (R)

No	Identified Risk	Type	Probability of Occurrence (P) in %		Total Impact (Costs) (It) in £		Risk Value (R=P x It) in £	
			P	P90	It	It90	Range of Risk Value	R90
1	Blocked (D8)	Failure Mode - Mid Event	6.54%	8.09%	621,788	645,820	24,240 - 56,930	53,855
2	Collapsed (D9)	Failure Mode - Mid Event	5.35%	7.35%	676,620	701,582	18,570 - 53,510	50,337
3	Inadequate Capacity (D10)	Failure Mode - Mid Event	4.92%	6.96%	620,224	643,788	14.390 - 46,500	43,418
4	Defective or Failed Channel Drains and Ditches (C3)	Failure Mode - Mid Event	16.80%	19.65%			78,830 - 135,740	129,545
	P(C3) = P(D8 + P(D9) + P(D10)						R(C3)=P(D8)*It(D8) + P(D9)*It(D9) + P(D10)*It(D10)	
Monte Carlo simulation using @RiskTM			First iteration		Sconnd iteration		Third iteration	
Model			Engineering model		Cost Model		Integrated model	

8.5 Tornado Graph

A tornado graph, a feature of @Risk^{TM}, was used to display a ranking of the input variables that have an influence on the risk values produced by the simulation as shown in Figure 8.7. The tornado graph in Figure 8.7 shows that the main contributor of risk values for various types of failure modes at the Clay Cross Tunnel site is the likelihood of flooding from surface water (X6). Whereas the least influential factors are identified as the cost of clearing drainage asset and pumping flood water (I_{12}) for blocked risk (RD8); delay cost with speed restrictions 5 MPH (I2b) for both collapsed (RD9) and inadequate capacity (RD9) risks; and likelihood of changes to the upstream drain (X12).

Whilst the factor which has the highest contribution is the risk associated with the environment (i.e. flooding from surface water) as shown in Figure 8.7, the second and fourth highest contributors are the likelihood of vegetation overgrowth (X25) and lack of debris clean out (X19) leading to the risk of a blocked C3 assets (RD8). Both of these risks are associated with maintenance in the model. It is therefore sensible to prioritize preventative maintenance to prevent X25 and X19 from occurring. .

As far as impact is concerned, Figure 8.7 shows that the damage cost of the depot (I_{52}) is the third highest scoring impact when considering the risk of a blocked drain (RD9) and the second highest when considering the collapsed drain (RD9), inadequate capacity (RD10), and defective or failed channel drains and ditches (RC3) respectively. This indicates that mitigation of damage to the depot needs to be prioritised. Based on the above analysis the anticipated of the costs and benefits of maintenance to prevent vegetation overgrowth and lack of debris clean out were considered within the cost benefit analysis presented below.

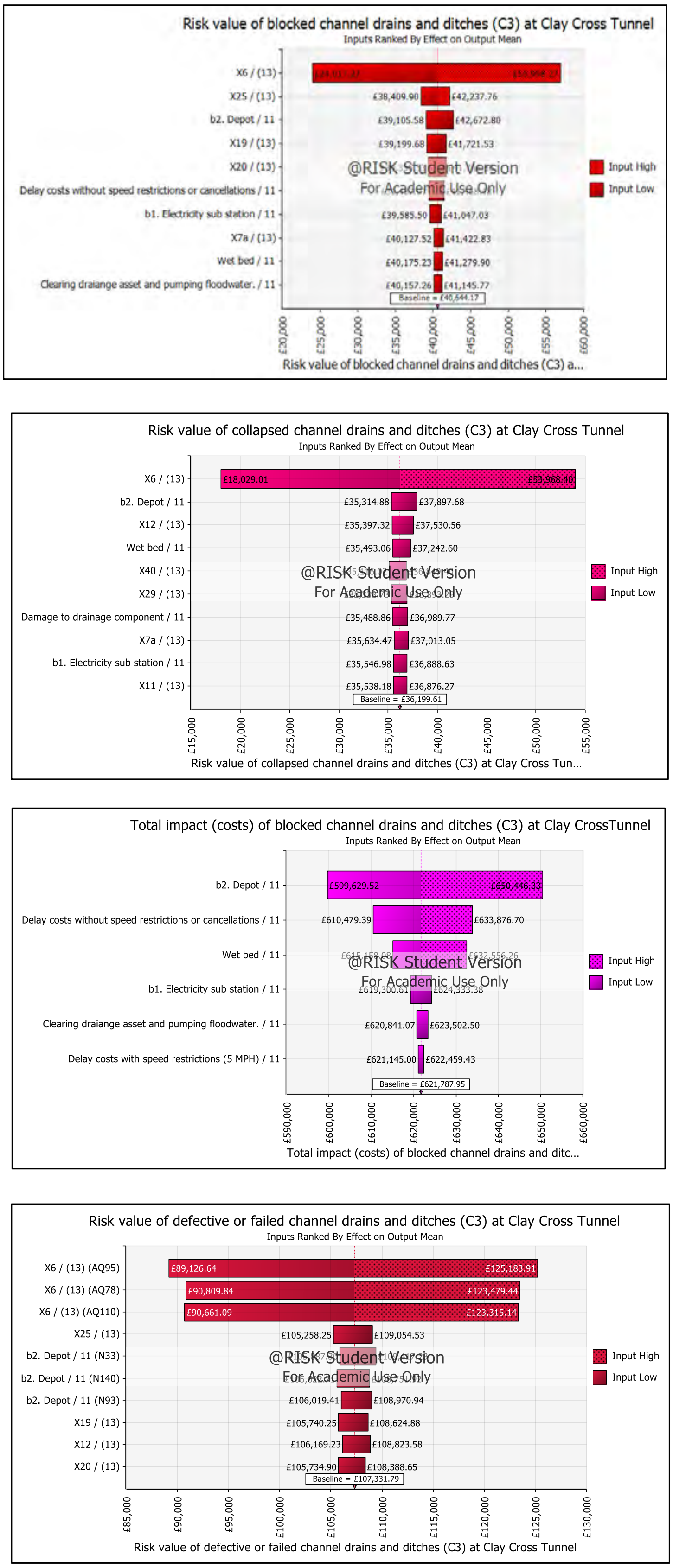

Figure 8.7 Tornado graphs from sensitivity analysis of input-output of MCS for three failure modes (i.e. blocked, collapsed, inadequate capacity) at Clay Cross Tunnel site

8.6 The Cost Benefit Analysis (CBA)

A cost benefit analysis (CBA) was performed to demonstrate how the results of the above analysis may be used to determine the net benefits of preventative drainage maintenance.

For the purpose of this research the CBA was performed by determining the net present value, *NPV*, of costs and benefits associated with preventative maintenance. The NPV was calculated using the following formulae (Lumby and Jones, 1999; Boardman *et al*., 2011; European Commission, 2014):

$NPV = PV(B) - PV(C)$ Eq. 8.1

Where,

NPV: net present value

PV(B): present value of expected benefits

PV(C): present value of costs

And $PV(B).= \sum_0^n \frac{Bt}{(1+r)^n}$. …Eq. 8.2

And

$PV\ (C)= \sum_0^n \frac{Ct}{(1+r)^n}$. …Eq. 8.3

Noting that (Vanmarcke, 2009)

Where,

$Bt = P.It - P^*.It^*$ Eq. 8.4

and

$Ct=.PMct$ Eq. 8.5

Substituting for benefits at time *t*, *Bt*, and the costs *Ct* from equation 8.4 and 8.5 into equation 8.2 and 8.3 yields:

$PV(C) = \sum_0^n \frac{PMct}{(1+r)^n}$ ...Eq. 8.6

and

$PV(B) = \sum_0^n \frac{(P.It - P^*It^*)}{(1+r)^n}$ Eq. 8.7

=

Bt: benefit at time *t* (reference year e.g. 2015)

Ct: cost at time *t*

P: risk probability without planned (preventive) maintenance at year n

P^*: risk probability with planned (preventive) maintenance at year n

It: the annual monetary losses (total social-economic impacts) without added planned (preventive) maintenance at year n

It: the expected reduction of annual monetary losses (total social-economic impacts) with added planned (preventive) maintenance at year n

PMct: annual planned (preventive) maintenance costs

n: the number of year(s) for which benefit, or cost is left deposited

r is the discount rate

Two types of CBA were compared. One of these is CBA with constant impact reduction and the other is CBA with gradual reduction. The former involves risk likelihood and impact reduction when the preventive maintenance applying in a designated frequency (e.g. 1 or 2 times per year) and simulates the NPV. The latter using similar parameters with gradual impact reduction and simulates the NPV. For both cases a period of analysis of 10 years was assumed, the year to which costs were discounted was 2015. This period was chosen to cover 10 years' projection within two Network Rail control periods (CP) ofi.e. CP5 from 2014 to 2019 and CP6 from 2019 to 2024 (Network Rail, 2018) and a discount rate (*r*) of 3.5 % (ORR, 2018) was used.

8.6.1 Using CBA with constant impact reduction

For the constant impact reduction approach two options were considered. For the first option impact reduction was assumed as constant 5% of the annual total impact value with 90% confidence (It90) whilst for the second option impact reduction was assumed as constant 10% of the annual total impact value with 90% confidence (It90) respectively. For these options it was assumed that preventive maintenance (as an added intervention to routine maintenance) would occur annually, one time per year for the first option, and twice per year for the second option respectively. The options are summarised below:

- Option 1: It90* = 5%*It90 per year every year from 2015 to 2024 (see Table 8.5)
- Option 2: It90* = 10%*It90 per year every year from 2015 to 2024 (see Table 8.6)

8.6.2 Using CBA with gradual impact reduction

According to Marquez *et al.* (2008), a potential train delay saving of 50% (10 years appraisal) can be achieved by using suitable preventive maintenance for trackside assets informed by remote condition monitoring. For the purpose of this illustration, it was assumed that appropriate preventive maintenance for drainage assets can reduce train delay time similarly. Two scenarios were considered both of which assumed preventative maintenance would occur one and twice per year; it was assumed that more frequent preventive maintenance may contribute the higher impact reduction compare to the less frequent treatment. One assumed an incremental reduction in impact of 2.5% per annum, reaching a level of 25% per annum after 10 years. The second option assumed an incremental reduction of 5% annually, reaching 50% after 10 years r. These scenarios are summarised as follows:

- Option 3: an impact reduction increasing gradually by 2.5% of the initial impact per year; for example: It90* = (2.5% * It90) in 2015 to It90* = (25% * It90) in 2024 (seeTable 8.7)
- Option 4: an impact reduction increasing gradually by 5% of the initial impact per year; For example: It90* = (5% * It90) in 2015 to It90* = (50% * It90) in 2024 (see Table 8.8)
- Option 5 no preventive maintenance

8.6.3 Calculation procedure for the CBA

For the above two cases the cost benefit analysis was carried out using the following procedures:

- Determine the types of preventive maintenance: as dicussed in Section 8.5, two risks comprising vegetation overgrowth (X25) and lack of debris clean out (X19) were considered to be undertaken blocked failure risk (RD9) at the Clay Cross Tunnel; these risks with relative high likelihood (see Chapter 7) are categorised as risks associated with maintenance factor which can be potentially carried out by the management of drainage assets. Therefore, two types of preventive maintenance were examined; these are undertake vegetation overgrowth removal' and 'debris clean out. If the insufficient routine maintenace on the assessed section has been subjected to these types of maintenance, these preventive maintenance will be treated as as additional maintennace to undertake the potential drainage risk occurring.
- Calculate the cost of the intended preventive maintenance: the cost for undertaking the vegetation overgrowth was estimated based on figures for this type of work provided by the British Railways Board (1993). It was assumed that two types of maintenance are required, such as undertake invasive scrub and cropping trees. Both require 10 man-days per quarter-mile or about 5 man-days per 200 m of homogeneous section length (one side of track). The

cost of employing a rail maintenance worker (experienced) was calculated as £28,000 per year, equivalent to £583.33 (5 days per week of work days) per week or £116.67 per day. This was based on data provided by the National Careers Service (2018). Thus the cost for one added preventive maintenance session per year was obtained by multiplication of the number of man-days for every task with its unit cost as follows:

- Vegetation overgrowth (i.e undetake invasive scrub, tree removal) =

  5 man-days * 1*£116.67 per day + 5 man-days * 1*£116.67 per day = £1166.70 for one side of track, the cost will be doubled for two sides of track=2*£1167.70= £2,333. Then, it was assumed that the company overheads are about 22% (Resor and Patel, 2002) and 15% insurance (site-safety, 2017) of the labour cost Hence, the estimation of unit cost for one time preventive maintenance per year was assumed approximately £3.197 (£2,333*1.37).
- For debris clean out, as no cost information could be found for this work, it was assumed that the requirement of man-days is similar to vegetation overgrowth, and the unit cost was calculated as £3,197.

- Calculate the annual monetary losses (risk value) without preventive maintenance of blocked C3 assets (D8) at Clay Cross Tunnel site, R90 (risk value with 90% confidence level): this value was obtained by the product (multiplication) of the probability of occurrence P90 (see section 6.4.5) by the total impact I90 (see section 7.4.2).
- Calculate the annual monetary losses (risk value) with preventive maintenance of blocked C3 assets failure (D8) at Clay Cross Tunnel site, R90*: this value was obtained by the product (multiplication) of the risk probability with planned (preventive) maintenance, P90* (see Table 8.3 and Figure 8.8) and the total impact It90* (see section 8.6.1 and section 8.6.2). The likelihood of blocked C3 assets with preventive maintenance was estimated

using Monte Carlo simulation (MCS) which was running by @Risk™ software on the spreadsheet in Table 8.3; in this estimation, it was assumed that by applying preventive maintenance, the likelihood of vegetation overgrowth (X25) and lack of debris clean out (X19) becomes 0 and then are excluded from the spreadsheet (reduction of risk likelihood).

- Calculate expected benefit as risk reduction: this was obtained from the difference of R90 and R90* (see Equation 8.4).
- Calculate the present value of the benefit as the sum of the discounted annual benefits from year 2015 to 2024 (see Equation 8.2).
- Calculate the present value of the cost as the sum of the discounted annual costs from year 2015 to 2024 (see Equation 8.5 and 8.3).
- Calculate the net present value (NPV) of every option (see Equation 8.1)

- Table 8.3 Spreadsheet for estimating the risk likelihood (by excluding vegetation overgrowth (X25) and lack of debris clean out (X19) of blocked C3 drainage assets at Clay Cross Tunnel site using @Risk ™ software

Range of number of incidents for basic event (years)	Basic event in fault tree for defective or failed channel drains and ditches for period 2007 - 2018	Code	Frequency of occurrence of basic event (fXi)			Basic event occurrence rate (λXi)			Probability *P* of one occurrence per year (Pxi)			
									x=1, t=1	x=1, t=1	x=1, t=1	x=1, t=1
			min (/ year)	mid (/ year)	max (/ year)	λmin (/ year)	λmid (/ year)	λmax (/ year)	PXi min (/ year)	PXi mid (/ year)	PXi max (/ year)	PXi (/ year)
(3)	(2)	(1)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0 - 9 in 10	Flooding from surface water	X6	0.00E+00	4.50E-01	9.00E-01	0.00E+00	4.53E-02	9.05E-02	0.00%	4.33%	8.27%	4.26%
1 in 100 - 1 in 30	Flooding from river	X7a	1.00E-02	2.17E-02	3.33E-02	1.01E-03	2.18E-03	3.35E-03	0.10%	0.22%	0.33%	0.22%
1 in 100 - 1 in 30	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	X20	1.00E-02	2.17E-02	3.33E-02	3.35E-03	6.71E-03	1.01E-02	0.33%	0.67%	1.00%	0.67%
1 in 100 - 1 in 30	Damage caused by other assets/ 3rd party assets	X40	1.00E-02	2.17E-02	3.33E-02	1.01E-03	2.18E-03	3.35E-03	0.10%	0.22%	0.33%	0.22%
										PD8_Blocked		5.37%
										PD8_Blocked_90		7.46%

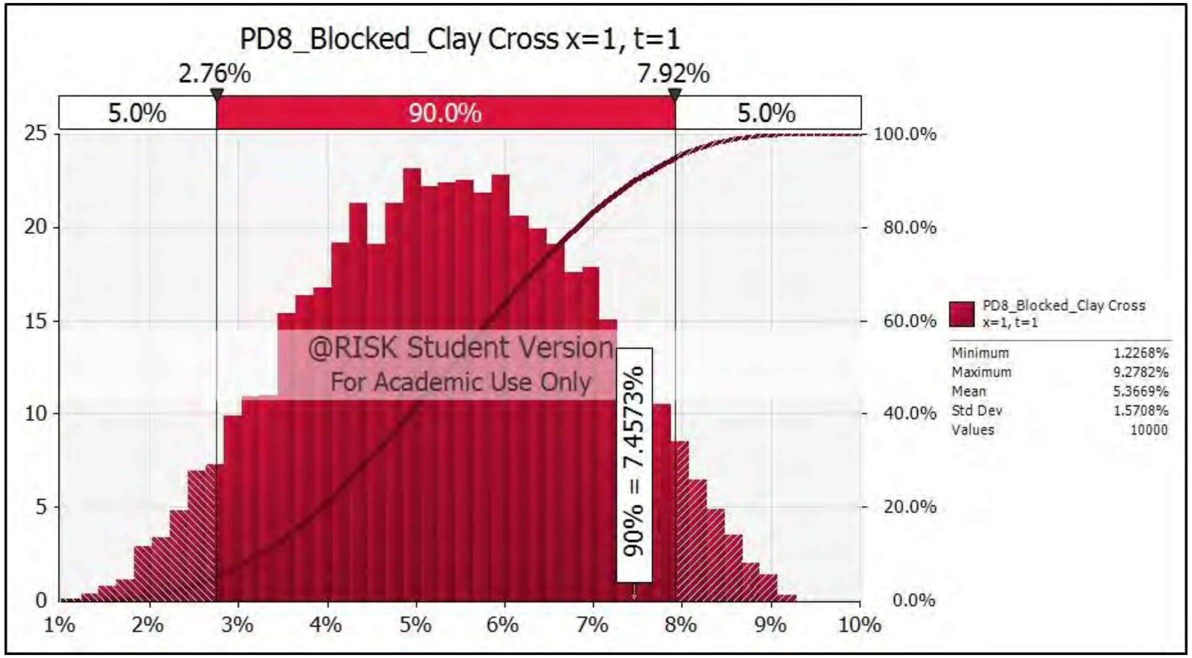

Figure 8.8 The range of likelihood of blocked (PD8) C3 drainage assets by excluding X25 and X19

8.6.4 Results of appraisal of railway drainage maintenance using the CBA approach

The results of the appraisal of railway drainage maintenance using the CBA approach are summarised in Table 8.5 for option 1, Table 8.6 for option 2, Table 8.7 for option 3, and Table 8.8 for option 4. The net present value (NPV) of the options are as follows:

- Option 1, NPV= £373,770
- Option 2, NPV= £298,009
- Option 3, NPV= £340,430
- Option 4, NPV= £231,331
- Option 5, NPV= £449,530

In terms of the NPV of risk reduction, the results show expected monetary losses; therefore, a low value of an NPV is preferable to a high value.Table 8.4 shows the summary of expected impact reduction for every option annually (excluding option 5 as base line, no preventive mainetanance)..

Table 8.4 The summary of expected impact reduction for every option annually for C3 assets at Clay Cross Tunnel

	Year										Expected impact reduction (cummulative)		
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024			
Option	1	2	3	4	5	6	7	8	9	10	Total	Total (discounted to 2015)	
1	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	50%	50%*0.73	37%
2	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	100%	100%*0.73	73%
3	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	138%	137.5%*0.73	101%
4	5.0%	10.0%	15.0%	20.0%	25.0%	30.0%	35.0%	40.0%	45.0%	50.0%	275%	275%*0.73	202%

Table 8.5 CBA for railway drainage maintenance subject to blocked failure (D8) of C3 assets at Clay Cross Tunnel site using option 1

Cost Benefit Analysis	**CBA for railway drainage maintenance - Blocked Failure (D8)**
Drainage assets	**Channel drains and dicthes (C3)**
Option 1:	**Impact reduction 5% per year (constant)**

Key Assumptions:

Discount rate	3.50%	
Appraisal period (years)	10	years
Frequency of preventive maintenance	1	time/year

Summary of the Results of the Analysis:

Present Value of Benefits	£428,801
Present Value of Costs	£55,032
Net Present Value	£373,770

P90	8.09%	It90	£645,820	
P90*	7.46%	It90*	£32,291	(5%*It90

Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Discount factor (start of year)	1.00000	0.96618	0.93351	0.90194	0.87144	0.84197	0.81350	0.78599	0.75941	0.73373
Risk value without preventive maintenance (R=P.It)	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224
Risk value with preventive maintenance (R*=P*.It*)	£2,408	£2,408	£2,408	£2,408	£2,408	£2,408	£2,408	£2,408	£2,408	£2,408
Total Benefits (R-R*)	£49,816	£49,816	£49,816	£49,816	£49,816	£49,816	£49,816	£49,816	£49,816	£49,816
Present Value of Benefits (start of year)	£49,816	£48,132	£46,504	£44,931	£43,412	£41,944	£40,525	£39,155	£37,831	£36,552
ΣPresent Value of Benefits	£428,801									
Cost 1 <undertake vegetation overgrowth>	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197
Cost 2 <debris clean out>	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197
Total Costs (start of year)	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393
Present Value of Costs (start year)	£6,393	£6,177	£5,968	£5,766	£5,571	£5,383	£5,201	£5,025	£4,855	£4,691
ΣPresent Value of Costs	£55,032									

Table 8.6 CBA for railway drainage maintenance subject to blocked failure (D8) of C3 assets at Clay Cross Tunnel site using option 2

Cost Benefit Analysis — CBA for railway drainage maintenance - Blocked Failure (D8)

Drainage assets — Channel drains and dicthes (C3)

Option 2: Impact reduction 10% per year (constant)

Frequency of preventive maintenance 2 times/year

Key Assumptions:

Discout rate	3.50%	
Appraisal period (years)	10	years
Frequency of preventive maintenance	2	times/year

Summary of the Results of the Analysis:

Present Value of Benefits	408,073
Present Value of Costs	110,064
Net Present Value	£298,009

P90	8.09%	It90	£645,820	
P90*	7.46%	It90*	£64,582	(10%*It90)

Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Discount factor (start of year)	1.00000	0.96618	0.93351	0.90194	0.87144	0.84197	0.81350	0.78599	0.75941	0.73373
Risk value without preventive maintenance (R=P.It)	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224
Risk value with preventive maintenance (R*=P*.It*)	£4,816	£4,816	£4,816	£4,816	£4,816	£4,816	£4,816	£4,816	£4,816	£4,816
Total Benefits (R-R*)	£47,408	£47,408	£47,408	£47,408	£47,408	£47,408	£47,408	£47,408	£47,408	£47,408
Present Value of Benefits (start of year)	£47,408	£45,805	£44,256	£42,759	£41,313	£39,916	£38,566	£37,262	£36,002	£34,785
ΣPresent Value of Benefits	£408,073									
Cost 1 <undertake vegetation overgrowth>	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393
Cost 2 <debris clean out>	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393
Total Costs (start of year)	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787
Present Value of Costs (start year)	£12,787	£12,354	£11,936	£11,533	£11,143	£10,766	£10,402	£10,050	£9,710	£9,382
ΣPresent Value of Costs	£110,064									

Table 8.7 CBA for railway drainage maintenance subject to blocked failure (D8) of C3 assets at Clay Cross Tunnel site using option 3

Cost Benefit Analysis	**CBA for railway drainage maintenance - Blocked Failure (D8)**
Drainage assets	**Channel drains and dicthes (C3)**
Option 3:	**Impact reduction 2.5% per year (gradual)**

Key Assumptions:

Discount rate	3.50%	
Appraisal period (years)	10	years
Frequency of preventive maintenance	1	time/year

Summary of the Results of the Analysis:

Present Value of Benefits	£395,462.28
Present Value of Costs	£55,031.81
Net Present Value	£340,430

P90	8.09%	It90	£645,820
P90*	7.46%	It90*	It90*=(2.5% * It90) in 2015 It90*=(25% * It90) in 2024

Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Discount factor (start of year)	1.00000	0.96618	0.93351	0.90194	0.87144	0.84197	0.81350	0.78599	0.75941	0.73373
Risk value without preventive maintenance (R=P.It)	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224
Risk value with preventive maintenance (R*=P*.It*)	£1,204	£2,408	£3,612	£4,816	£6,020	£7,224	£8,428	£9,633	£10,837	£12,041
Total Benefits (R-R*)	£51,020	£49,816	£48,612	£47,408	£46,204	£45,000	£43,796	£42,592	£41,388	£40,184
Present Value of Benefits (start of year)	£51,020	£48,132	£45,380	£42,759	£40,264	£37,889	£35,628	£33,477	£31,430	£29,484
ΣPresent Value of Benefits	£395,462									
Cost 1 <undertake vegetation overgrowth>	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197
Cost 2 <debris clean out>	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197	£3,197
Total Costs (start of year)	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393
Present Value of Costs (start year)	£6,393	£6,177	£5,968	£5,766	£5,571	£5,383	£5,201	£5,025	£4,855	£4,691
ΣPresent Value of Costs	£55,032									

Table 8.8 CBA for railway drainage maintenance subject to blocked failure (D8) of C3 assets at Clay Cross Tunnel site using option 3

Cost Benefit Analysis	**CBA for railway drainage maintenance - Blocked Failure (D8)**									
Drainage assets	**Channel drains and dicthes (C3)**									
Option 4:	**Impact reduction 5% per year (gradual)**									
Key Assumptions:										
Discout rate	3.50%									
Appraisal period (years)	10	years								
Frequency of preventive maintenance	2	times/year								
Summary of the Results of the Analysis:										
Present Value of Benefits	341395		P	8.09%	It90	£645,820				
Present Value of Costs	110064		P*	7.46%	It90*	I90*=(5% * It90) in 2015 I90*=(50% * It90) in 2024				
Net Present Value	£231,331									
Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Discount factor (start of year)	1.00000	0.96618	0.93351	0.90194	0.87144	0.84197	0.81350	0.78599	0.75941	0.73373
Risk value without preventive maintenance (R=P.It)	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224
Risk value with preventive maintenance (R*=P*.It*)	£2,408	£4,816	£7,224	£9,633	£12,041	£14,449	£16,857	£19,265	£21,673	£24,081
Total Benefits (R-R*)	£49,816	£47,408	£45,000	£42,592	£40,184	£37,775	£35,367	£32,959	£30,551	£28,143
Present Value of Benefits (start of year)	£49,816	£45,805	£42,008	£38,415	£35,018	£31,806	£28,771	£25,906	£23,201	£20,649
ΣPresent Value of Benefits	£341,395									
Cost 1 <undertake vegetation overgrowth>	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393
Cost 2 <debris clean out>	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393	£6,393
Total Costs (start of year)	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787	£12,787
Present Value of Costs (start year)	£12,787	£12,354	£11,936	£11,533	£11,143	£10,766	£10,402	£10,050	£9,710	£9,382
ΣPresent Value of Costs	£110,064									

Table 8.9 CBA for railway drainage maintenance subject to blocked failure (D8) of C3 assets at Clay Cross Tunnel site using option 5

Cost Benefit Analysis	**CBA for railway drainage maintenance - Blocked Failure (D8)**									
Drainage assets	**Channel drains and dicthes (C3)**									
Option 5:	**No preventive maintenance**									
Key Assumptions:										
Discount rate	3.50%									
Appraisal period (years)	10	years								
Frequency of preventive maintenance	1	time/year								
Summary of the Results of the Analysis:										
Present Value of Benefits	£449,530		P90	8.09%	It90	£645,820				
Present Value of Costs	£0		P90*	0.00%	It90*	£0	(5%*It90			
Net Present Value	£449,530									
Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Discount factor (start of year)	1.00000	0.96618	0.93351	0.90194	0.87144	0.84197	0.81350	0.78599	0.75941	0.73373
Risk value without preventive maintenance (R=P.It)	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224
Risk value with preventive maintenance (R*=P*.It*)	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
Total Benefits (R-R*)	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224	£52,224
Present Value of Risk without Benefits	£52,224	£50,458	£48,752	£47,103	£45,510	£43,971	£42,484	£41,048	£39,660	£38,319
ΣPresent Value of Risk without Benefits	£449,530									
Cost 1 <undertake vegetation overgrowth>	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
Cost 2 <debris clean out>	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
Total Costs (start of year)	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
Present Value of Costs (start year)	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
ΣPresent Value of Costs	£0									

8.7 Verification of Results

The results of the case studies (see Chapters 6, 7, and 8) were verified incorporating expert elicitation. This was arranged through a workshop with experts from Network Rail track bed team at the Birmingham office. The workshop was divided into three sessions to verify the estimations of likelihood, impact, and risk values of railway drainage failures. The results were scrutinised by the experts; they also provide insight into the results. Overall, the experts confirmed that the results are sensible and justified. The notes of this meeting are presented in Appendix 8.

8.8 Summary

Chapter 8 has described how the appraisal of drainage maintenance was utilised as a case study, to demonstrate the risk-informed framework described in Chapters 4 and 5. The case study demonstrated the applicability of the risk-informed framework as a diagnostic tool that can used to assess risks associated with poor drainage. Its use can provide insight into the identified risks, and it facilitates the identification of drainage assets at the greatest failure risk.

In terms of the case study, Clay Cross Tunnel was identified as the riskiest; whereas Ardsley Tunnel was indicated as the least risky among the selected sites when considering the score of the risk value (R) in the semi-quantitative risk analysis. Ardsley Tunnel was shown to be the least risky site because of its total impact (It) having low annual monetary losses and high likelihood of drainage failure. Clay Cross Tunnel, in comparison, was recognized to be the riskiest site, due to its high value of both probability and total impact (costs). In second place was the Draycott site; the risk score was slightly lower than for Clay Cross. The findings for

Clay Cross, Draycott, and Ardsley Tunnel are consistent with the annual delay cost calculation, which ranked Clay Cross as the highest cost, followed by Draycott and Ardsley respectively.

Further analysis on the riskiest site, Clay Cross Tunnel, identified three failure modes comprising blocked (D8), collapsed (D9), and inadequate capacity (D10) of C3 assets. Risk quantification which was used to estimate risk values of these failure modes. The results identified D8 as the highest risk value, followed by D9, and D10. Thereafter, these values were used to prioritize the failure risk and determine suitable preventive maintenance (e.g. undertake vegetation overgrowth as one type of preventive maintenance for blocked failure mode).

In terms of risk quantification, the results of the tornado graphs emphasise the contribution of both specific probability and impact parameters when risk occurs. An appraisal approach using a cost benefit analysis (CBA) was utilised along with a Monte Carlo simulation (MCS) technique for the blocked failure mode to demonstrate…. Using the CBA four scenarios for drainage maintenance of blocked drainage assets failure were explored. A barrier for adopting the proposed framework is the limitation of historical data dealing with identified risks for estimating the associated risk impacts and likelihood (probability of occurrence). Furthermore, the effectiveness of the CBA can be improved by incorporating impact reduction data (e.g. a reduction in the amount of delay after preventive maintenance has been applied).

9 DISCUSSION

9.1 Introduction

The aim of this research has been to develop a risk-informed methodology which can be used by railway track asset managers to plan appropriate railway track drainage interventions and facilitate the prioritisation for preventive maintenance of those areas of the track at greatest failure risk. To this end, the framework incorporates an engineering model to help identify risks and assign probabilities of occurrence for the risks, a cost model to determine the impacts of these events, and, an integrated model to determine risk values for the appraisal of drainage maintenance. The development of the components of the model has been described in Chapter 4. Chapters 5 to 8 demonstrated the use of the models for three case studies.

This chapter provides a critical review of the methodology followed in this research to develop the risk-informed framework.

9.2 Summary of the Research

The research carried out in this project can be summarised as follows:

1. **The development of a theoretical framework for assessing the track sections at the greatest drainage failure risk**

It was found in the literature review (Chapter 3) that a framework incorporating a risk-informed approach was appropriate to assess the risks associated with poor drainage of ballasted railway track. The framework consists of engineering, cost, and cost benefit analysis (CBA) models for the appraisal of railway drainage maintenance and is shown conceptually in Figure 4.1 Schematic research methodology.

The engineering model consists of:

i) risk identification for the total possible risk and failure mechanisms (failure modes) associated with poor drainage of ballasted railway track;

ii) estimation of the probability of occurrence (likelihood) of the identified risk.

The cost model consists of:

i) the potential impacts as adverse outcomes of the drainage failure risk occurring;

ii) estimation of the cost of the total impact.

The integrated model and appraisal maintenance consisted of:

i) risk semi-quantification which ranks and compares the identified risks;

ii) ii) risk quantification of those risks which have been ranked most highly from the risk-semi quantification process. The risk quantification process involves the multiplication of the estimated probability of occurrence by the total impact. The former is obtained using the engineering model, the latter from the cost model. The estimated risk values were used further for the appraisal of drainage maintenance using the CBA technique.

2. **The application of the theoretical framework for assessing the track sections at the greatest drainage failure risk**

The applicability and usefulness of the framework was demonstrated using three case studies which considered the drainage risks of parts of the UK's rail network. This involved:

1. Identifying potential causal events which may contribute to various failure modes (i.e. blocked, collapsed, clogged filter, and inadequate capacity of drains) which may lead to defective or failed drainage assets, through the developed engineering model.
2. Soliciting expert judgement through a workshop, questionnaires and discussions to assist with the model validation and risk identification processes.

3. Quantifying the identified risks by including their probability of occurrence (engineering model) and impacts (cost model) individually.
4. Ranking and quantifying risk values (i.e. failure modes) using the integrated model to carry out the semi-quantitative and quantitative analysis.
5. Conducting CBA for the appraisal of drainage maintenance of ballasted railway track for sections with the greatest failure risk.

9.3 Objectives of the Research

The progress made towards meeting the objectives of the research is described below (see Section 1.3).

1. Achievement of objective 1

Drainage has an essential role to remove water adequately and ensure the integrity of a railway track's substructure. Chapter 2 provides a comprehensive literature review of subsurface and surface drainage of ballasted railway track, in respect of uncertainties which might affect performance, failure modes, potential causes of failure, and the maintenance of drainage assets. Network Rail's drainage standards and discussions with key personnel from its drainage division, provided an insight into the current drainage problems in the railway industry in general and the UK's railway industry in particular.

The comprehensive literature review identified eight main risk categories, namely: (i) environmental, (ii) subgrade, (iii) design, (iv) component (material) deterioration, (v) maintenance, (vi) installation, (vii) traffic, and (viii) land use. The opinions of experienced railway drainage engineers and asset managers elicited via a workshop confirmed these categories. Each category was composed of different individual risks, see Table 4.1 to Table 4.3.

A lack of maintenance was suggested by the engineers/managers as the main reason that a drainage infrastructure asset fails.

2. Achievement of objective 2

The review investigated whether the discipline (techniques) of risk assessment can provide a suitable framework which can assist railway drainage management to assess risks. To this end, the literature review in Chapter 3 identified risk assessment as a sequential process; comprising of establishing the context and identifying, analysing, and reviewing a risk. As part of the literature review, previous studies relating to the use of a risk-informed approach were scrutinised (see Sections 3.3-3.6) to identify concepts and approaches which may be relevant to this research. The studies by Veldhuis *et al.* (2011), Ma *et al.* (2013), Tzanakakis (2013), Spink *et al.* (2014), Barnett (2015) and Usman *et al.* (2017) were found to be particularly useful to the present study, since they examine risk assessment techniques to assist the decision-making process for drainage assets' infrastructure in various fields (i.e. urban, railway station, highway, and railway). Moreover, based on the findings of the literature review, the assessment of risk in the railway industry is increasingly recognized as an important part of the asset management decision-making process. Risk analysis facilitates track asset managers to better understand the risks and offers a range of probabilistic values to be considered, instead of a single deterministic value.

The findings of the review were used to develop Figure 4.2, a risk assessment framework for railway drainage assets.

3. Achievement of objective 3

The procedure presented in Sction 5.1 shows how an engineering model incorporating a fault tree as a risk identification tool can be used by decision makers to identify causal events and failure modes, their relationships, and failure mechanisms (pathways); and categorise them into specific types of contributing factors. Thereafter, the probability of occurrence (likelihood) of identified risks are quantified using data from historical records and literature as inputs (see Sections 4.2, 4.7, and 5.2). To deal with uncertainties, the inputs which are modelled using a justified probability distribution are aggregated by carrying out a Monte Carlo simulation (MCS) to provide ranges of the estimated risks' likelihood (see Sections4.7 and 5.2).

4. Achievement of objective 4

A cost model was built in Chapter 5 which could identify and quantify potential impacts (costs) associated with poor drainage on a ballasted railway track. The cost model takes into account costs associated with unplanned maintenance; delay costs; additional passenger travel costs; alternative travel mode (usually bus) transfer costs; property (other than farming) damage costs; and farming land damage costs. The model aggregates the potential range of costs for each identified impact using an MCS technique.

5. Achievement of objective 5

An integrated model in the developed framework was built in Chapter 4 to perform a semi-quantitative and quantitative analysis. The framework uses semi-quantitative risk analysis to identify the significance of each risk, to enable the most influential risks in an assessed site to be identified. Any risk considered high or very high from the semi-quantitative risk analysis process was further investigated through quantitative risk analysis; this process was conducted to justify the parts of a railway drainage assets' network with the greatest risk.

The quantitative risk analysis component of the framework consists of three processes: (i) a process to determine the probability of a defective or failed drainage asset occurring (engineering model); (ii) impact (cost model); and (iii) risk values (integrated model), as presented in Sections 4.7 to 4.12. This theoretical framework was thereafter demonstrated through three case stuides. This is described fully in Chapters 5 to 8.

6. Achievement of objective 6

Three sites on the UK mainline railway were selected (i.e. Ardsley Tunnel, Clay Cross Tunnel, and Draycott) to demonstrate the applicability of the developed models. Ardsley Tunnel is located near Leeds, whereas Clay Cross Tunnel and Draycott are located near Derby (see Chapter 6). The selection of the sites was assisted by a senior drainage engineer who confirmed that these three sites had been affected by frequent flooding; exacerbated by poor drainage, leading to various costly social-economic impacts.

Chapter 6 describes the use of the case studies to demonstrate the engineering model, Chapter 7 shows how the cost model is used, and Chapter 8 shows how the integrated model is used to obtain risk values and to perform maintenance appraisal using CBA.

The results of the case studies clearly demonstrated the applicability of the theoretical framework, albeit further refinements of the process are recommended for future research. Knowledge was captured from a diverse range of experts in the field, who are well versed in terms of experience. Their judgment was used to validate the potential risk and was demonstrated in a case study, which considered assessing the risk of the drainage asset in respect to maintenance appraisal.

9.4 Critical Review of the Research

The methodology adopted for the development of a risk-informed framework, which quantifies the probability and impact of the identified risks for the appraisal of drainage maintenance of ballasted railway track, is discussed under the following headings:

1. Failure knowledge
2. Risk identification
3. Risk semi-quantification
4. Risk quantification
5. Cost benefit analysis (CBA)
6. The case studies
7. The developed tool

9.4.1 Failure knowledge

The developed fault trees incorporate the literature and expert elicitation in presenting the causes of blocked, collapsed, clogged filter, and inadequate capacity of drainage assets of ballasted railway track. A comprehensive understanding of railway drainage failures and how they occur was obtained from the sources of knowledge in Chapters 3 and 4. Moreover, the fault tree provides a feature of importance analysis, to seek the most influential causes based on their position in the fault tree structure (see Section 4.6.3.2). However, the causes included in these fault trees were predominantly related to the UK's rail environments; hence, for other rail environments, a restructuring of the fault trees may be required to include or exclude or provide alternative causes of failure.

The identified limitation of the developed fault trees is the assumption of causal and failure events as independent events. Consequently, the developed model did not designate dependencies between the failure mechanisms in the development of the fault tree (FT); this means the FT did not assign the interactions between failure modes (i.e. blocked, collapsed, clogged filter, and inadequate capacity). As described in Section 3.3.6, the dependency, e.g. likelihood of of a blockage if a collapse occurs. Accordingly, the likelihood of a failure event can be relatively reduced by their dependent's probability (see Eq 3.1). This means, from the impact of assuming an independent event, the likelihood outputs are relatively higher than the dependent risk. However, this condition requires dependency to be provided. Therefore, it is recommended that future work should address this aspect to improve the developed fault trees.

9.4.2 Risk identification

The method adopted for risk identification, described in Section 5.3, comprised of a literature review and canvassing expert opinion. The literature review was utilised to identify the potential risks associated with poor drainage of railway ballasted track. Thereafter, this was augmented by canvassing the opinion of a group of experts in a focus group discussion (FGD), namely a drainage workshop. The use of expert opinion on the risk identification was found to be a valuable technique to:

1. Elicit expert knowledge and experiences, where prototype techniques will be used to assess the causes of failure of railway drainage (i.e. subsurface, surface) assets.
2. Engage meaningfully the various stakeholders in model development.

Historical data (evidence-based methods (BSI, 2010)) could have been used for identifying risks and estimating their associated impact and probability, if available. The records on the drainage incidents could be used to generate an engineering model (see Section 4.7) to identify risks and estimate their probability of occurrence (likelihood). However, for the case studies, historical data was not widely available. This is likely to be the case of the majority of the UK railway network as it is aged. Instead of using historical data (i.e. incident records), a literature review and a site map of the drainage assets were used to quantify the identified risks.

For the development of the engineering model, a team of experts from Network Rail was consulted via a workshop to verify the initial list of identified risks that was gathered from the literature, to check the failure mechanisms, or to amend additional causes based on the industrial point of view. The facilitated drainage workshop allowed the experts to discuss their opinions and to share their expertise. As a result, it was possible to identify complex potential faults and incidents leading to failure risk. The workshop also helped to avoid bias, which might occur during individual consultations. It also helped to build consensus among experts through group discussion. Furthermore, these types of involvement in the risk identification process by those who are accountable for drainage asset risk and for further risk treatment actions, reinforce their responsibility and collaboration.

It might be argued that the facilitated workshop had the following difficulties:

1. resources associated with recruiting experts for a day-long workshop;
2. time required to coordinate the number of experts (, n = 11) i.e. nine from the railway industry (Network Rail) and two from academic researchers (University of Birmingham)) attending the event;
3. bringing a sufficient number of experts together (in one location) at the same time.

In this research, the opinion of the experts is designated as equally weighted. However, for further development, a variety of weightings can be considered in respect to some factors, including knowledge (e.g. academic or professional degrees), experiences, position in company or institution. This technique may help to combine expert opinion from across companies and institutions to be justified.

9.4.3 Risk semi-quantification

Where the ranking of the identified risk or prioritising the risk mitigation strategy is not important and only the quantification of the actual impacts of the risks are required, the risk semi-quantification stage can be disregarded, and the quantification stage can be carried out directly after risk identification. However, when adopting a risk assessment strategy for assessing drainage risks where there are potentially a large number of risks it was decided to include a semi-quantification stage as recommended by a number of asset management standards (e.g. ISO, 2014). This stage allows the number of risks to be analysed by a potentially time consuming quantification process to be reduced. In particular the semi-quantification process allows the ranking of the risks using a straightforward and easy to apply process.

9.4.4 Risk quantification

A review of the risk quantification process utilised in this study is presented below.

9.4.4.1 Quantification of probability of occurrence

The selection of the appropriate techniques for risk quantification depends on the criteria required for risk quantification (see Section 4.6). Herein, the combination of a fault tree (FT) and Monte Carlo Simulation (MCS) was used to quantify the probability occurrence of the identified risks. The combination of FT-MCS was chosen because it enables one to identify and interrelate the contributing factors and events which lead to poor drainage and, quantify the frequency of occurrence of the causal (risk) event(s) to estimate the likelihood of the associated risks (see Sections 3.5 and 4.7). The justification of this modelling tools is presented in Section 3.6. However, there may be other occasions (such as a well-defined system with established failure database) when other techniques could be more appropriate. The quantification of the probability of occurrence was demonstrated using case studies (see Chapter 6).

In terms of input data for the likelihood estimations, the incident data in this research was assigned for a decade (10 years) assessment. In contrast, climate change predictions or scenarios often designate into the more extended period. For further development, this possible to include when the data of a more prolonged period of observations are available concerning developing a framework induced climate change.

9.4.4.2 Quantification of total impact

The cost model uses MCS to quantify the total impact in the form of the potential monetary loss as adverse outcomes of railway drainage failure. The total impact consists of: (i) unplanned maintenance costs (ii) delay costs (iii) additional passenger travel costs (iv) alternative travel mode (usually bus) transfer costs (v) property (other than farming) damage costs (vi) farming land damage costs (see Section 4.8). For the case studies, (iii), (iv), and (vi) were excluded from the estimation due to the absence of these impacts in historical data (see Chapter 7). The total impact was calculated based on historical data (see Appendix 4) and broad information provided in the literature, e.g. ORR (2013), Penning-Rowsell *et al.* (2013). Consequently, it is recognised that the values so obtained may not be exact for the site at hand. However, in practice it likely that the drainage engineer on site will have more accurate actual unit cost and estimations provided by the rail operator and maintenance contractor). This will allow for a more accurate estimate of the cost risks.

Moreover, a delay with speed restrictions was included in the estimation of the total impact. It was assumed that a speed restriction had been arranged when flooding reached a specific water level (e.g. above the rail head). This decision was made to reduce the train speed for safer operation. Based on this assumption, the derailment risk, which may associate with speed and track condition factor, was not considered.

9.4.4.3 *Quantification of risk values*

The integrated model used MCS to quantify risk values based on both risk parameters (i.e. the probability of occurrence and cost impacts). The results obtained from risk quantification on the case studies can be used by decision-makers to determine the riskiest site and the most likely failure mode. This information is potentially valuable for prioritising the allocation of maintenance resources. It is recognised that MCS is not conceptually straightforward to grasp, the results require interpretation and that specialist software (i.e @Risk^{TM}) is required to run the MCS. This software also requires a licence to be purchased for each person using the software (in the order of several thousands of pounds). Therefore, in order for the practical implementation of model proposed herein, training will need to be provided in using MCS and interpreting the results produced by the software. This will need to be provided either to track engineers or to specialist risk managers.

9.4.4.4 *Tornado charts' analysis*

Tornado charts were produced for risk likelihood and values to identify the track sections and parts of a site most at risk of failure. It can be used to compare the relative importance as well as the impact of input variables with a high degree of uncertainty to those are less important or negatable. The tornado charts displayed the inputs of risk parameters (i.e. likelihood, impacts); they are ranked in order of greatest influence on the overall risk value (cost). The findings of the case study (i.e. Clay Cross Tunnel) show that the probability of occurrence of risks related to the environmental factor (i.e. X6 (flooding from surface water) had the greatest influence on the overall risk. The other factors affecting the occurrence, in order of influence, are risks associated with maintenance factors (i.e. vegetation overgrowth (X25), a lack of debris clean out (X19)) and damage caused by other assets/3rd party assets (X40). This was due to the frequent flooding incidents involving these risks as recorded from 2009 to 2018 (see Appendix

4). However, the charts also indicated that damage to non-residential areas (depot) (I_{53}) also had influence as a risk parameter (impact); this was due to a potential area that may be affected by this risk.

9.4.5 Cost Benefit Analysis (CBA)

The CBA utilized the net present value (NPV) to assess the risk costs and benefits of the worthiness of preventive maintenance to tackle the identified risks over a specific appraisal time (i.e. 10 years). The cost is associated with the required preventive maintenance; whereas the benefit is associated to the total impact (cost) reduction (total impact (cost) without preventive maintenance – total impact (cost) with preventive maintenance); both these parameters (i.e. cost, benefit) are required to calculate the CBA values.

As discussed in Section 8.6, a cost benefit analysis (CBA) was used to evaluate appraisal values, namely the net present value (NPV). The NPV technique was used as a method to appraise the preventive maintenance costs and benefits of an impact reduction in monetary terms. The NPV was chosen because it can be used to rank failure modes in terms of impact reduction by considering the preventive maintenance. The NPV technique requires a discount rate to be used. Herein a single discount rate of 3.5% (ORR, 2018) was used for the purposes of the case study. However, it is acknowledged that different results may have been obtained had different discount rates and unit costs been used.

9.4.6 The Case Studies

As discussed in Chapter 6, the study areas were located near Leeds (Ardsley Tunnel) and in Derbyshire (Clay Cross Tunnel and Draycott). These sites were chosen as they contained warehouses, power units, a field, land for further development and dense areas of residential properties. Digital mapping on the study area was completed in 2013 (Appendix 4), with railway incidents' data available in electronic format. The accuracy of the data was confirmed by the senior drainage engineer. The developed tool was successfully demonstrated using the case study area. Based on the questionnaire and discussion with senior drainage engineer, the availability of risks and detailed information of the selected sites was not typical. Hence, the proposed framework can be applied to any site and will benefit from such a comprehensive data set that may updated or improved. In terms of future development, since drainage assets are made from a variety of materials which deteriorate at different rates, are of varying ages and of unknown maintenance history, a numerical model of the deteriorated drainage assets could be used to more precisely calculate the likelihood of failure. Such information will improve inputs of the developed engineering model.

9.4.7 The developed tool

The procedure presented in Section 4.6 shows how an engineering model incorporating fault trees can be used by decision-makers as a diagnostic tool to identify the risks associated with poor subsurface and surface railway drainage and quantify failure probabilities (likelihood). It also reveals potential failure modes and relative rankings of their failure contributors. The features of the developed tool show great potential as a research tool. Firstly, it offers insight of the assessed drainage asset by providing the range of failure likelihood. Secondly, as shown in Sections 8.5, it can be used as a tool for proactive approach to reduce potential incident frequencies. These features are potentially valuable to facilitate asset managers to review the failure likelihood of drainage assets in the wider and complex rail network.

Since the developed framework also incorporates cost and integrated models, these can be used to examine various impact scenarios and their associated costs and risk values (i.e. probability multiplied by impact) of the assessed homogeneous section in respect to rank and prioritise appropriate interventions for the riskiest site and most likely failure mode. The tool can also be further developed to assess drainage failure risks for an entire network level by providing a drainage risk database. This feature will provide information associated with railway drainage risk in wider perspective and assist a more reliable decision to be made when comparing various risk values of the assessed sites within the network. The most challenging part of such a development would be assigning the frequency of occurrence of drainage risks continuously.

In addition, the appraisal feature in the developed model can be used as a rational and transparent approach to help asset managers to argue for an allocate scarce resources for preventive maintenance. This feature incorporates benefit (B) and cost (C) values in its calculation; benefit was assumed as a result of risk values reduction in various scenarios whereas cost was appointed to cost of preventive maintenance. Thus, the B value depends on probability (P') and total impact (It') reduction for various scenarios (see 8.5). However, since the impacts reduction data (e.g. reduction of delay minutes) after applying preventive maintenance were not available, it was challenging to measure the effectiveness of the interventions. This was foreseen during the development of the tool and can be improved in any implementation when the required data is available.

9.5 The Applicability of the Tool for industry

The developed tool can assist asset managers to plan appropriate railway track drainage interventions, by facilitating the prioritisation of preventive maintenance of those areas of the track at greatest failure risk. Accordingly, the tool can be positioned on the second out of three levesl of drainage asset management hierarchy (see Figure 2.2 in Section 2.2.2). In industry, Network Rail is currently exploring solutions to improve decision making within the asset management of railway drainage systems in two stages. To this end, decision support tools capable of modelling scenarios at a system level is being considered to aid business planning (see Appendix 9). The aim is firstly, to develop a bottom-up decision support tool by CP6 (2019-2024) and secondly, to establish a top-down whole life cycle and cost model for drainage by CP7 (2024-2029). However, the development of NR tools is still at infancy. The risk-informed framework developed within this research can potentially be adopted for the effective management of railway drainage assets

9.6 Value of the Research

The principal value of the research is the development of a risk-informed tool that can facilitate decision makers to assess drainage asset failure risk. As there are barriers to assess the drainage asset failure risk (e.g. limitation of historical data), such a tool should therefore help to facilitate decision makers (e.g. railway asset managers) to argue for funds and allocate the paucity of resources available for drainage asset maintenance. The former is particularly important since drainage asset management is often seen in the industry as unimportant compared to the management of other types of railway infrastructure. A tool which allows the impact of failure of drainage assets to be quantified, such as that proposed herein, can help to address this anomaly.

A risk-informed framework for the appraisal of drainage assets with the greatest failure risk was not evident in the literature, despite the need for such a framework being identified therein (DfT, 2014). The literature identified one study that had used a probabilistic fault tree to estimate the likelihood of urban water infrastructure flooding by using mainly incident data from municipal call centres (Veldhuis *et al.*, 2011). However, the study did not investigate the incidents severity and did not facilitate preventive intervention.

Of additional value to the industry has been the development of the failure charts (i.e. Engineering model, see Chapter 5). As far as Network Rail is concerned, this allows its drainage engineers for the first time to relate failure modes to the causes of failure. As such it facilitates the identification of appropriate preventative maintenance.

9.7 Summary of the Discussion

This chapter has reviewed the research methodology adopted in this research for the development of a risk-informed framework which can be used to asses railway drainage assets at the greatest risk of failure. In particular, the effectiveness of the framework and its associated techniques and software, and assumptions made throughout the research were discussed.

The usefulness and involvement of expert elicitation for risk identification and model validation, using a focus group discussion (FGD) via a drainage workshop, a questionnaire, interviews for the case studies, and results verification, was discussed.

The applicability and advantages of the tool was discussed in the particular context of the case study, and where appropriate, suggestions made to enable improvements to the tool to be affected in future work. The tool utilized a recognized risk-informed approach as an appropriate framework to use in assessing the risks associated with poor drainage of ballasted railway track. The tool incorporated the risk assessment process and cost benefit analysis (CBA).

Moreover, suggestions have been offered to facilitate future developmental work and improvements to the framework to utilise it as a tool for assessing and maintaining drainage assets. Examining risk parameters (i.e. likelihood and impact) after the implication of preventive maintenance was also discussed. The latter was suggested to consider the likelihood of excessive deterioration of drainage assets (i.e. subsurface and surface) by developing a numerical model, rather than using historical incident data alone. Conclusions from the research, together with recommendations for future research, are presented in the following chapter.

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Accomplished Work

The work presented in this thesis may be regarded as a first stage in the development of a risk-informed tool to facilitate railway asset managers to enable the prioritisation of preventive maintenance of drainage assets at greatest failure risk.

The research has demonstrated the objectives outlined in Chapter 1 by:

1. Exploring the risks associated with poor subsurface and surface drainage of ballasted railway track, through a review of the causes, failure modes (and pathways) and contributing factors (see Chapter 2).
2. Exploring the viability of risk-informed techniques for the proposed tool (see Chapter 3).
3. Developing an engineering model, to identify the causal factors for drainage asset failure, and to quantify the probabilities of the occurrence (likelihood) of railway drainage risk (see Chapters 4, 5, and 6).
4. Developing a cost model to quantify socio-economic impacts of railway drainage risk (see Chapters 4, 5, and 7).
5. Developing an integrated model to quantify risk values by combining the models from items 3 and 4 above. The integrated model, incorporating an economic appraisal approach, enables the prioritisation of preventive maintenance of drainage assets at the greatest failure risk (see Chapters 4, 5, and 8.)
6. Demonstrating the developed framework using data collected from three sites on parts of the UK's railway network (see Chapters 5, 6, 7, and 8).

10.2 Conclusions

The key conclusions of the research are as follows:

- A risk-informed framework is suitable for identifying and quantifying the risks associated with poor (failed) drainage of ballasted railway track.
- The appraisal approach is suitable for prioritising the preventive maintenance of drainage assets at greatest failure risk.
- In order for the tool to be able to assess the drainage risks in network levels, its further development needs to incorporate risk mitigation, a risk database and mapping, and interdependendent failure modes.

10.3 Findings

It was found that the various modelling processes to perform the risk-informed framework may be implemented successfully using the following knowledge and techniques:

10.3.1 Failure knowledge

A variety of factors contribute to poor subsurface and surface drainage of ballasted railway track, as discussed in Chapter 2. The factors can be categorised as environmental, subgrade, design, component (material) deterioration, installation, maintenance, traffic, and land use. Moreover, a combination of these factors and their associated risks may lead to various failure modes, including blocked, collapsed, inadequate capacity, and clogged filter media of subsurface and surface drainage assets.

10.3.2 Suitability of selected sites and historical data for the case studies

As noted in Section 6.3 the developed tool was successfully demonstrated using three selected case studies (i.e. Ardsley Tunnel, Clay Cross Tunnel, and Draycott). The suitability of the selected sites was confirmed by a senior asset engineer (drainage) due to: (i) a frequent flood risk from surface water (heavy rainfall) had been recorded in the last 10 years (2009–2018); (ii) the fact that they represented both types of railway track, i.e. Ardsley and Clay Cross Tunnel were built on earthworks cutting, Draycott was built on non-earthworks track; (iii) historical data (i.e. incidents data, map of drainage assets).. However, the historical data was limited and did not cover all identified risks; whereas the frequency of occurrence of the remaining risks relied on assumptions based on the literature. It is therefore this data which needs to be updated when available, to avoid an over or under-valued estimation.

10.3.3 Expert elicitation

Canvassing expert elicitation was shown to be a viable means of validating and identifying potential risks and impacts. This elicitation was used on three occasions as follows (see Sections 4.1, 5.6, and 6.2.5):

1 Firstly, a focus group discussion (FGD) was found to be a useful means of eliciting expert opinion to validate risks within the proposed fault tree structures.

2 Secondly, a questionnaire allied to a discussion involving a drainage expert was found to be useful to provide insight into drainage assets in the selected sites and identify their risk (availability). This approach of involving an expert worked well. It may be regarded that the interaction between the drainage expert and the risk analysis expect which took place during this process may be similar to that which might happen in practice. The information provided to the expert seemed to be sufficient to allow the expert to provide adequate information to the risk analysis to allow for the developed tool to be populated and provide sensible results. This tends to confirm the validity of the proposed expert elicitation approach.

3 Thirdly, a verification of the outputs of risk parameters estimation (i.e. likelihood, impact, and risk value) and maintenance appraisal involving experts from track bed team was found

to be useful to provide insight into the estimated parameters in respect to current problems in the UK railway drainage (e.g. blockages failure modes on cutting site, maintenance decision for the 'high importance routes. The experts confirmed that the results are sensible and justified, and the outputs provided an indicator to measure how risky a drainage asset is, and which failure modes and maintenance interventions should be undertaken.

10.3.4 Risk identification and semi-quantitative analysis

In this research, an engineering model incorporating a fault tree and a contributing factor diagram was found to be an appropriate approach; by means of linking logically failure (the undesired event), failure modes and their causal events. The model has successfully deconstructed drainage failure into failure modes and causal (risk) events. There are 46 basic events, 49 mid events associated with poor drainage of ballasted railway track (see Table 4.1 to Table 4.3). These risks have been validated (i.e. position in the proposed fault structure, risk items) during the FGD session at a drainage workshop at the University of Birmingham, involving nine experts from Network Rail (drainage division) and academics from the Department of Civil Engineering at the University of Birmingham. Moreover, a preliminary assessment using an importance analysis based on a generic fault tree structure found train loads (i.e. dead, live) to be likely contributors to substructure drainage (i.e. pipes, catchpits and manholes); whereas weak underlying soil (subgrade) and a variety of floods are likely to affect both subsurface and surface drainage (i.e. channel drains and ditches, outfall, culvert) failure.

In terms of case studies, a semi-quantitative analysis was used to rank the risk values of failed or defective channel drains and ditches (C3). It was found that the riskiest site was Clay Cross Tunnel, followed by Draycott, and Ardsley Tunnel. It was also found that blocked C3 assets were more likely to occur, compared to collapsed and inadequate capacity, respectively. Based on this, further assessment needs to be conducted using quantitative analysis to provide suitable risk information for decision-makers.

10.3.5 Quantitative analysis using Monte Carlo simulation

As a well-known technique, a Monte Carlo simulation (MCS) was found to be appropriate for risk quantification within the proposed framework. It enables the estimation of the range of probability (likelihood) of an event occuring (determined through the engineering model), and the range of possible impact (determined through the cost model) to be combined to determine risk values (integrated model). It was found that the quantification of engineering, cost, and integrated models was able to provide the range of probability of occurrence, total impacts, and risk values with a variety of levels of confidence (see Chapter 6, 7, and 8).

In terms of the cost model, six main impact categories of drainage failure were identifed from the literature (see Section 2.7). These are unplanned maintenance costs, delay costs, additional passenger travel costs, alternative travel mode (usually bus) transfer costs, property (other than farming) damage costs and farming land damage costs.

It was also found that one feature of MCS, namely the tornado graph, was useful to assess the influental causes contributing to the likelihood of drainage failure risks, their impacts and risk values.

10.3.6 Appraisal of drainage maintenance

Cost benefit analysis (CBA) under uncertainty (i.e. incorporating risk values), was found to be an appropriate approach to enable the prioritisation of preventive maintenance of drainage assets at greatest failure risk.

With further engagement of the management of drainage assets, the developed framework will enable the provision of a deeper insight into the risks associated with poor railway drainage, as well as mitigation responses.

10.4 Recommendations for Further Research

While the results presented in Chapters 6 to 8 have demonstrated the capability of the framework, to further develop and improve it for practitioners, the following additional research is recommended:

10.4.1 Developed fault trees

Despite the comprehensive model development presented in Chapter 4, it is possible that an exhaustive list of failure may cause may not have been identified. The generic model included various potential failure causes; however, an analysis of a higher number of drainage assets networks may further identify other causes. Moreover, it is recommended that the interactions between the failure modes in the failure trees be considered.

10.4.2 Improvements to the data

A database of the historical occurrence of drainage risks would enable the refinement and improvement of the risk parameters used in the developed tool. Such a database would include: risk likelihood for subsurface and surface drainage failure; impacts to the surrounding area when a risk occurs; and risk mitigation, such as reduction of risk likelihood and impact after the occurrence of preventive maintenance. In addition, the risk database could be further developed by incorporating a digital map of drainage assets to provide their risk levels.

10.4.3 Deterioration model for railway drainage assets

As described in the engineering model, the deterioration of drainage assets was found to be one of the contributing factors to drainage risk. The likelihood of this risk was estimated based on the assets' service life. However, these assets are made from a variety of materials which deteriorate at different rates, are of varying ages and have unknown maintenance history. Therefore, a numerical deterioration model could potentially improve the developed tool, as it would enable the remaining life of the drainage assets, and therefore their likelihood of failure, to be better quantified.

10.4.4 Appraisal of drainage maintenance based on actual cost

In terms of the appraisal process, a benefit was assumed to be equal to the monetary value of risk reduction. To improve this, an actual record of impact reduction could be obtained, along with actual quotations and cost estimations of preventive maintenance from engaged contractors where possible.

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APPENDIX 1 Publications

Publications

1. Usman, K, Burrow. M.P.N, Ghataora. G.S, Sasidharan. M (2019) Using Probabilistic Fault Tree Analysis and Monte Carlo Simulation to Examine the Likelihood of Risks Associated with Ballasted Railway Drainage Failure, **Journal of Transporation Research Record** (Under review)
2. Usman, K., Burrow, M.P.N., Ghataora, G.S., Sihota, M. (2019) Identifying Risks Associated with Poor Drainage of Ballasted Railway Track Using Expert Elicitation: Case Study at the Ardsley Tunnel Site **Proceedings of the Railway Engineering 2019**, July 3-4, 2019, Edinburgh, UK.
3. Usman, K, Ghataora, G.S., Burrow, M.P.N., Sihota, M (2017) Fault Tree for Poor Drainage Mechanisms of Railway Ballasted Track. **Journal of Permanent Way Institution** (PWI), October 2017. Volume 135. Part 4.
4. Usman, K., Burrow, M., Ghataora, G.S. (2015) Railway Track Subgrade Failure Mechanisms Using a Fault Chart Approach. **Procedia Engineering Elsevier**, 125: 547-555

APPENDIX 2 Focus Group Discussion (FGD) ThroughDrainage Workshop

Drainage Workshop

Presentation (A2-1)

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Workshop :

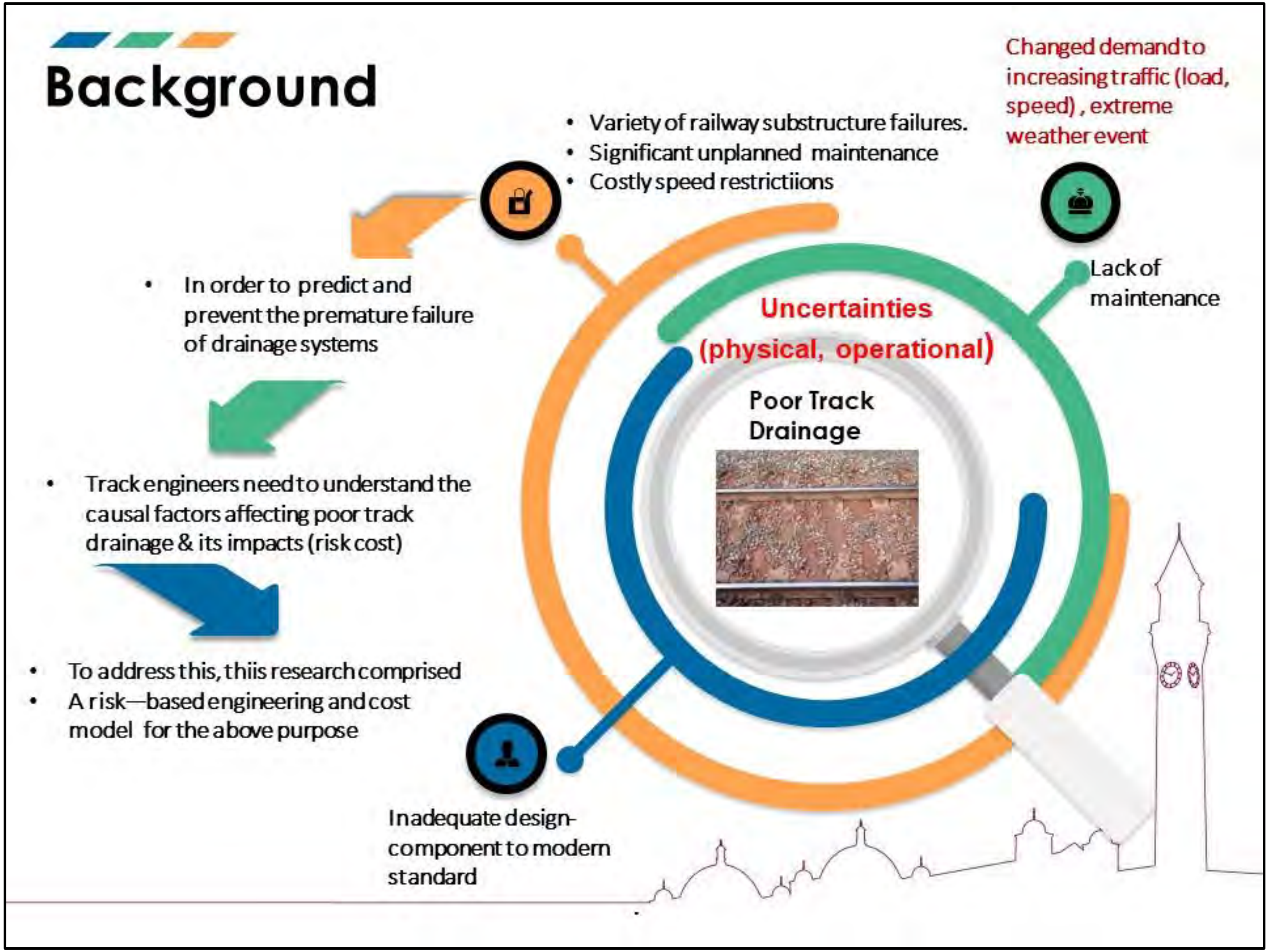
The Development of a Risk-Based Assessment Framework for the Appraisal of the Maintenance of Railway Ballasted Track Drainage

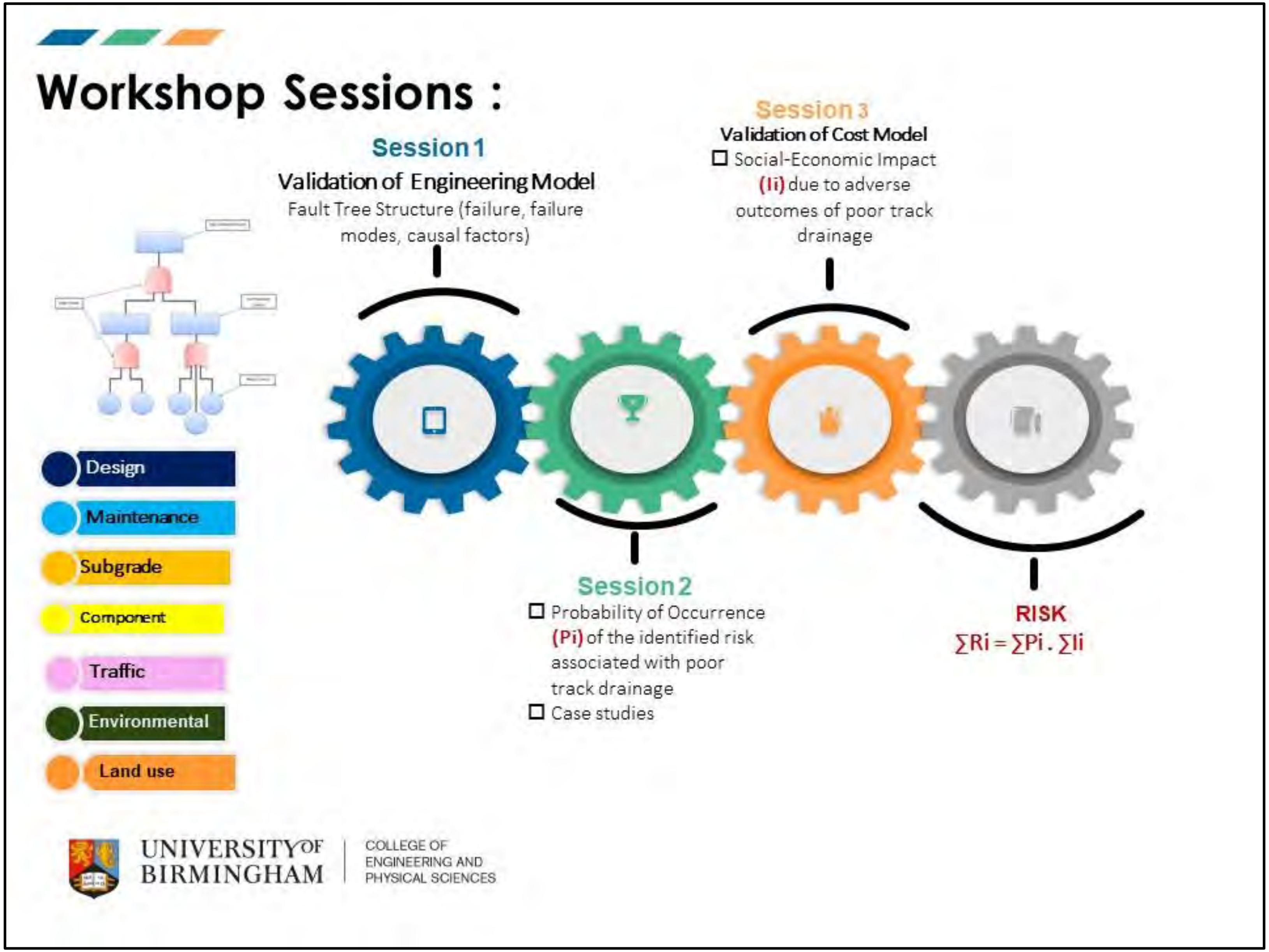
Kristianto Usman *– PhD Researcher University of Birmingham*

Supervisors :

M.P.N. Burrow *– Senior Lecturer University of Birmingham*

G.S. Ghataora *– Senior Lecturer University of Birmingham*


Background
Changed demand to increasing traffic (load, speed) , extreme weather event
Variety of railway substructure failures.
Significant unplanned maintenance
Costly speed restrictiions
In order to predict and prevent the premature failure of drainage systems
Lack of maintenance
Uncertainties (physical, operational)
Poor Track Drainage
Track engineers need to understand the causal factors affecting poor track drainage & its impacts (risk cost)
To address this, thiis research comprised
A risk—based engineering and cost model for the above purpose
Inadequate design-component to modern standard



Workshop Sessions :
Session 1
Validation of Engineering Model
Fault Tree Structure (failure, failure modes, causal factors)
Session 2
Probability of Occurrence (Pi) of the identified risk associated with poor track drainage
Case studies
Session 3
Validation of Cost Model
Social-Economic Impact (Ii) due to adverse outcomes of poor track drainage
RISK
∑Ri = ∑Pi . ∑Ii
Design
Maintenance
Subgrade
Component
Traffic
Environmental
Land use
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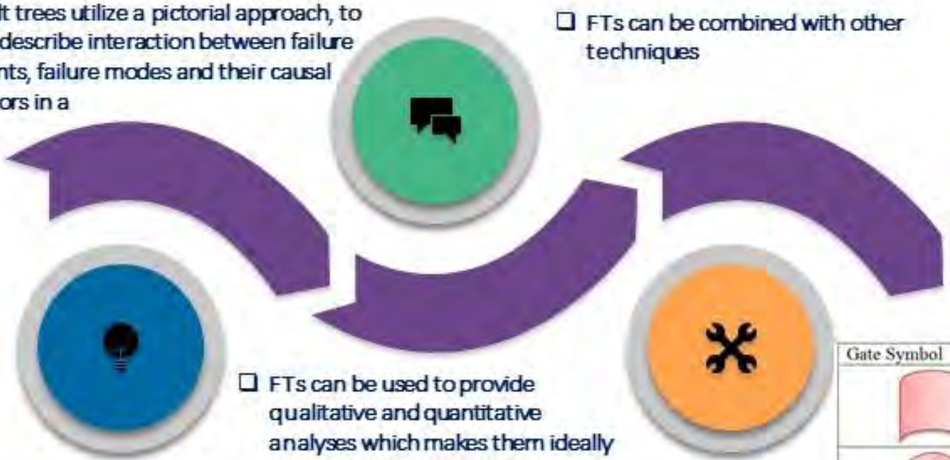
Fault Tree (FT)

The Fault Tree (FT) approach was used for the analysis of drainage failure as it was felt to offer the following specific advantages (BSI, 2010):

- ❑ Fault trees utilize a pictorial approach, to the describe interaction between failure events, failure modes and their causal factors in a
- ❑ FTs can be combined with other techniques
- ❑ FTs can be used to provide qualitative and quantitative analyses which makes them ideally suited to scrutinise railway infrastructure drainage failure where numerical failure data and expert opinion is likely to be required.



Gate Symbol	Name	Causal Relation
	OR	Output event occurs if any one of the input events occurs
	AND	Output event occurs if all input events occur
	BASIC	Basic event for which failure data is available.
	INTERMEDIATE EVENT	System or component event description
	TRANSFER	Indicates that this part of the fault tree is developed in a different part of the diagram or on a different page.

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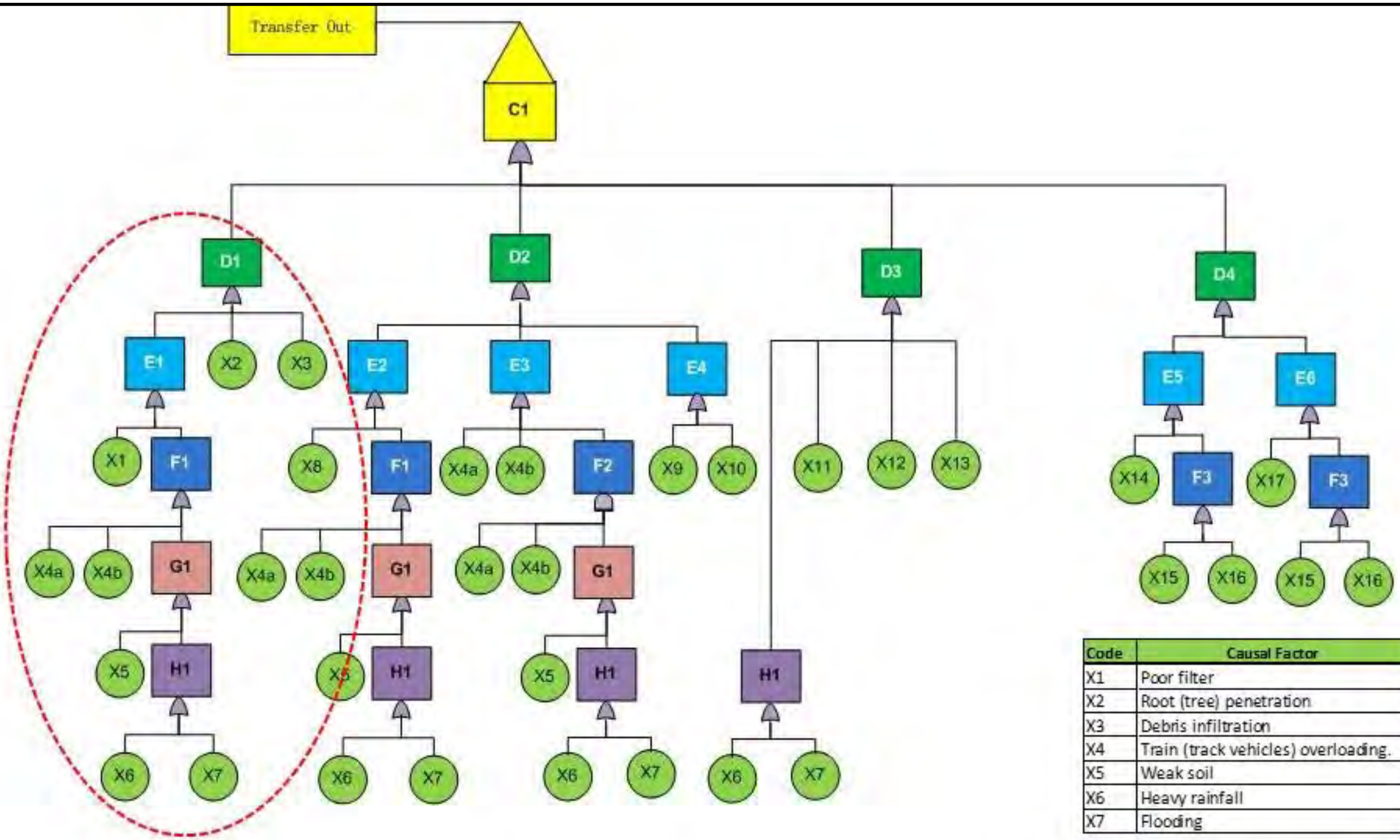

Code	Causal Factor
X1	Poor filter
X2	Root (tree) penetration
X3	Debris infiltration
X4	Train (track vehicles) overloading.
X5	Weak soil
X6	Heavy rainfall
X7	Flooding

C1.Failure/ Deffective Pipe Sub-Fault Tree Chart

Code	Causal Factor
H1	Extreme climate event
G1	Softening below drain level
F1	Settlement (change of gradient)
E1	Silting pipe
D1	Blocked pipe

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Boolean Algebra for Poor Track Drainage Fault Tree

$$P(A1) == P(B1) \cup P(B2) = P(B1) + P(B2) = P(C1) + P(C2) + P(C3) + PC4) + P(C5) \ldots \quad (1)$$

Boolean Algebra for Failure/ Deffective Pipe Sub-FT

$$P(C1) = P(D1) \cup P(D2) \cup P(D3) \cup P(D4) = P(D2) + P(D2) + P(D3) + P(D4) \ldots \quad (2)$$

$$P(D1) = P(E1) + P(X2) + P(X3) = P(X1) + P(F1) + P(X2) + P(X3) \ldots \quad (3)$$

$$P(D2) = P(E2) + P(E3) + P(E4) = P(X8) + P(F1) + P(X4a) + P(X4b)$$
$$+ P(F2) + P(X9) + P(X10) \ldots \quad (4)$$

$$P(D3) = P(H1) + P(X11) + P(X12) + P(X13) \ldots \quad (5)$$

$$P(D4) = P(E5) + P(E6) = P(X14) + P(F3) + P(X17) + P(F3) \ldots \quad (6)$$

$$P(F1) = P(X4a) + P(X4b) + P(G1) = P(X4a) + P(X4b) + P(X5) + P(H1) \ldots \quad (7)$$

$$P(F2) = P(X4a)*P(X4b)*P(G1) = P(X4a)*P(X4b)*(P(X5) + P(H1)) \ldots \quad (8)$$

$$P(F3) = P(X15) + P(X16) \ldots \quad (9)$$

$$P(H1) = P(X6) + P(X7) \ldots (10)$$

$$P(C1) = (P(X1) + P(X2) + P(X3) + 3*P(X4a) + 3*P(X4b) + P(X4a)*P(X4b)*(P(X5) + P(X6)$$
$$+ P(X7)) + 2*P(X5) + 3*P(X6) + 3*P(X7) + P(X8) + P(9) + P(10) + P(X11) +$$

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No. (1)	Source (2)	Pathway (3)	Direct Outcome (DO) Impact on Track Performance (4)	[illegible] (5)	Indirect Outcome (IO) Impact on Operational Performance Result (Economic) (6)	Impact to Maintenance Cost (Economic) (7): Track Drainage (7.1)	Track Support System (7.2)	Receptors (8)
1	Failure/ defective	Water leaking from the pipe or water seeping	Subgrade softening and ballast		Speed restriction	Pipe repair	Track level (geometry) adjustment	Track Owner (DO, IO)
	pipe	in the track bed and may infiltrate subgrade	pocket (ballast depressed into overstressed			Pipe replacement	Tamping	(i.e Network Rail)
a	Blocked pipe		subgrade due to repetitive loading and		Delay times and cost	Water jetting	Ballast compaction following tamping	Train Operator (IO)
b	Collapsed pipe		facilitate water ponding) lead to track				Stoneblower	Passengers (IO)
c	Filter Media Problem on		deformation or track subgrade failure		Additional daily transport cost	Ballast pocket treatment:		
	Surrounding Pipe				for passengers	Install lateral carrier drain	Formation treatment	
d	Capacity problem				(taking bus or another train)	to remove water from ballast pocket		
	(Hydraulic Surcharging)		Ballast fouled by upward pumping				Ballast cleaning / undercutting	
			/ jetting action (mud pumping) from		Additional time and cost to reach the		-Partial depth clean	
			soft subgrade and infiltrate the ballast layer.		passenger destination		-Shoulder clean	
							-Full depth clean	
					Environmental cost for vehicles			
					emissions (bus)		Ballast renewal	
2	Failure/ defective	Water may flooding into the ballast layers	Wet ballast or ballast wash out			Catchpits & manholes repair		
	catchpits and manholes	from the catchpits and or manholes	, reduce its interlocking (stiffness) and lead		Environmental cost for pollution	Catchpits & manholes replacement		
a	Blocked catchpits and manholes		to track deformation		induced by railway spill during flood event			
b	Collapsed catchpits and manholes							
c	Capacity problem of catchpits				Cost for bus operation			
	and manholes (hydraulic surcharging)							
					Flooding to the surrounding area			
3	Failure/ defective	Water may flooding into the ballast layers	Wet ballast or ballast wash out			Vegetation removal		
	channel drains and ditches	from the channel drain and ditches	, reduce its interlocking (stiffness) and lead			Ditching and grading		
a	Blocked channel drains and ditches		to track deformation			Channel drain and ditches repair		
b	Collapsed channel drains and ditches					Channel drain and ditches replacement		
c	Capacity problem of channel drains							
	and ditches (hydraulic surcharging)							
4	Failure/ defective	Water may return to the outfall and	Wet ballast or ballast wash out			Outfall repair		
	Outfall	flooding into the ballast layers	, reduce its interlocking (stiffness) and lead			Outfall replacement		
a	Blocked outfall		to track deformation					
b	Collapsed outfall							
c	Capacity problem of outfall							
	(hydraulic surcharging)							
5	Failure/ defective	Water spill out from the culvert and	Embankment or cutting slope			Install cut off and horizontal drains	slope remediation	
	Culvert	infiltrate the embankment or cutting slope	softening lead to track deformation					
a	Blocked culvert		or earthworks failure			Cleaning completely	Soil improvement	
b	Collapsed culvert					or partially plugged culverts.		
d	Capacity problem of culvert					Replacement or repair of undersized and	Ballast renewal to solve the ballast pocket	
	(hydraulic surcharging)					damaged culverts.	problem in the embankment	

TIc (Total Impact Cost)=

$\sum_{i=1}^{n}(UMci + PMci)$ **+ TDc + PTRc+PTIc + Ec + Bc**

Impacts (cost) for rail owner subject to maintenance allocation

-Operating & Maintenance (track) :

Where, $\sum_{i=1}^{n}(UMci + PMci)$

UMci : Unplanned maintenance cost

Pmci : Planned maintenance cost

Impacts (cost) as compensation for TOC (Train Operator Company)

Total Delay Cost x Delay cost perminute

$$TDc = \sum_{i=1}^{n} Di * Delay\ cost\ perminute$$

Impacts (cost) as compensation for Passengers

- -Passenger compensation from TOC
- -Additional travel cost (time delay to intended station destination, crowd, mode/route change)

PTRc : Percentage of additional travel cost x Average daily travel cost x Average daily number of passengers on the incident line

PTIc : Passenger additional time cost = additional time to recach the intended destination x average unit cost of wages perhour

Impacts (cost) as environmental cost for vehicle emission

Ec : Total (bus x number of trips) x distance x environmental cost per km

TABLE 2

Environmental Cost of Transport

Pence (1999) per passenger kilometre

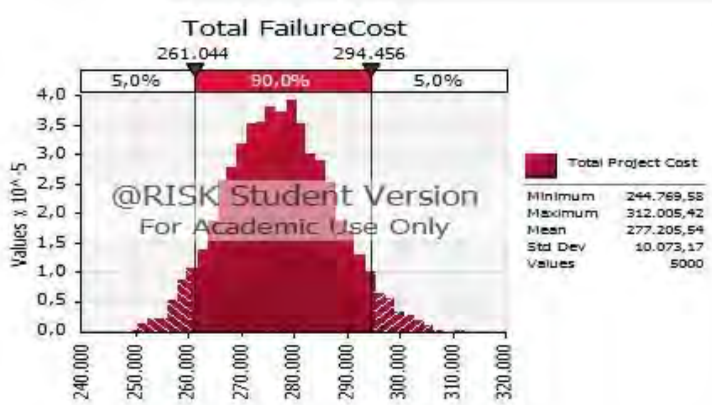
	Roads			*Railways*
	High	Central	Low	
Noise and vibration	0.58	0.47	0.26	0.35
Air quality	1.06	0.83	0.61	0.18
Climate change	0.56	0.35	0.19	0.26

Source: Railtrack, 2000. The source used for the calculations in this publication is European Conference of Ministers of Transport (1998).

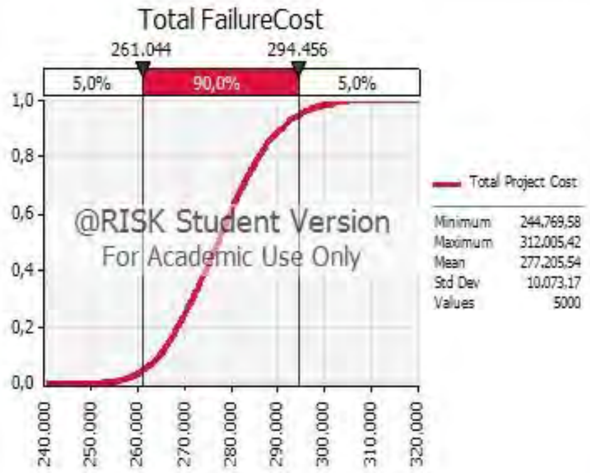
Impacts (cost) as additional cost for bus operation

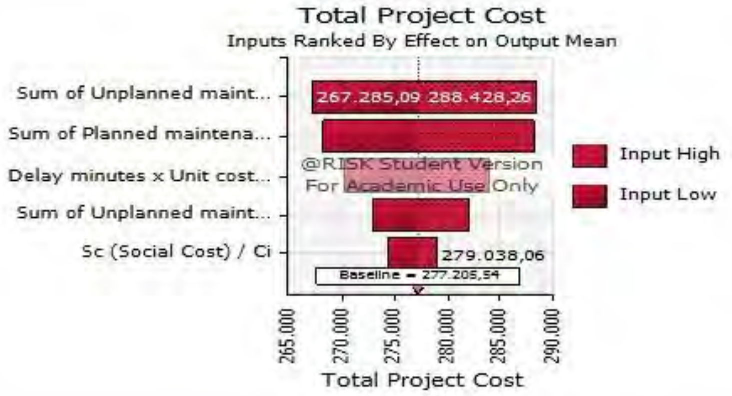
Bc : Total (bus x number of trips) x distance x operational cost of bus per km

Cost elements	Base Case	Minimum	Most Likely	Maximum	Minimum	Most Likely	Maximum	Ci	Assumption
Sum of Unplanned maintenance cost type 1	100.000	90%	100%	125%	90.000	100.000	125.000	102.500,00	Pert Distribution
Sum of Unplanned maintenance cost type 2	50.000	90%	100%	125%	45.000	50.000	62.500	51.250,00	Pert Distribution
Sum of Planned maintenance cost (i.e tamping)	83.333	90%	100%	125%	75.000	83.333	104.167	87.500,00	Triangular Distribution
Delay minutes x Unit cost	16.193	7.862	16.193	27.079	7.862	16.193	27.079	17.044,31	Triangular Distribution
Sc (Social Cost)	18.450	90%	100%	125%	16.605	18.450	23.063	18.911	Additonal travel cost perday
									5 pound; 738 psg; 5 trip
Output									
Totals (TFc)	267.976							277.206	
Summary statistics									
Probability of meeting base case value	18,71%								
Total budget required for 95.0% confidence	294.506								
Contingency required for 95.0% confidence	26.530								



Summary Statistics for Total Failure Cost			
Statistics		**Percentile**	
Minimum	244.770	**5%**	261.044
Maximum	312.005	**10%**	264.388
Mean	277.206	**15%**	266.653
Std Dev	10.073	**20%**	268.381
Variance	101468660,7	**25%**	270.024
Skewness	0,141725452	**30%**	271.583
Kurtosis	2,807398027	**35%**	272.957
Median	277.032	**40%**	274.396
Mode	280.494	**45%**	275.636
Left X	261.044	**50%**	277.032
Left P	5%	**55%**	278.342
Right X	294.456	**60%**	279.611
Right P	95%	**65%**	280.850
Diff X	33.412	**70%**	282.367
Diff P	90%	**75%**	284.075
#Errors	0	**80%**	285.793
Filter Min	Off	**85%**	287.748
Filter Max	Off	**90%**	290.509
#Filtered	0	**95%**	294.456





Change in Output Statistic for Total Failure Cost			
Rank	**Name**	**Lower**	**Upper**
1	Sum of Unplanned maintenance cost type 1 / Ci	267.285	288.428
2	Sum of Planned maintenance cost (i.e tamping) / Ci	268.310	288.091
3	Delay minutes x Unit cost / Ci	270.353	284.000
4	Sum of Unplanned maintenance cost type 2 / Ci	273.017	282.096
5	Sc (Social Cost) / Ci	274.367	279.038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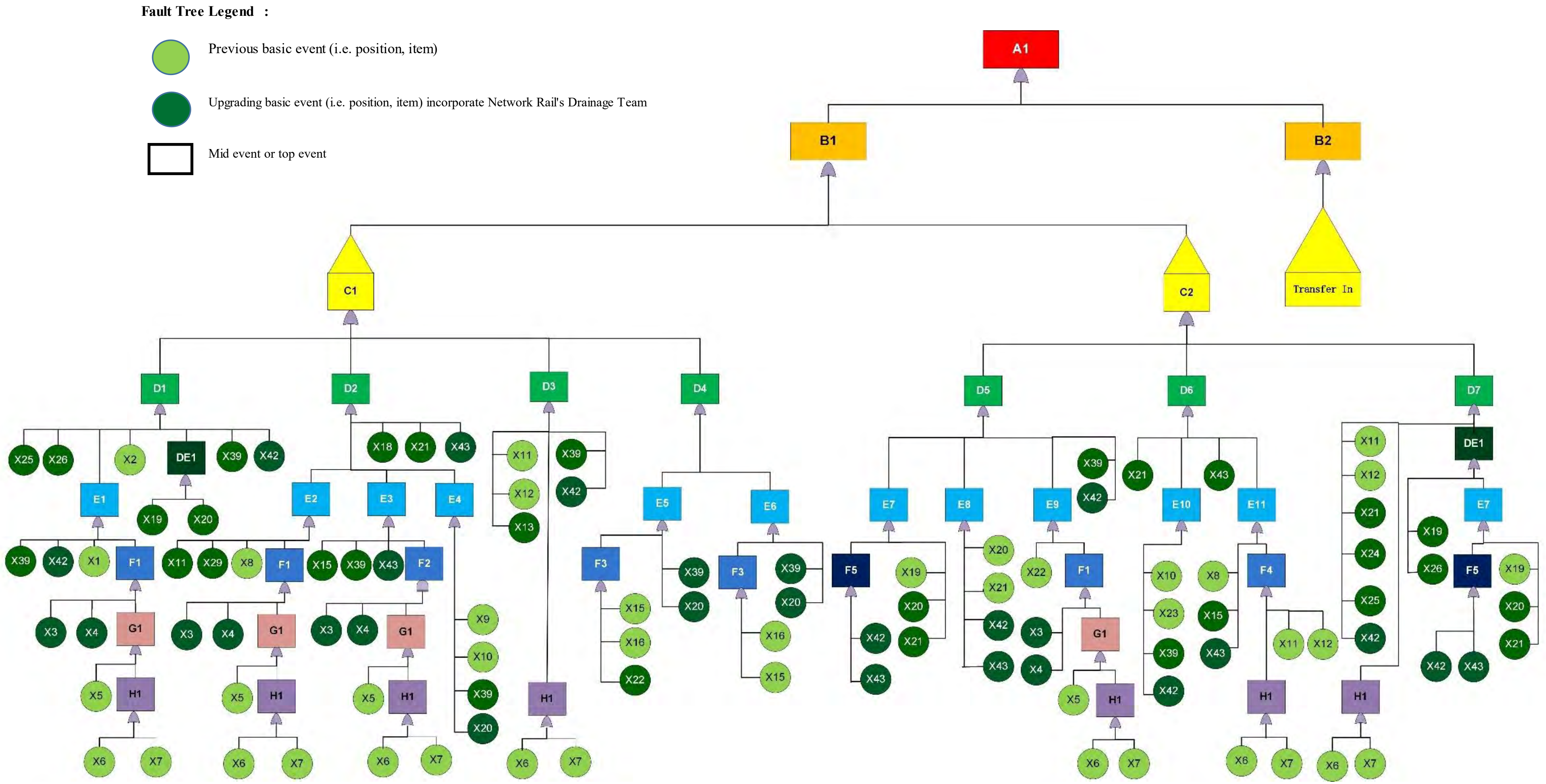
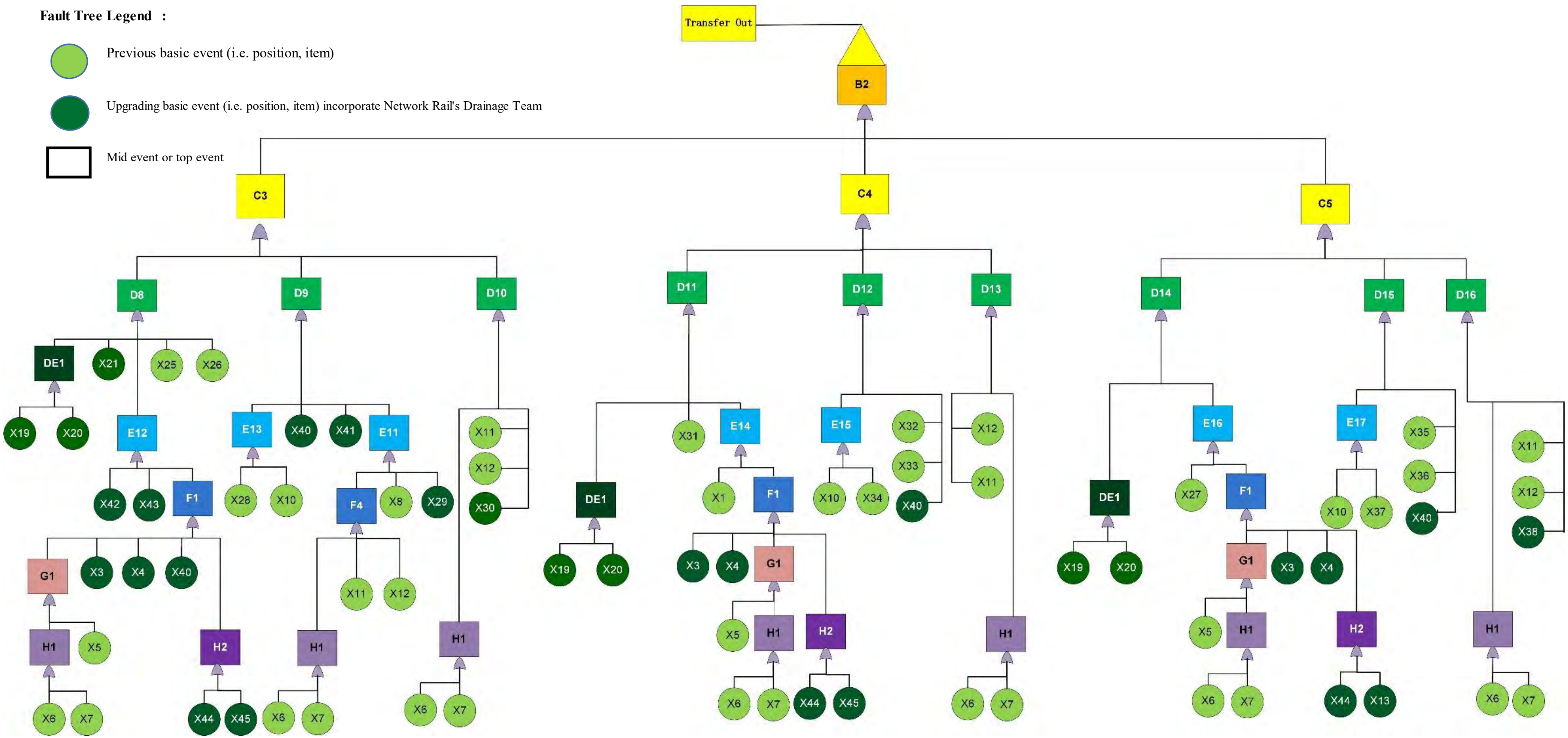
Drainage Workshop

The Validated Fault Tree (A2-1)

- **Fault tree for drainage of ballasted railway track (A1)**
- **Sub fault tree for subsurface drainage (B1): pipe (C1), catchpits and manholes (C2)**



- **Sub fault tree for surface drainage (B2): channel drains and ditches (C3), outfall (C4), culvert (C5)**



Drainage Workshop

The Validated Risks Item (A2-2)

Table A2-1 Causal factors of poor railway track drainage (basic event)

Code	Causal Event/ Risk Item	Type	Contributing Factor
X1	Poor filter	Basic event	Subgrade
X2	Root (tree) penetration	Basic event	Environmental
X3	Train dead load (track vehicles) overloading.	Basic event	Traffic
X4	Train live load (dynamic load, speed) overloading.	Basic event	Traffic
X5	Weak soil	Basic event	Subgrade
X6	Flood risk from surface water (heavy rainfall)	Basic event	Environmental
X7a	Flood risk from rivers	Basic event	Environmental
X7b	Flood risk from the sea	Basic event	Environmental
X7c	Flood risk from reservoirs	Basic event	Environmental
X8	Excessive soil pressure	Basic event	Subgrade
X9	Aging pipe	Basic event	Component
X10	Weathering (chemical)	Basic event	Environmental
X11	Change to land use (catchment area)	Basic event	Land use
X12	Changes to drain upstream	Basic event	Land use
X13	Inadequate pipe gradient	Basic event	Design
X14	Inappropriate design of granular filter	Basic event	Design
X15	Fines accumulation from trenches surround pipe	Basic event	Maintenance
X16	Fines accumulation from pipe(s) surround drain	Basic event	Maintenance
X17	Inappropriate design of geotextile filter	Basic event	Design
X18	Scour of pipe	Basic event	Environmental
X19	Lack of debris clean out	Basic event	Maintenance
X20	Non ballast material infiltration	Basic event	Maintenance
	(waste from the train, spillage from the train, fly tipping)		
X21	Poor ballasting practices	Basic event	Maintenance
X22	Lack of silt trap	Basic event	Design
X23	Aging catchpits and manholes	Basic event	Component
X24	Insufficient depth catchpits and manholes	Basic event	Design
X25	Vegetation overgrowth	Basic event	Maintenance
X26	Spoil tipping	Basic event	Maintenance
X27	Defective trash screen	Basic event	Maintenance
X28	Aging channel drains and ditches material	Basic event	Component
X29	Scour around channel drains and ditches	Basic event	Environmental
X30	Inadequate gradient of channel drains and ditches	Basic event	Design
X31	Seized flap valve	Basic event	Component
X32	Scour around headwall, apron and cascade	Basic event	Environmental
X33	Structural defect on headwall, apron and cascade	Basic event	Component
X34	Aging outfall material	Basic event	Component
X35	Structural defect of culvert	Basic event	Component
X36	Sour of culvert (inlet or outlet)	Basic event	Environmental
X37	Aging culver material	Basic event	Component
X38	Inadequate culvert gradient	Basic event	Design
X39	Inadequate design (i.e. inadequate data, inappropriate product selection)	Basic event	Design
X40	Damage caused by other assets/ 3rd party assets	Basic event	Land Use
X41	Damage caused by burrowing animals	Basic event	Maintenance
X42	Damage caused by lack of structural maintenance	Basic event	Maintenance
X43	Damage caused by poor installation	Basic event	Installation
X44	Prolong extreme hot weather	Basic event	Environmental

Table A2-1Causal factor of poor railway track drainage (mid event)

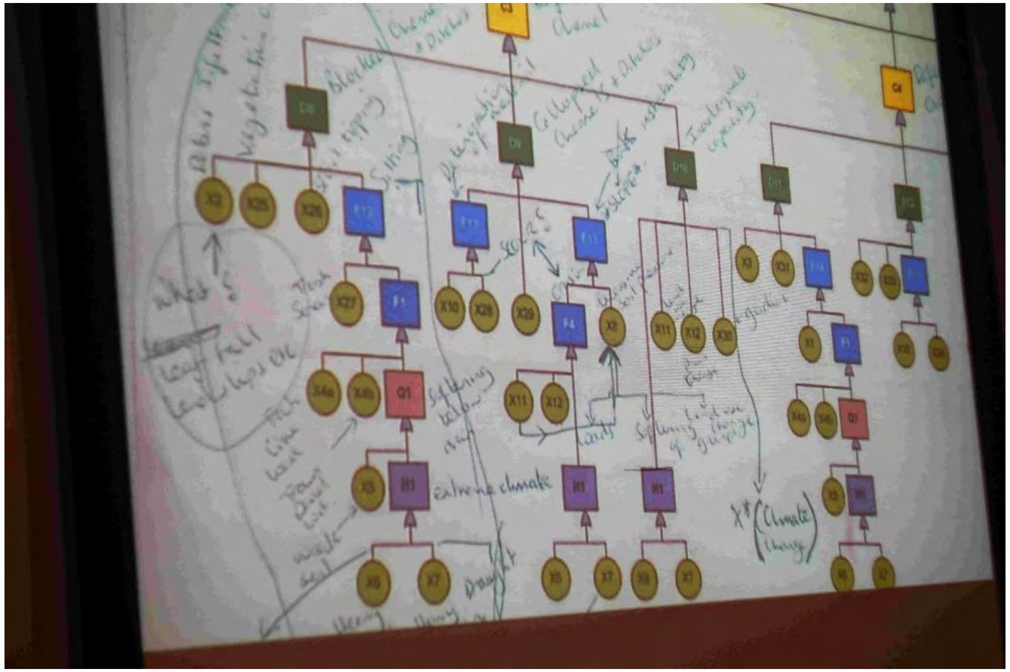
Code	Causal Event/ Risk Item	Type	Contributing Factor
H1	Excessive water infiltration to track bed	Mid event	Environmental
G1	Softening below drain level	Mid event	Subgrade
F1	Settlement due to change of gradient	Mid event	Subgrade
F2	Cess heave	Mid event	Subgrade
F3	Fines accumulation from surround pipe	Mid event	Maintenance
F4	Erosion	Mid event	Environmental
F5	Damaged or missing covers of catchpits and manholes	Mid event	Maintenance
E1	Silting pipe	Mid event	Maintenance
E2	Ground movement	Mid event	Subgrade
E3	Overstress	Mid event	Traffic
E4	Deterioration of pipe material	Mid event	Component
E5	Granular clogged (i.e. Collector, carrier, french/land drain)	Mid event	Design
E6	Geotextile clogged (i.e. Collector, carrier drain)	Mid event	Design
E7	Catchpits and manholes blocked by debris	Mid event	Maintenance
E8	Chambers filled or burried with material	Mid event	Maintenance
E9	Silting catchpits and manholes	Mid event	Maintenance
E10	Deterioration of catchpits and manholes material	Mid event	Deterioration
E11	Bank instability	Mid event	Subgrade
E12	Silting channel drain and ditches	Mid event	Maintenance
E13	Deterioration of channel drains and ditches material	Mid event	Component
E14	Silting outfall	Mid event	Maintenance
E15	Deterioration of outfall material	Mid event	Component
E16	Silting culvert	Mid event	Maintenance
E17	Deterioration of culvert material	Mid event	Component
DE1	Debris infiltration	Mid event	Maintenance

Table A2-3 Causal factor of poor railway track drainage (i.e. mid events, top event)

Code	Causal Event/ Risk Item	Type	Failure Mode
D1	Blocked pipe	Mid event	Pipe failure
D2	Collapsed pipe	Mid event	Pipe failure
D3	Inadequate capacity of pipe	Mid event	Pipe failure
D4	Filter media problem of surrounding pipe	Mid event	Pipe failure
D5	Blocked catchpits and manholes	Mid event	Catchpits and manholes failure
D6	Collapsed catchpits and manholes	Mid event	Catchpits and manholes failure
D7	Inadequate capacity of catchpits and manholes	Mid event	Catchpits and manholes failure
D8	Blocked channel drains and ditches	Mid event	Channel drains and ditches failure
D9	Collapsed channel drains and ditches	Mid event	Channel drains and ditches failure
D10	Inadequate capacity of channel drains and ditches	Mid event	Channel drains and ditches failure
D11	Blocked outfall	Mid event	Outfall failure
D12	Collapsed outfall	Mid event	Outfall failure
D13	Inadequate capacity of outfall	Mid event	Outfall failure
D14	Blocked culvert	Mid event	Culvert failure
D15	Collapsed culvert	Mid event	Culvert failure
D16	Inadequate capacity of culvert	Mid event	Culvert failure
C1	Defective of failed pipe	Mid event	Pipe failure
C2	Defective or failed catchpits and manholes	Mid event	Catchpits and manholes failure
C3	Defective or failed channel drains and ditches	Mid event	Channel drains and ditches failure
C4	Defective or failed outfall	Mid event	Outfall failure
C5	Defective or failed culvert	Mid event	Culvert failure
B1	Defective or failed subsurface track drainage	Mid event	Subsurface track drainage failure
B2	Defective or failed surface track drainage	Mid event	Surface track draunage failure
Code	**Undesired Event**	**Type**	**Failure Mode**
A1	Poor track drainage (i.e. Subsurface drainage, surface drainage)	Top Event	Track drainage failure

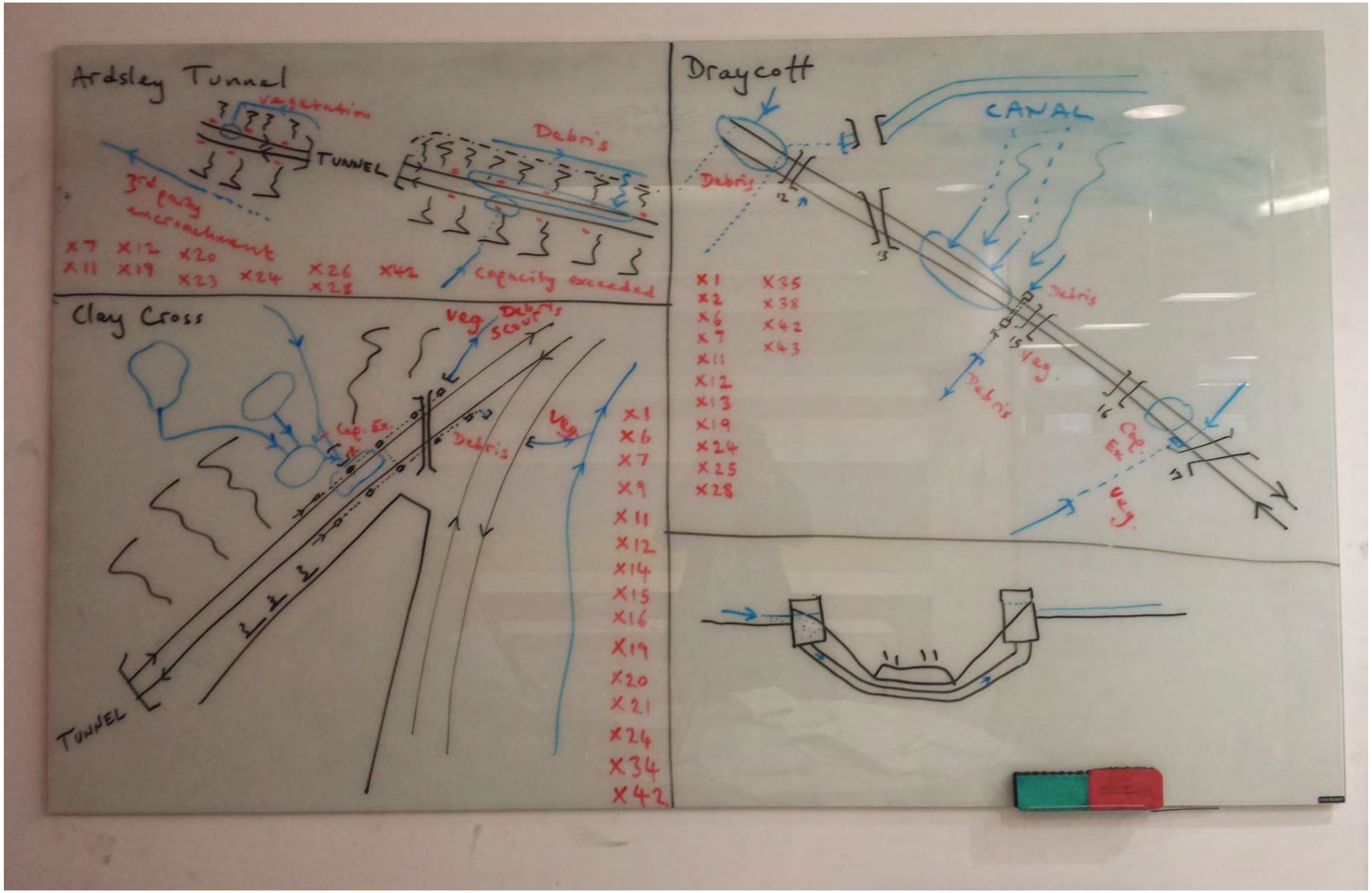
Drainage Workshop

Photographs (A2-3)


extreme climate

APPENDIX 3 Discussion and Questionnaire

Illustration of railway drainage risks at three selected sites: Ardsley Tunnel, Clay Cross Tunnel, Draycott



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THE DEVELOPMENT OF A RISK-INFORMED FRAMEWORK FOR THE APPRAISAL OF DRAINAGE MAINTENANCE OF BALLASTED RAILWAY TRACK

Drainage of Ballasted Railway Track - Channel Drains and Ditches (C3)

Questionnaire

Please fill complete the questionnaire manually or electronically

Send file to Kristianto Usman

KXU384@BHAM.AC.UK

This study is being undertaken in collaboration with Network Rail (Contact: Ms Mona Sihota)

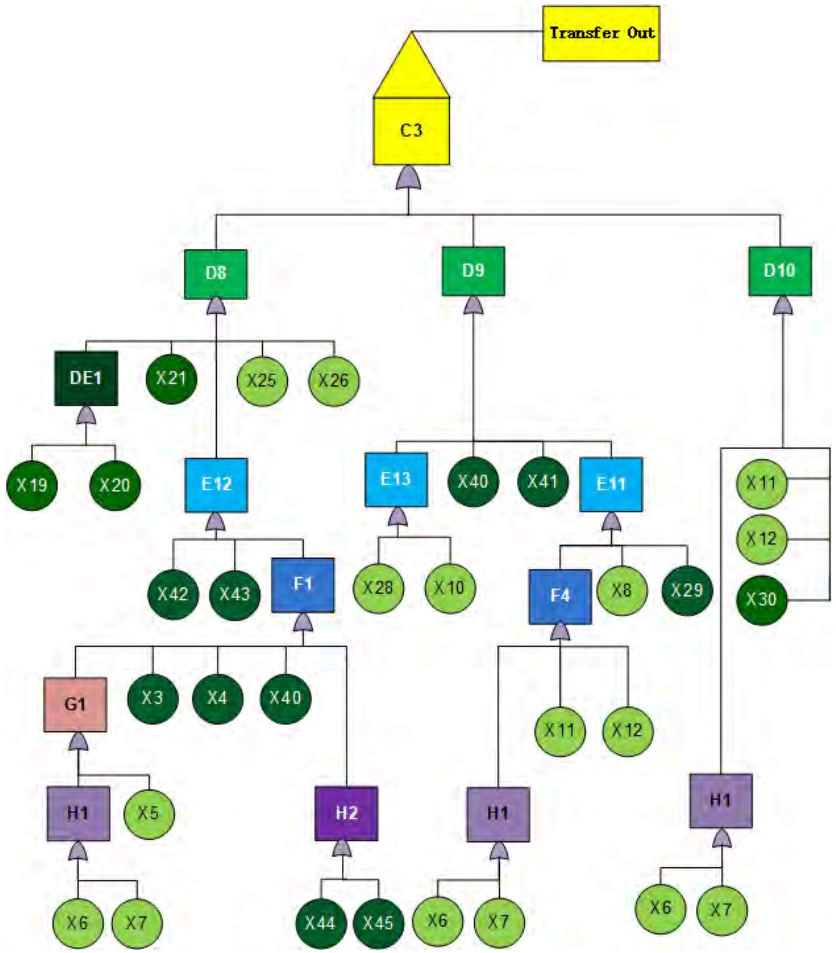

Figure 99 Sub-Fault Tree (FT) for Channel Drains and Ditches (C3)

There are 30 pathways that lead to fault C3 - Channel Drains and Ditches.

Fault codes (D#, E#, F#, G#, H# and X#), causal events and pathway is listed below.

Table A3-1 Causal factors of poor railway track drainage (basic event) for C3 (channel drains and ditches)

Code	Causal Event	Type	Contributing Factor
X3	Train dead load (track vehicles) overloading.	Basic event	Traffic
X4	Train live load (dynamic load, speed) overloading.	Basic event	Traffic
X5	Weak soil	Basic event	Subgrade
X6	Heavy rainfall	Basic event	Environmental
X7	Flooding	Basic event	Environmental
X8	Excessive soil pressure	Basic event	Subgrade
X10	Weathering (chemical)	Basic event	Environmental
X11	Change of land use (catchment area)	Basic event	Land use
X12	Changes to drain upstream	Basic event	Land use
X19	Lack of debris clean out	Basic event	Maintenance
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	Basic event	Maintenance
X21	Poor ballasting practices	Basic event	Maintenance
X25	Vegetation overgrowth	Basic event	Maintenance
X26	Spoil tipping	Basic event	Maintenance
X28	Aging channel drains and ditches material	Basic event	Component
X29	Scour around channel drains and ditches	Basic event	Environmental
X30	Inadequate gradient of channel drains and ditches	Basic event	Design
X40	Damage caused by other assets/ 3rd party assets	Basic event	Land Use
X41	Damage caused by burrowing animals	Basic event	Maintenance
X42	Damage caused by lack of maintenance	Basic event	Maintenance

Table A3-2 Causal factors of poor railway track drainage (mid and top event) for C3 (channel drains and ditches)

Code	Causal Event	Type	Contributing Factor
H1	Excessive water infiltration to track bed	Mid event	Environmental
H2	Excessive shrinkage below drain level due to moisture loss	Mid event	Environmental
G1	Softening below drain level	Mid event	Subgrade
F1	Settlement (change of gradient)	Mid event	Subgrade
F4	Erosion	Mid event	Environmental
E11	Bank instability	Mid event	Subgrade
E12	Silting in channel drain and ditches	Mid event	Maintenance
E13	Deterioration of channel drains and ditches material	Mid event	Component
DE1	Debris infiltration	Mid event	Maintenance
D8	Blocked channel drains and ditches	Mid event	Failure Mode
D9	Collapsed channel drains and ditches	Mid event	Failure Mode
D10	Inadequate capacity of channel drains and ditches	Mid event	Failure Mode
C3	Failure/ defective channel drains and ditches	Mid event	Failure Mode
B2	Failure/ defective surface track drainage	Mid event	Failure Mode
Code	**Undesired Event**	**Type**	**Factor Group**
A1	Poor track drainage arrangement (i.e. Subsurface drainage, surface drainage)	Top Event	Failure Mode

Fault Tree Legend :

Previous basic event (i.e. position, item)

Upgrading basic event (i.e. position, item) incorporate Network Rail's Drainage Team

Mid event or top event

Failure Mode: Blocked Channel Drains and Ditches

The list below shows failure mode pathways which lead to failure mode C3.

Please note the various colours are simply indicating repetition of core in the fault tree, since the same failure more can lead to a range of outcomes.

1) X19 – DE1 -D8 – C3
2) X20– DE1 – D8 – C3
3) X21 – D8 – C3
4) X25 – D8 – C3
5) X26 – D8 -C3
6) X6 – H1 – G1 – F1 – E12 – D8 – C3
7) X7 – H1 – G1 – F1 – E12 – D8 – C3
8) X44 – H2 - F1 – E12 – D8 – C3
9) X45 – H2 - F1 – E12 – D8 – C3
10) X5 – G1 – F1 – E12 – D8 – C3
11) X3 – F1 – E12 – D8 – C3
12) X4 – F1 – E12 – D8 – C3
13) X40 – F1 – E12 – D8 – C3
14) X42 – E12 – D8 – C3
15) X43 – E12 – D8 – C3

Failure Mode: Collapsed Channel Drains and Ditches

1) X6 – H1 – G1 – F4 – E11 – D9 – C3
2) X7 – H1 – G1 – F4 – E11 – D9 – C3
3) X11 – F4 – E11 – D9 – C3
4) X12 – F4 – E11 – D9 – C3
5) X10 – E13 – D9 – C3

6) X28 – E13 – D9 – C3
7) X40 – D9 – C3
8) X41 – D9 – C3
9) X8– E11 – D9 – C3
10) X29– E11 – D9 – C3

Failure Mode: Inadequate Capacity of Channel Drains and Ditches

11) X6 – H1 – D10 – C3
12) X7 – H1 – D10 – C3
13) X11 – D10 – C3
14) X12 – D10 – C3
15) X30 – D10 – C3

Questionnaire for poor drainage of railway ballasted track subject to channel drain and ditches (C3). This questionnaire is entailed to a selected part of railway network which has been identified as a prone site to drainage risk and homogeneous impact (e.g. route with high importance). **The length of the selected part is 200 m.**

For question Q1 please highlight with any colour (if form is filled electronically) tick (if form is filled manually) in the Table A3-1a, A3-1b, and A3-1c subject to the availability each risk occurring at the selected sites as follows:

- ***Ardsley Tunnel site (Table A3-1a))***
- ***Clay Cross Tunne site (Table A3-1b)***
- ***Draycott (Table A3-1c)***

Table A3-1a Form to complete subject to availability of each risk occurring at the Ardsley Tunnel site

Code	Causal Event	Type	Contributing Factor
X3	Train dead load (track vehicles) overloading.	Basic event	Traffic
X4	Train live load (dynamic load, speed) overloading.	Basic event	Traffic
X5	Weak soil	Basic event	Subgrade
X6	Heavy rainfall	Basic event	Environmental
X7	Flooding	Basic event	Environmental
X8	Excessive soil pressure	Basic event	Subgrade
X10	Weathering (chemical)	Basic event	Environmental
X11	Change of land use (catchment area)	Basic event	Land use
X12	Changes to drain upstream	Basic event	Land use
X19	Lack of debris clean out	Basic event	Maintenance
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	Basic event	Maintenance
X21	Poor ballasting practices	Basic event	Maintenance
X25	Vegetation overgrowth	Basic event	Maintenance
X26	Spoil tipping	Basic event	Maintenance
X28	Aging channel drains and ditches material	Basic event	Component
X29	Scour around channel drains and ditches	Basic event	Environmental
X30	Inadequate gradient of channel drains and ditches	Basic event	Design
X40	Damage caused by other assets/ 3rd party assets	Basic event	Land Use
X41	Damage caused by burrowing animals	Basic event	Maintenance
X42	Damage caused by lack of maintenance	Basic event	Maintenance

Table A3-1b Form to complete subject to availability of each risk occurring at the Clay Cross Tunnel site

Code	Causal Event	Type	Contributing Factor
X3	Train dead load (track vehicles) overloading.	Basic event	Traffic
X4	Train live load (dynamic load, speed) overloading.	Basic event	Traffic
X5	Weak soil	Basic event	Subgrade
X6	Heavy rainfall	Basic event	Environmental
X7	Flooding	Basic event	Environmental
X8	Excessive soil pressure	Basic event	Subgrade
X10	Weathering (chemical)	Basic event	Environmental
X11	Change of land use (catchment area)	Basic event	Land use
X12	Changes to drain upstream	Basic event	Land use
X19	Lack of debris clean out	Basic event	Maintenance
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	Basic event	Maintenance
X21	Poor ballasting practices	Basic event	Maintenance
X25	Vegetation overgrowth	Basic event	Maintenance
X26	Spoil tipping	Basic event	Maintenance
X28	Aging channel drains and ditches material	Basic event	Component
X29	Scour around channel drains and ditches	Basic event	Environmental
X30	Inadequate gradient of channel drains and ditches	Basic event	Design
X40	Damage caused by other assets/ 3rd party assets	Basic event	Land Use
X41	Damage caused by burrowing animals	Basic event	Maintenance
X42	Damage caused by lack of maintenance	Basic event	Maintenance

Table A3-1c Form to complete subject to availability of each risk occurring at the Draycott site

Code	Causal Event	Type	Contributing Factor
X3	Train dead load (track vehicles) overloading.	Basic event	Traffic
X4	Train live load (dynamic load, speed) overloading.	Basic event	Traffic
X5	Weak soil	Basic event	Subgrade
X6	Heavy rainfall	Basic event	Environmental
X7	Flooding	Basic event	Environmental
X8	Excessive soil pressure	Basic event	Subgrade
X10	Weathering (chemical)	Basic event	Environmental
X11	Change of land use (catchment area)	Basic event	Land use
X12	Changes to drain upstream	Basic event	Land use
X19	Lack of debris clean out	Basic event	Maintenance
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	Basic event	Maintenance
X21	Poor ballasting practices	Basic event	Maintenance
X25	Vegetation overgrowth	Basic event	Maintenance
X26	Spoil tipping	Basic event	Maintenance
X28	Aging channel drains and ditches material	Basic event	Component
X29	Scour around channel drains and ditches	Basic event	Environmental
X30	Inadequate gradient of channel drains and ditches	Basic event	Design
X40	Damage caused by other assets/ 3rd party assets	Basic event	Land Use
X41	Damage caused by burrowing animals	Basic event	Maintenance
X42	Damage caused by lack of maintenance	Basic event	Maintenance

Questionnaire result: Ardsley Tunnel Site

Table A3-3 Availability of each risk occurring at the Ardsley Tunnel site

Code	Basic Event/ Risk	Availability	Frequency (years)	Source of Data
X5	Weak soil	-		
X6	Flooding from surface water	√	0 - 8 in 10	NR's record
X7a	Flooding from river	√	1 in 1000 - 1 in 100	UK's flood map
X7b	Flooding from sea	-		
X7c	Flooding from reservoirs	-		
X8	Excessive soil pressure	-		
X10	Weathering (chemical)	-		
X11	Change to land use (catchment area)	√	1 in 100 - 1 in 30	Literature
X12	Changes to drain upstream	√	1 in 100 - 1 in 30	Literature
X19	Lack of debris clean out	√	0 - 1 in 10	NR's record
X20	Non ballast material infiltration	√	1 in 100 - 1 in 30	Literature
	(waste from the train, spillage from the train, fly tipping)			
X21	Poor ballasting practices	-		
X25	Vegetation overgrowth	√	0 - 1 in 10	NR's record
X26	Spoil tipping	√	1 in 100 - 1 in 30	Literature
X28	Aging channel drains and ditches material	√	0 - 1 in 50	Literature
X29	Scour around channel drains and ditches	-		
X30	Inadequate gradient of channel drains and ditches	-		
X40	Damage caused by other assets/ 3rd party assets	√	0 - 1 in 10	NR's record
X41	Damage caused by burrowing animals	-		
X42	Lack of silt clean out (channel drains) or excavate (ditches)	√	1 in 30 - 1 in 10	Literature
X43	Damage caused by poor installation	-		
X44	Prolonged hot weather	-		

Questionnaire result: Clay Cross Tunnel Site

Table A3-4 Availability of each risk occurring at the Clay Cross Tunnel site

Code	Basic Event/ Risk	Availability	Frequency (years)	Source of Data
X5	Weak soil	-		
X6	Flooding from surface water	√	0 - 8 in 10	NR's record
X7a	Flooding from river	√	1 in 1000 - 1 in 100	UK's flood map
X7b	Flooding from sea	-		
X7c	Flooding from reservoirs	-		
X8	Excessive soil pressure	-		
X10	Weathering (chemical)	-		
X11	Change to land use (catchment area)	√	1 in 100 - 1 in 30	Literature
X12	Changes to drain upstream	√	1 in 100 - 1 in 30	Literature
X19	Lack of debris clean out	√	0 - 1 in 10	NR's record
X20	Non ballast material infiltration	√	1 in 100 - 1 in 30	Literature
	(waste from the train, spillage from the train, fly tipping)			
X21	Poor ballasting practices	-		
X25	Vegetation overgrowth	√	0 - 1 in 10	NR's record
X26	Spoil tipping	√	1 in 100 - 1 in 30	Literature
X28	Aging channel drains and ditches material	√	0 - 1 in 50	Literature
X29	Scour around channel drains and ditches	-		
X30	Inadequate gradient of channel drains and ditches	-		
X40	Damage caused by other assets/ 3rd party assets	√	0 - 1 in 10	NR's record
X41	Damage caused by burrowing animals	-		
X42	Lack of silt clean out (channel drains) or excavate (ditches)	√	1 in 30 - 1 in 10	Literature
X43	Damage caused by poor installation	-		
X44	Prolonged hot weather	-		

Questionnaire result: Draycott Site

Table A3-5 Availability of each risk occurring at the Draycott site

Code	Basic Event/ Risk	Availability	Frequency (years)	Source of Data
X5	Weak soil	-		
X6	Flooding from surface water	√	0 - 12 in 10	NR's record
X7a	Flooding from river	√	1 in 100 - 1 in 30	UK's flood map
X7b	Flooding from sea	-		
X7c	Flooding from reservoirs	√	1 in 1000- 1 in 100	UK's flood map
X8	Excessive soil pressure	-	-	-
X10	Weathering (chemical)	-		
X11	Change to land use (catchment area)	√	1 in 100 - 1 in 30	Literature
X12	Changes to drain upstream	√	1 in 100 - 1 in 30	Literature
X19	Lack of debris clean out	√	1 in 30 - 1 in 10	Literature
X20	Non ballast material infiltration			
	(waste from the train, spillage from the train, fly tipping)			
X21	Poor ballasting practices			
X25	Vegetation overgrowth	√	1 in 30 - 1 in 10	Literature
X26	Spoil tipping			
X28	Aging channel drains and ditches material	√	1 in 50 - 1 in 30	Literature
X29	Scour around channel drains and ditches			
X30	Inadequate gradient of channel drains and ditches	-		
X40	Damage caused by other assets/ 3rd party assets			
X41	Damage caused by burrowing animals	-		
X42	Lack of silt clean out (channel drains) or excavate (ditches)	√	1 in 100 - 1 in 30	Literature
X43	Damage caused by poor installation	√	1 in 100 - 1 in 30	Literature
X44	Prolonged hot weather	-		

APPENDIX 4 Historical Data-Network Rail

- **Historical data of incidents associated with drainage problems at selected sites:**
  - **Ardsley Tunnel**
  - **Clay Cross Tunnel**
  - **Draycott**

- **Data providing by Network Rail UK**

Ardsley Tunnel Site

Period	Business Year	Incident Date	Year	Month	Incident Number	Incident Start Time	Incident Description	Incident FMS
2012/13_P01	2012/13	27 April 2012	2012	4	756940	07:00	ARDSLEY TNL FLOODING	445778
2012/13_P03	2012/13	22 June 2012	2012	6	878367	22:51	ARDSLEY TNL FLOODING	452193
2012/13_P04	2012/13	06 July 2012	2012	7	908272	13:59	ARDSLEY TUNNEL FLOODING	453907
2012/13_P05	2012/13	05 August 2012	2012	8	974892	17:32	ARDSLEY TNL FLOODING	457410
2012/13_P07	2012/13	24 September 2012	2012	9	83766	15:16	ARDSLEY TUNNEL FLOODING	462491
2012/13_P07	2012/13	24 September 2012	2012	9	84011	17:00	ARDSLEY TNL TC/L8	462491
2012/13_P10	2012/13	22 December 2012	2012	12	337210	14:48	ARDSLEY TUNNEL FLOODING	472168
2015/16_P09	2015/16	12 December 2015	2015	12	887516	15:57	WKF WHRDJN FLOODING	606920

First year reported	Exact Location	Assets Affected	ELR	Exact Mileage From	Exact Mileage To	SRS	Text	Total	PfPI Costs
2012	Ardsley Tunnel	tbc	DOL2	180.1200		G.06	DESCRIPTION*** 27-APR-2012 07:04:00 *** QGP0005 *** *** 27/04/12 07:04 #QGP0005 *** CREATED FAULT NO/STATUS 445778 / OPEN EQUIPMENT DESC WAKEFIELD 175.0 704-HOLBECK E. JN : 175 : 704 : 185 : 544 : UP FAST/MAIN : W AKEFIELD 5812132 FAILED AT 27/04/2012 06:46:13 PLACE ARDSLEY TUNNEL 56915 DISCIPLINE PWAY SUFFIX TRACK (P.W) ATTEND LEEDS PWAY : RAB303 MAINTAIN LEEDS IMDM/IME RAB000 IN ORDER REPORTED BY YORK IECC SSM 0372757 RECTIFY AT REPORTED AS WAKEFIELD 175.0704-HOLBECK E. JN : 175 : 704 : 1 85 : 544 : UP FAST/MAIN : WAKEFIELD : TRACK 5812132 EQUIP COMMENTS DETAILS	404	£32,834

							06:49 MESSAGE ON MOBILE FOR PWSM ON CALL# 2B01 REPOR TED FLOOD WATER AT THE LEEDS END OF ARDSLEY TUNNEL. 1B23 TO EXAMINE. DESCRIPTION*** 30-APR-2012 14:00:00 *** QGP6272 *** *** 30/04/12 14:00 #QGP6272 *** AMENDED FMS STATES 'WATER RUNNING OFF ADJACENT FIELDS. DRAINAGE WOR KING AND BALLAST IN GOOD ORDER'. FAULT NUMBER ADDED.		
2012	Ardsley Tunnel	L208	DOL2	180.1200	181.0000	G.06	23:04 YORK SSM REPORTS THAT DRIVER 2F 2B35 HAS EXAMINED THE UP LIN E AND REPORTED THAT THE FLOODING STARTS 50YDS BEFORE LEEDS E ND OF TUNNEL AND THROUGH SIGNAL LENGTH UP TO L208 ON THE UP. NOT QUITE UP TO RAILHEAD YET SO OK FOR NORMAL WORKING AT PR ESENT. PWAY ON CALL ADVISED AND REQUESTED TO ATTEND. HE ADVISES ETA 23:55. 23:15 DRIVER OF 1F70 WAS REQUESTED TO EXAMINE DOWN LINE AND HE REP ORTS THAT THE WATER IS ABOVE RAIL HEAD AND ALSO RUNNING FAST ENOUGH TO DISLODGE BALLAST. JOB NOW STOPPED ON THE DOWN DONCASTER. PWAY UPDATED. LEEDS MOM EN ROUTE ETA 23:40. ALL PARTIES UPDATED. 00:19 MOM HAS REPORTED THAT ALONG WITH PWAY THEY HAVE WALKED THROU GH THE WHOLE SECTION AND CONFIRM THA THE DOWN LINE IS COMPLE TELY UNAFFECTED NO SIGN OF ANY WATER PRESENT. THE UP LINE WILL BE SUBJECT TO 5MPH ONCE LINE BLOCK GIVEN UP . TRACK CIRCUIT ON THE UP LINE HAS ALSO CLEARED. 00:47 ADVISED BY PWAY THAT HE WILL RETURN AT 03:30 BEFORE THE FIRS T TRAIN TO REPORT IF LINE OK FOR LINE SPEED OR 5MPH. DESCRIPTION*** 26-JUN-2012 11:34:00 *** QGP6272 *** *** 26/06/12 11:34 #QGP6272 *** AMENDED FMS STATES THIS WAS A FLASH FLOOD CAUSED BY HEAVY RAIN. ** RESPONSIBLE MANAGER CODE UPDATED FROM IQGG TO XQGL ** REASON CODE UPDATED FROM JK TO X2	422	£18,125
2012	Ardsley Tunnel	tbc	DOL2	180.1200	181.0000	G.06	ATTEND LEEDS PWAY : RAB303 MAINTAIN LEEDS IMDM/IME RAB000 IN ORDER REPORTED BY YORK IECC SSM 0372757 RECTIFY AT REPORTED AS WAKEFIELD 175.0704-HOLBECK E. JN : 175 : 704 : 1 85 : 544 : UP FAST/MAIN : WAKEFIELD : TRACK 5812132 EQUIP COMMENTS DETAILS MOVING FLOOD WATER ON UP LINE LEEDS END OF ARDSLEY T UNNEL. LINE BLOCKED. 13:37 YOERK IECC REPORTED UP DONCASTER LINE BLOCKED AT ARDSLEY TUN NEL. DRIVER ON 2B17 13:20 LEEDS-DONCASTER REPORTED MOVING FL OOD	904	£29,895

							WATER ON THE UP LINE ON THE LEEDS SIDE ENTRANCE TO THE T UNNEL. LEEDS MOM AT HORSFORTH WITH FLOODING. LEEDS P/WAY ADVISED ETA 14:20HRS. GROUP PAGE SENT. DESCRIPTION*** 07-JUL-2012 02:48:00 *** QGP3130 *** *** 07/07/12 02:48 #QGP3130 *** AMENDED CROSS COUNTRY REQUESTED SERVICE RECOVERY FROM 1337HRS AT 024 0HRS CONFERENCE. SERVICE RECOVERY FOR CROSS COUNTRY CLOSED AT 2359HRS. DESCRIPTION*** 07-JUL-2012 06:03:00 *** QGP3130 *** *** 07/07/12 06:03 #QGP3130 *** AMENDED 908272 ARDSLEY NORTHERN RAIL REQUESTED SERVICE RECOVERY FROM 1300HRS AT 050 0HRS CONFERENCE. SERVICE RECOVERY FOR NORTHERN RAIL CLOSED AT 2359HRS. DESCRIPTION*** 07-JUL-2012 11:23:00 *** QGP0525 *** *** 07/07/12 11:23 #QGP0525 *** AMENDED SERVICE RECOVERY GRANTED TO EAST COAST FROM 1300 AND CLOSED 2359 06/07/12		
2012	Ardsley Tunnel	L8 TC	DOL2	180.1200	181.0000	G.06	FAILED AT 05/08/2012 17:32:44 PLACE ARDSLEY TUNNEL 56915 DISCIPLINE SIGNALLING SUFFIX TRACK CIRCUIT ATTEND LEEDS SIG FAULTS : RAB111 MAINTAIN LEEDS IMDM/IME RAB 000 IN ORDER REPORTED BY YORK IECC SSM ... RECTIFY AT REPORTED AS YORK (LEEDS) : L8 : UP FAST/MAIN : TRACK CCT -DC MED VOLT AC IMMUNE 6029262 EQUIP COMMENTS DETAILS L8 T/C SOWC APOT 1A13 UP DONNY LINE HOLDING L206 SIG NAL AT DANGER CAUSE DESCRIPTION*** 05-AUG-2012 19:40:00 *** QGP0023 *** *** 05/08/12 19:40 #QGP0023 *** AMENDED SERVICE RECOVERY GRANTED TO EAST COAST AT 1816 AND TO CROSS COUNTRY TRAINS AT 1841 HOURS. DESCRIPTION*** 06-AUG-2012 01:16:00 *** QGP5846 *** *** 06/08/12 01:16 #QGP5846 *** AMENDED SR CLOSED TO BOTH EC AND XC AT 2359HRS. DESCRIPTION*** 06-AUG-2012 08:38:00 *** QGP5003 *** *** 06/08/12 08:38 #QGP5003 *** AMENDED CAUSE TRACK FLOODED AFTER HEAVY RAIN FALL ACTION 18:50 FLOODWATER BELOW RAILHEAD NORMAL WORKING RESUM ED ** REASON CODE UPDATED FROM IC TO JK *** 06/08/12 08:38 #QGP5003 *** AMENDED CCIL REF 884072 DESCRIPTION*** 07-AUG-2012 14:16:00 *** QGP6272 *** *** 07/08/12 14:16 #QGP6272 *** AMENDED DRAINAGE PROPERLY MAINTAINED. ** RESPONSIBLE MANAGER CODE UPDATED FROM IQGG TO XQGL ** REASON CODE UPDATED	283	£9,841

							FROM JK TO X2 RESOLUTION*** 06-AUG-2012 07:51:00 *** QGP0026 *** * 06/08/12 07:51 #QGP0026 * DISPUTED INCORRECT DELAY CODE RECODE TO EXTR WEATH/FLOODING		
2012	Ardsley Tunnel	tbc	DOL2	180.1200	181.0000	G.06	DESCRIPTION*** 24-SEP-2012 15:44:00 *** QGP5842 *** *** 24/09/12 15:44 #QGP5842 *** AMENDED 15:35 YORK IECC SSM REPORTED THAT THE DRIVER OF 1S45 0925 PLYMOUTH - ABERDEEN HAD REPORTED FLOWING WATER TO RAIL HEIGHT ON THE UP LINE. WATER IS DRAINING FROM THE DOWN SIDE CUTTING FACE AND THOUGH ONTO THE UP LINE. THE DOWN LINE REMAINS OPEN FOR TRAFFIC. NO WORD YET FROM THE MOM. DESCRIPTION*** 24-SEP-2012 16:40:00 *** QGP2394 *** *** 24/09/12 16:40 #QGP2394 *** AMENDED 16:11 YORK IECC SSM REPORTED THAT THE LINE HAD BEEN EXAMINED AS FI T FOR LINESPEED AT 1608. THE LINE BLOCKAGE HAS BEEN HANDED B ACK AT 1609 AND THE P/WAY WILL OBSERVE THE PASSAGE OF THE F IRST 'COUPLE' OF TRAINS AT LINESPEED. LEEDS MOM WILL REMAIN ON SITE TO MONITOR THE SITUATION THROUGHOUT THE EVENING. DESCRIPTION*** 24-SEP-2012 19:47:00 *** QGP3131 *** *** 24/09/12 19:47 #QGP3131 *** AMENDED WEATHER WARNINGS ISSUED FOR HEAVY RAIN ** RESPONSIBLE MANAGER CODE UPDATED FROM IQGG TO XQGL ** REASON CODE UPDATED FROM JK TO X2 DESCRIPTION*** 25-SEP-2012 17:55:00 *** QGP8207 *** *** 25/09/12 17:55 #QGP8207 *** AMENDED AT 1600 CONFERENCE SR GRANTED TO EAST COAST AND CROSS COUNT RY FROM 1515. SR CLOSED WITH XC 2243 AND WITH EC 2359. DESCRIPTION*** 27-SEP-2012 11:01:00 *** QGP6000 *** *** 27/09/12 11:01 #QGP6000 *** AMENDED AMENDED BY ROUTE PERFORMANCE PLS MERGE 084118 2J47 WTG DVR LDS INTO 083766 COND HU711 LAI W INTO HUD ON 2W82 DUE TO THIS IRN THEN BOOKED BREAK AT HUD RESULTING IN COND MISSING BOOKED PASS RIDE ON 1P46 HUD-LDS. DESCRIPTION*** 02-OCT-2012 13:54:00 *** QGP2781 *** *** 02/10/12 13:54 #QGP2781 *** AMENDED RESOLUTION*** 19-MAR-2013 14:06:00 *** QGP0028 *** * 19/03/13 14:06 #QGP0028 * ACCEPTED BY USER RESOLUTION*** 01-OCT-2012 16:22:00 *** QGP0295 *** * 01/10/12 16:22 #QGP0295 * DISPUTED INCORRECT DELAY	1068	£26,560

							CODE DISPUTED RESOLUTION*** 01-OCT-2012 16:21:00 *** QGP0295 *** * 01/10/12 16:21 #QGP0295 * ACCEPTED BY USER RESOLUTION*** 25-SEP-2012 09:01:00 *** QGP0026 *** * 25/09/12 09:01 #QGP0026 * DISPUTED INCORRECT DELAY CODE NEEDS MERGING WITH 84011		
2012	Ardsley Tunnel	L8 TC	DOL2	180.1200	181.0000	G.06	DESCRIPTION*** 24-SEP-2012 17:59:00 *** QGP3121 *** *** 24/09/12 17:59 #QGP3121 *** CREATED REPORTED BY YORK IECC DETAILS SOWC ON OWN ACCORD HOLDS L206 AT RED. DESCRIPTION*** 02-OCT-2012 13:55:00 *** QGP2781 *** *** 02/10/12 13:55 #QGP2781 *** AMENDED DESCRIPTION*** 02-OCT-2012 13:57:00 *** QGP2781 *** *** 02/10/12 13:57 #QGP2781 *** AMENDED AMENDED AS PER LEEDS MTCE REQUEST. UNABLE TO MERGE WITH 8376 6 (X2) AS MORE THAN 7 DAYS OLD (REQUEST MADE TO DQS ON DAY 2) ** RESPONSIBLE MANAGER CODE UPDATED FROM IQGG TO XQGL ** REASON CODE UPDATED FROM IC TO X2 RESOLUTION*** 25-SEP-2012 09:01:00 *** QGP0026 *** * 25/09/12 09:01 #QGP0026 * DISPUTED INCORRECT DELAY CODE NEEDS MERGING WITH 83766	672	£17,281
2012	Ardsley Tunnel	tbc	DOL2	180.1200	181.0000	G.06	14:48 ADVISED BY YORK SSM - DRIVER OF 1A36 REPORTED RUNNING WATER ON UP LINE @ SOUTH PORTAL OF ARDSLEY TUNNEL. UP LINE BLOCKED. 15:09 MOM TAKEN LB TO WALK TO SITE 15:14 YORK SSM FURTHER REPORTS 1S45 CAUTIONED ON DOWN - REPORTS FL OODING IS @ NORTH PORTAL ON UP. MOM UPDATED - ALREADY EN ROU TE TO NORTH PORTAL. 15:19 MOM ON SITE @ NORTH PORTAL 15:22 MOM REPORTS GENTLY RUNNING WATER (NOT DISTURBING BALLAST) @ NORTH END PORTAL UP LINE. ABOVE RAIL FOOT BUT BELOW RAILHEAD TO ALLOW LINESPEED ONCE LB HANDED BACK. OVER RUNNING DRAINS DUE TO VOLUME OF WATER RUNNING OFF THIRD PARTY LAND. LEAVES & DEBRIS REMOVED FROM A COUPLE OF DRAINAGE CHANNELS. 15:35 MOM CLEAR - UP LINE OPEN @ LINESPEED. PARTIED UPDATED DESCRIPTION*** 22-DEC-2012 16:13:00 *** QGP0023 *** *** 22/12/12 16:13 #QGP0023 *** AMENDED SERVICE RECOVERY GRANTED TO NORTHERN TRAINS AT 1448 EAST COA ST TRAINS AT 1505 AND CROSS COUNTRY TRAINS AT 1511 HOURS.	272	£7,271

							DESCRIPTION*** 22-DEC-2012 19:05:00 *** QGP0023 *** *** 22/12/12 19:05 #QGP0023 *** AMENDED SERVICE REC9OVERY CLOSED WITH EAST COAST TRAINS AT 1730 HOUR S. SERVICE RECOVERY CLOSED WITH NORTHERN TRAINS AT 1627 HOURS. DESCRIPTION*** 23-DEC-2012 05:49:00 *** QGP3130 *** *** 23/12/12 05:49 #QGP3130 *** AMENDED SERVICE RECOVERY FOR CROSS COUNTRY CLOSED AT 2359HRS. RESOLUTION*** 02-JAN-2013 16:00:00 *** QGP6152 *** * 02/01/13 16:00 #QGP6152 * ACCEPTED BY USER RESOLUTION*** 02-JAN-2013 15:59:00 *** QGP6152 *** * 02/01/13 15:59 #QGP6152 * CODE CHANGED * 02/01/13 15:59 #QGP6152 * DISPUTED PARTIAL ACCEPTANCE INCORRECT FAULT NUMBER INSERTED SHOULD BE 472168		
2012	Ardsley Tunnel	tbc	DOL2	180.1200	181.0000	G.06	DESCRIPTION*** 12-DEC-2015 16:06:00 *** QGP5842 *** *** 12/12/15 16:06 #QGP5842 *** CREATED WKF WHRDJN FLOODING DETAILS1A37 RPTS WATER CASCADING DOWN EMBANKMENT 10M ON APPR OACH TO OLD TINGLEY VIADUCT NEAR ARDSELY TUNNEL ON UP. NEX T TRAIN 2N18 WILL EXAMINE. CAUSE ACTION 15:23ADVISED BY YORK SSM THAT DRIVER OF 1A37 (15:05 LEEDS TO KINGS X) RPTS WATER CASCADING DOWN EMBANKMENT 10M ON APPROA CH TO OLD TINGLEY VIADUCT NEAR ARDSELY TUNNEL ON UP. RUNNI NG NORMALLY AT PRESENT. NEXT TRAIN 2N18 WILL EXAMINE. LEEDS PWAY ADVISED AND J. CLIFFE ARRANGING STAF DESCRIPTION*** 13-DEC-2015 04:04:00 *** QGP0023 *** *** 13/12/15 04:04 #QGP0023 *** AMENDED SERVICE RECOVERY GRANTED TO NORTHERN TRAINS FROM 17:14 TO 19 :06 HRS.	994	£48,005

Clay Cross Tunnel Site

Period	Business Year	Incident Date	Year	Month	Incident Number	Incident Start Time	Incident Description	Incident FMS
2009/10_P03	2009/10	10 June 2009	2009	6	170629	19:20	CLAYXNJ FLOODING RC: Report of Flooding at the North end of Clay Cross Tunnel	52440
2009/10_P08	2009/10	01 November 2009	2009	11	524014	10:38	CLAYXS FLOOD (R) SR	56181
2009/10_P09	2009/10	23 November 2009	2009	11	589405	13:06	CLAYXS TNL FLOOD (R) SR over railhead on Dn line with possible displacement of ballast	56698
2009/10_P09	2009/10	06 December 2009	2009	12	625985	08:13	CLAYXNJ TRACK FLOODING: Down Main blocked due to flooding water rapidly moving at Railhead height for 90yds	56982
2012/13_P07	2012/13	24 September 2012	2012	9	83777	15:38	CLAYXS FLOODING:	84613
2012/13_P09	2012/13	25 November 2012	2012	11	258288	08:00	CLAYXNJ FLOODING: Up/Dn Main Line blocked Clay Cross tunnel to Down Clay Cross loops 829pts	84613
2013/14_P08	2013/14	21 October 2013	2013	10	33466	12:53	CLAYXNJ FLOODING	
2014/15_P03	2014/15	09 June 2014	2014	6	591524	13:30	CLAYXS FLOODING	100980
2016/17_P09	2016/17	21 November 2016	2016	11	696308	16:39	CLAYX FLOODING	125122

First year reported	Exact Location	Assets Affected	ELR	Exact Mileage From	Exact Mileage To	SRS	Text	Total	PfPI Costs
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DESCRIPTION*** 10-JUN-2009 20:12:00 *** QGP3125 *** *** 10/06/09 20:12 #QGP3125 *** CREATED 52440 / OPEN EQUIPMENT DESC LONDON RD JN -CLAY CROSS STH JN : 127 : 1179 : 147 : 1507 : DOWN FAST/MAIN : 127.1179 3428697 FAILED AT 10/06/2009 19:21:36 PLACE CLAY CROSS TUNNEL 47003 DISCIPLINE PWAY SUFFIX TRACK (P.W) ATTEND DERBY PWAY : MAC160 MAINTAIN LOSCOE S&T MTCE MAB110 IN ORDER REPORTED BY TRAIN CREW . RECTIFY AT REPORTED AS LONDON RD JN -CLAY CROSS STH JN : 127 : 1179 : 1 47 : 1507 : DOWN FAST/MAIN : 127.1179 : TRACK 3428697 EQUIP COMMENTS DETAILS REPORT OF FLOODING AT THE NORTH END OF CLAY CROSS TU NNEL DESCRIPTION*** 11-JUN-2009 14:57:00 *** QGP3131 *** *** 11/06/09 14:57 #QGP3131 *** AMENDED RESOLUTION*** 15-JUN-2009 16:01:00 *** QVP0100 *** * 15/06/09 16:01 #QVP0100 * ACCEPTED BY USER 920 RESOLUTION*** 12-JUN-2009 12:11:00 *** QVP3131 *** * 12/06/09 12:11 #QVP3131 * ACCEPTED BY USER 904 RESOLUTION*** 11-JUN-2009 09:03:00 *** QVP0100 *** * 11/06/09 09:03 #QVP0100 * DISPUTED PARTIAL ACCEPTANCE 907 * 11/06/09 09:03 #QVP0100 * CODE CHANGED RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW REASON CODE UPDATED FROM JK TO X2	506	£17,880
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DISCIPLINE PWAY SUFFIX TRACK (P.W) ATTEND DERBY PWAY: MAC160 MAINTAIN LOSCOE S&T MTCE MAB110 IN ORDER REPORTED BY DY PSB. RECTIFY AT REPORTED AS LONDON RD JN -CLAY CROSS STH JN : 127 : 1179 : 1 47 : 1507 : DOWN FAST/MAIN : 127.1179 : TRACK 3428697 EQUIP COMMENTS DETAILS 5F48 REPORTS WATER CASCADING FROM CLAY CROSS NTH POR TAL ONTO DOWN MAIN-UP MAIN NOT AFFECTED-CAUTIONING D/M FROM DC4848 CAUSE ACTION	234	£7,246

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							DESCRIPTION*** 01-NOV-2009 12:02:00 *** QVP2967 *** *** 01/11/09 12:02 #QVP2967 *** AMENDED 10:30 5F48 DRIVER CONTACTED CHESTERFIELD WORKSTATION TO REPORT FLO ODING AT THE NORTH END OF CLAY CROSS TUNNEL. THE WATER IS AB OVE THE RAILHEAD ON THE LEFT HAND SIDE LEG OF THE DOWN MAIN. THE UP MAIN IS CURRENTLY CLEAR. 5 MPH IMPOSED ON THE DOWN M AIN. ADDITIONAL LEAF FALL TEAM ADVISED AND EN ROUTE FROM LON G EATON AREA. PWAY ALSO EN ROUTE. 11:24 1M35 DRIVER REPORTS THAT FLOODING IS NOW AFFECTING THE UP MA IN AS WELL 5 MPH NOW IN PLACE ON THE UP MAIN. LEAF FALL TEA M AT CLAY CROSS BUT REPORT DIFFICULTIES ACCESSING THE LOCATI ON DESCRIPTION*** 02-NOV-2009 15:39:00 *** QGP3131 *** *** 02/11/09 15:39 #QGP3131 *** AMENDED SEVERE WEATHER WARNING IN PLACE ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2		
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	RECTIFY AT REPORTED AS LONDON RD JN -CLAY CROSS STH JN : 127 : 1179 : 1 47 : 1507 : DOWN FAST/MAIN : 127.1179 : TRACK 3428697 EQUIP COMMENTS DETAILS NOTES.1S35 REPORTS FLOODING WATER ON DOWN MAIN AT NT H PORTAL OF CLAY CROSS. CAUSE ACTION 4M11 TO EXAMINE THE LINE. 13:45 DRIVER ON 4M11 REPORT WATER ABOVE RAIL LEVEL OVER ALL LINES BALLAST BEING DISLODGED STOP ON THE DOWN 5 MPH ON THE UP DESCRIPTION*** 23-NOV-2009 14:07:00 *** QVP0637 *** *** 23/11/09 14:07 #QVP0637 *** AMENDED TDTL ADVISED AND REPORTS 'JK' PENDING ANY FURTHER INFO. DESCRIPTION*** 23-NOV-2009 14:14:00 *** QVP0637 *** *** 23/11/09 14:14 #QVP0637 *** AMENDED 14:01 DOWN LINE REOPENED AT 5 MPH. 1S39/1E40 WILL DIVERT VIA THE EREWASH VALLEY. DESCRIPTION*** 23-NOV-2009 14:39:00 *** QVP0637 *** *** 23/11/09 14:39 #QVP0637 *** AMENDED 14:17 LINE SPEED ON THE UP. DESCRIPTION*** 23-NOV-2009 15:45:00 *** QGP3131 *** *** 23/11/09 15:45 #QGP3131 *** AMENDED RECODED TO X2 AFTER CONSULTATION WITH RAM. 23/11/2009 14:31:21 [PAGE UPDATE] 14:17 UP LINE RE-OPENED A T LINE SPEED DN LINE STILL AT 5MPH. 23/11/2009 15:33:58	1051	£32,026

							[PAGE UPDATE] UPDATE FROM SITE: DERBY PW REPORTS DOWN CESS RAIL IS CURRENTLY UNDER WATER. THE 5 MPH ESR TO REMAIN ON WITH STAFF MONITORS REMAINING ON SITE UFN. ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2		
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DESCRIPTION*** 06-DEC-2009 08:56:00 *** QVP3124 *** *** 06/12/09 08:56 #QVP3124 *** CREATED DERBY CONTROL ADVISE TRACK FLOODING AT CLAY CROSS TUNNEL ARE A. 5F38 CANCELLED. DOWN MAIN LINE BLOCKED FROM 0813. DESCRIPTION*** 06-DEC-2009 09:33:00 *** QVP3124 *** *** 06/12/09 09:33 #QVP3124 *** AMENDED FAULT NO/STATUS 56982 / OPEN EQUIPMENT DESC LONDON RD JN -CL AY CROSS STH JN : 127 : 1179 : 147 : 1507 : DOWN FAST/MAIN : 127.1179 3428697 FAILED AT 06/12/2009 08:16:23 PLACE CLAY CROSS TUNNEL 47003 DISCIPLINE PWAY SUFFIX TRACK (P.W) ATTEND DERBY PWAY : MAC160 MAINTAIN LOSCOE S&T MTCE MAB110 IN ORDER REPORTED BY . RECTIFY AT REPORTED AS LONDON RD JN -CLAY CROSS STH JN : 127 : 1179 : 1 47 : 1507 : DOWN FAST/MAIN : 127.1179 : TRACK 3428697 EQUIP COMMENTS DETAILS DOWN MAIN BLOCKED DUE TO FLOODING WATER RAPIDLY MOVI NG AT RAILHEAD HEIGHT FOR 90YDS NTH OF CLAY CROSS TUNNEL. DESCRIPTION*** 07-DEC-2009 16:23:00 *** QGP3131 *** *** 07/12/09 16:23 #QGP3131 *** AMENDED	72	£2,510
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DESCRIPTION*** 24-SEP-2012 15:44:00 *** QGP3111 *** *** 24/09/12 15:44 #QGP3111 *** CREATED CLAYXS FLOODING DERBY TRC ADVISED 1F38 REPORTED FLOODING IN THE CLAY CROSS A REA. DESCRIPTION*** 24-SEP-2012 19:48:00 *** QGP3131 *** *** 24/09/12 19:48 #QGP3131 *** AMENDED WEATHER WARNINGS ISSUED FOR HEAVY RAIN ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2 RESOLUTION*** 29-DEC-2012 06:44:00 *** QVP0146 *** * 29/12/12 06:44 #QVP0146 * ACCEPTED BY USER RESOLUTION*** 27-SEP-2012 17:40:00 *** QVPDERK *** * 27/09/12 17:40 #QVPDERK * DISPUTED INCORRECT MANAGER CODE DELAY ALSO TO 1E82 1C25 1P24 AND 5U82 ALSO DISPUTED SHOULD BE DOWN TO PREVIOUSLY MENTIONED POSSESSION OVERRUN.	1305	£47,259

							RESOLUTION*** 26-SEP-2012 16:37:00 *** QVPDERK *** * 26/09/12 16:37 #QVPDERK * DISPUTED PARTIAL ACCEPTANCE DELAYS TO 6Y09 1E34 1F00 1R52 AND 1C20 WRONGLY ATTRIBUTED AND SHOULD BE DOWN TO TDA 085230 POSSESSION OVERRUN. AS FA R AS FLOODING IS CONCERNED THE LINES BETWEEN DERBY AND CLAY CROSS WERE BACK TO LINESPEED WITH THE UP THE LAST ONE TO GO BACK AT 1903 THE PREVIOUS NIGHT PLEASE REATTRIBUTE THE DELA Y TO THESE TRAINS. RESOLUTION*** 26-SEP-2012 16:27:00 *** QVPDERK *** * 26/09/12 16:27 #QVPDERK * DISPUTED INCORRECT MANAGER CODE 2		
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DESCRIPTION*** 25-NOV-2012 08:48:00 *** QGP0003 *** *** 25/11/12 08:48 #QGP0003 *** CREATED CLAYXNJ FLOODING DETAILS LINE BLOCKED **FLOODING WATER** UP/DN MAIN CLAY CROS S TUNNEL TO DOWN CLAY CROSS LOOPS 829PTS OWING TO FLOODING B ETWEEN DERBY AND CHESTERFIELD ALL LINES ARE BLOCKED. TRAIN S ERVICES THROUGH THESE STATIONS MAY BE SUBJECT TO DISRUPTION ON ALL ROUTES AT SHORT NOTICE. AN ESTIMATE FOR THE RESUMPTIO N OF NORMAL SERVICES WILL BE PROVIDED AS SOON AS THE PROBLEM HAS BEEN FULLY ASSESSED. DESCRIPTION*** 25-NOV-2012 08:49:00 *** QGP0003 *** *** 25/11/12 08:49 #QGP0003 *** AMENDED ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2 DESCRIPTION*** 25-NOV-2012 09:50:00 *** QGP0003 *** *** 25/11/12 09:50 #QGP0003 *** AMENDED 09:27 XC ADVISE THAT NO DISPENSATION CAN BE GIVEN FOR HST T O RUN THROUGH FLOOD WATER XC ADVISE NO DRIVER ROUTE KNOWLE DGE TO RUN VIA EAST MIDS AND NO ROUTE CONDUCTOR AVAILABLE EMT ASKED IF ANY DRIVER AVAILABLE TO ASSIST WITH ROUTE CONDU CTING BUT SPARE DRIVERS HAVE ALL BEEN USED . 1V48 TO RUN BACK TO SHEFFIELD FROM CHESTERFIELD TO CLEAR UP LINE YORK TRC ADVISED AND XC HST CURRENTLY TO BE BLOCKED TO DERBY UNTIL FLOOD LEVEL SUBSIDES RESOLUTION*** 26-APR-2013 15:08:00 *** QVPDQM1 *** * 26/04/13 15:08 #QVPDQM1 * ACCEPTED BY USER	129	£6,332

							RESOLUTION*** 27-NOV-2012 10:12:00 *** QVP0155 *** * 27/11/12 10:12 #QVP0155 * DISPUTED PARTIAL ACCEPTANCE DISPUTED PENDING REVIEW OF XC COMPANY SPECIFIC INSTRUCTIONS RELATING TO CLASS 220/221/HST STOCK. RESOLUTION*** 25-NOV-2012 18:46:00 *** QVP0154 *** * 25/11/12 18:46 #QVP0154 * ACCEPTED BY USER		
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DESCRIPTION*** 21-OCT-2013 13:25:00 *** QGM0637 *** *** 21/10/13 13:25 #QGM0637 *** CREATED DETAILS TRACK FLOODING REPORTED CLAY CROSS TUNNEL NORTH ABO VE RAILHEAD	156	£10,103
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DESCRIPTION*** 09-JUN-2014 14:08:00 *** QGP2967 *** *** 09/06/14 14:08 #QGP2967 *** CREATED DETAILS NOTES. 1F28 DRIVER REPORTS FLOOD WATER AT THE NORTH PORTAL OF CLAY CROSS TUNNEL DESCRIPTION*** 09-JUN-2014 16:14:00 *** QGP0023 *** *** 09/06/14 16:14 #QGP0023 *** AMENDED SERVICE RECOVERY GRANTED TO NORTHERN TRAINS AT 1423 HOURS. DESCRIPTION*** 09-JUN-2014 16:19:00 *** QGP0023 *** *** 09/06/14 16:19 #QGP0023 *** AMENDED PLEASE DISREGARD SERVICE SERVICE RECOVERY TEXT - NOT APPLICA BLE TO THIS INCIDENT. DESCRIPTION*** 09-JUN-2014 17:07:00 *** QGP2967 *** *** 09/06/14 17:07 #QGP2967 *** AMENDED ** RESPONSIBLE MANAGER CODE UPDATED FROM IQGN TO ** REASON CODE UPDATED FROM JK TO X2	357	£27,815
2009	Clay Cross Tunnel (north)	Clay Cross Tunnel to 829 points	SPC8	147.0484	147.0990	I.03	DESCRIPTION*** 21-NOV-2016 17:01:00 *** QGP2967 *** *** 21/11/16 17:01 #QGP2967 *** CREATED 16:39DM CLAY CROSS NORTH TUNNEL PORTAL POSSIBLE FLOODING REP ORTED BY 1E48 (1345 READING - NEWCASTLE). NEXT TRAIN IN EITH ER DIRECTION TO BE S&C THROUGH THE AREA. 1V62 (1100 GLASGOW - PZ) ON THE UP AND 1F43 (1426 ST PX - SHEFF) ON THE DOWN. 16:42NOTTM MOM ADVISED AND EN-ROUTE FROM NOTTM ETA 17.42. XC T AND EMT ADVISED DESCRIPTION*** 23-NOV-2016 09:22:00 *** QGP6000 *** *** 23/11/16 09:22 #QGP6000 *** AMENDED AMENDED BY LEVEL 2 696435 EMT MERGED AS PER CCIL	1,698	£174,227

Draycott Site

Period	Business Year	Incident Date	Year	Month	Incident Number	Incident Start Time	Incident Description	Incident FMS
2012/13_P04	2012/13	06 July 2012	2012	7	908904	19:05	BORROWASH FLOODING	80948
2012/13_P09	2012/13	25 November 2012	2012	11	258244	08:13	LNGEDRY FLOODINGL: flood water to the top of the railhead on the DM at Bridge 15 Sawley, 5mph imposed.	84606
2012/13_P10	2012/13	20 December 2012	2012	12	331504	13:00	LNGEDRY FLOODING	
2012/13_P10	2012/13	20 December 2012	2012	12	340674	13:00	LNGEDRY FLOODING L4	
2012/13_P10	2012/13	20 December 2012	2012	12	340674	13:00	LNGEDRY FLOODING L4	
2012/13_P10	2012/13	22 December 2012	2012	12	337024	13:23	LNGEDRY FLOODING 22/11	85320
2012/13_P10	2012/13	22 December 2012	2012	12	337024	13:23	LNGEDRY FLOODING 22/11	85320
2013/14_P11	2013/14	27 January 2014	2014	1	295890	03:14	LGE FLOODING	96924
2013/14_P11	2013/14	01 February 2014	2014	2	309727	10:42	LNGEDRY FLOODING	
2015/16_P12	2015/16	09 February 2016	2016	2	13524	05:15	LNGEDRY FLOODING	117113
2017/18_P13	2017/18	12 March 2018	2018	3	875878	tbc	LNGEDRY FLOODING	136733
2018/19_P01	2017/18	02 April 2018	2018	4	927809	tbc	LNGEDRY FLOODING	136733

First year reported	Exact Location	Assets Affected	ELR	Exact Mileage From	Exact Mileage To	SRS	Text	Total	PfPI Costs
2012	Draycott	Bridge 16 and TD4437	SPC6	120.1144	122.1494	I.03	06/07/2012 21:47 DRIVER HAS STATED THAT WATER WAS ABOVE RAILHEAD FURTHER BACK TOWARDS TRENT 06/07/2012 21:52 P-WAY R/R ADVISED AND HEADING BACK TOWARDS BRIDGE 15 TO CHEC K WATER LEVEL. DESCRIPTION*** 07-JUL-2012 06:48:00 *** QGP0003 *** *** 07/07/12 06:48 #QGP0003 *** AMENDED DESCRIPTION*** 07-JUL-2012 19:42:00 *** QGP3134 *** *** 07/07/12 19:42 #QGP3134 *** AMENDED AS PER EMCC SSM ADVISED 1C75 STOPPED AT SAWLEY TO REPORT POS SIBLE FLOODING. F2000 UPDATE 07/07/2012 19:17:04 [PAGE UPDATE] EMCC SSM ADVI SE WATER LEVEL IN THE VICINITY OF BRIDGE 16 HAS BEEN REPORTE D BY 1C75 AS UPTO THE PANDROL CLIPS. THIS HAS NOT CHANGED SI NCE P-WAY R/R EXAMINED LAST AND TRAINS OK TO CONTIMUE TO RUN NORMALLY DESCRIPTION*** 09-JUL-2012 06:48:00 *** QVP3122 *** *** 09/07/12 06:48 #QVP3122 *** AMENDED FAULT NO/STATUS 80948 / CODED EQUIPMENT DESC RATCLIFFE JCN - SPONDON : 118 : 1320 : 126 : 594 : DOWN FAST/MAIN : 118.132 0 3427597 FAILED AT 06/07/2012 19:05:09 PLACE DRAYCOTT (NOONING LANE) 46976 DISCIPLINE PWAY SUFFIX TRACK (P.W) ATTEND DERBY PWAY : MAC160 MAINTAIN DERBY S&T MTCE MAC110 IN ORDER 08/07/2012 20:12:00 REPORTED BY 1F56 DVR .. RECTIFY AT 08/07/2012 20:12:00 REPORTED AS EQUIP COMMENTS DETAILS NOTES. REPORT OF MOVING WATER ON APPROACH TO TD4437 AT DRAYCOTT (O/B 13 - O/B 12) BY 1F56 ON THE DM. CAUSE FLOOD WATER ACTION LEVELS HAVE NOW SUBSIDED AND NO FURTHER RAIN FALL.	239	£11,814
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 25-NOV-2012 08:19:00 *** QGP0003 *** *** 25/11/12 08:19 #QGP0003 *** CREATED LNGEDRY FLOODING REPORT OF FLOODING AT DRAYCOTT UP/DN MAINS 06:32 STAFF ON SITE AT DRAYCOTT REPORTS FLOOD WATER ON BOTH LINES BUT STILL 1' BELOW RAILHEAD SO NORMAL RUNNING 06:38 ON SITE STAFF ADVISES WATER HAS BUILT UP ON THE DOWN MAIN N OW 5MPH BUT UP MAIN STILL NORMAL. 06:54 ON SITE STAFF REPORTS THAT WATER HAS NOW ALSO BUI8LT UP ON T HE UP MAIN 5MPH ALSO REQUIRED HERE BR15 - 122M 67CH.	2657	£100,418

							DESCRIPTION*** 25-NOV-2012 08:50:00 *** QGP0003 *** *** 25/11/12 08:50 #QGP0003 *** AMENDED ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2 DESCRIPTION*** 25-NOV-2012 10:20:00 *** QGP0003 *** *** 25/11/12 10:20 #QGP0003 *** AMENDED 09:55 1S39 TO TERMINATE AT DERBY TO FORM A 1Z48 IN PATH OF 1V48 60 LATE DEPARTURE FROM DERBY TDA ADVISED RESOLUTION*** 26-APR-2013 15:08:00 *** QVPDQM1 *** * 26/04/13 15:08 #QVPDQM1 * ACCEPTED BY USER RESOLUTION*** 27-NOV-2012 10:14:00 *** QVP0155 *** * 27/11/12 10:14 #QVP0155 * DISPUTED PARTIAL ACCEPTANCE DISPUTED PENDING REVIEW OF XC COMPANY SPECIFIC INSTRUCTIONS RELATING TO 220/221/HST STOCK IN RELATION TO FLOODWATER RESOLUTION*** 26-NOV-2012 22:22:00 *** QVP0154 *** * 26/11/12 22:22 #QVP0154 * ACCEPTED BY USER RESOLUTION*** 25-NOV-2012 20:04:00 *** QVP0154 *** * 25/11/12 20:04 #QVP0154 * ACCEPTED BY USER RESOLUTION*** 25-NOV-2012 18:47:00 *** QVP0154 *** * 25/11/12 18:47 #QVP0154 * ACCEPTED BY USER		
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 20-DEC-2012 13:39:00 *** QVP2967 *** *** 20/12/12 13:39 #QVP2967 *** CREATED DY PW ON SITE ADVISES WATER LEVEL ON THE DOWN MAIN IS NOW 25 MM FROM THE TOP OF THE RAIL HEAD AND AS SUCH A 5MPH TO BE IM POSED. THIS IS AT O/B 12 OVER APPROX 250YDS TOWARDS BRIDGE 1 6 DESCRIPTION*** 21-DEC-2012 11:08:00 *** QGP2781 *** *** 21/12/12 11:08 #QGP2781 *** AMENDED AS PER EAST MIDS PERFORMANCE TEAM. OTHER FORMS OF TRANSPORT AFFECTED AND DRAINS WERE CLEAR BUT OVERWHELMED ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2 DESCRIPTION*** 02-JAN-2013 14:17:00 *** QVP4508 *** *** 02/01/13 14:17 #QVP4508 *** AMENDED RESOLUTION*** 26-APR-2013 15:08:00 *** QVPDQM1 *** * 26/04/13 15:08 #QVPDQM1 * ACCEPTED BY USER RESOLUTION*** 24-DEC-2012 12:28:00 *** QVP0534 *** * 24/12/12 12:28 #QVP0534 * DISPUTED INCORRECT MANAGER CODE DISPUTED PENDING REVIEW OF DELAYS OCCURING FROM TRAINS RUNNI NG AT 3 MPH VICE 5 MPH RESOLUTION*** 21-DEC-2012 09:54:00 *** QVP0154 ***	5610	£228,245

							* 21/12/12 09:54 #QVP0154 * ACCEPTED BY USER RESOLUTION*** 20-DEC-2012 15:49:00 *** QVP0146 *** * 20/12/12 15:49 #QVP0146 * ACCEPTED BY USER		
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 24-DEC-2012 12:33:00 *** QGP2781 *** *** 24/12/12 12:33 #QGP2781 *** CREATED INCIDENT CREATED AT DERBY CONTROL REQUEST AFTER DISCUSSION W ITH NR LNE RPMM. INCIDENT CREATED IN RESPONSE TO 331504 SEVERE FLOODING ESR (5MPH) IMPOSED. DERBY CONTROL ADVISE - 'EAST MIDLANDS TRAINS HAVE COMPANY SPECIFIC INSTRUCTIONS THAT REQUIRE THEIR FLEET TO RUN ON CAR WASH SETTING WHEN RUNNING THROUGH FLOODWATER; THIS MEANS THAT THE Y ARE TRAVELLING AT 3 MPH WHEREAS THE GROUP STANDARD RULE BO OK ALLOWS TRAINS TO RUN AT 5 MPH. THE EXTENT OF THE FLOODING HAS MEANT THAT THE DISTANCE OF TH E 5 MPH HAS OFTEN BEEN A MILE OR MORE. ON THIS BASIS I BELIEVE THAT A PROPORTION OF THE DIRECT DELA Y INCURRED SHOULD BE ATTRIBUTABLE TO THE TOC AS THEY ARE RUN NING AT 3 MPH INSTEAD OF 5 MPH'. INCIDENT CREATED - DELAY TO ATTRIBUTION TO FOLLOW. EMT DRC A WARE. DESCRIPTION*** 11-APR-2013 07:58:00 *** QGP0500 *** *** 11/04/13 07:58 #QGP0500 *** AMENDED DESCRIPTION*** 04-JUN-2013 08:19:00 *** QGP4055 *** *** 04/06/13 08:19 #QGP4055 *** AMENDED ACCEPTED BY NR AT LEVEL 4 04/06/13 ** RESPONSIBLE MANAGER CODE UPDATED FROM MEM5 TO XQVW ** REASON CODE UPDATED FROM M8 TO X2 RESOLUTION*** 04-JUN-2013 08:36:00 *** QVP4055 *** * 04/06/13 08:36 #QVP4055 * ACCEPTED BY USER RESOLUTION*** 24-DEC-2012 12:35:00 *** EMG0900 *** * 24/12/12 12:35 #EMG0900 * DISPUTED INCORRECT MANAGER CODE LEVEL 2 TO INVESTIGATE PLEASE * 24/12/12 12:35 #EMG0900 * CODE CHANGED RESPONSIBLE MANAGER CODE UPDATED FROM TEMA TO MEM5 REASON CODE UPDATED FROM TZ TO M8	604	£34,616
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 24-DEC-2012 12:33:00 *** QGP2781 *** *** 24/12/12 12:33 #QGP2781 *** CREATED INCIDENT CREATED AT DERBY CONTROL REQUEST AFTER DISCUSSION W ITH NR LNE RPMM. INCIDENT CREATED IN RESPONSE TO 331504 SEVERE FLOODING ESR (5MPH) IMPOSED. DERBY CONTROL ADVISE - 'EAST MIDLANDS TRAINS HAVE COMPANY SPECIFIC	5	£285

							INSTRUCTIONS THAT REQUIRE THEIR FLEET TO RUN ON CAR WASH SETTING WHEN RUNNING THROUGH FLOODWATER; THIS MEANS THAT THE Y ARE TRAVELLING AT 3 MPH WHEREAS THE GROUP STANDARD RULE BO OK ALLOWS TRAINS TO RUN AT 5 MPH. THE EXTENT OF THE FLOODING HAS MEANT THAT THE DISTANCE OF TH E 5 MPH HAS OFTEN BEEN A MILE OR MORE. ON THIS BASIS I BELIEVE THAT A PROPORTION OF THE DIRECT DELA Y INCURRED SHOULD BE ATTRIBUTABLE TO THE TOC AS THEY ARE RUN NING AT 3 MPH INSTEAD OF 5 MPH'. INCIDENT CREATED - DELAY TO ATTRIBUTION TO FOLLOW. EMT DRC A WARE. DESCRIPTION*** 11-APR-2013 07:58:00 *** QGP0500 *** *** 11/04/13 07:58 #QGP0500 *** AMENDED DESCRIPTION*** 04-JUN-2013 08:19:00 *** QGP4055 *** *** 04/06/13 08:19 #QGP4055 *** AMENDED ACCEPTED BY NR AT LEVEL 4 04/06/13 ** RESPONSIBLE MANAGER CODE UPDATED FROM MEM5 TO XQVW ** REASON CODE UPDATED FROM M8 TO X2 RESOLUTION*** 04-JUN-2013 08:36:00 *** QVP4055 *** * 04/06/13 08:36 #QVP4055 * ACCEPTED BY USER RESOLUTION*** 24-DEC-2012 12:35:00 *** EMG0900 *** * 24/12/12 12:35 #EMG0900 * DISPUTED INCORRECT MANAGER CODE LEVEL 2 TO INVESTIGATE PLEASE * 24/12/12 12:35 #EMG0900 * CODE CHANGED RESPONSIBLE MANAGER CODE UPDATED FROM TEMA TO MEM5 REASON CODE UPDATED FROM TZ TO M8		
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 22-DEC-2012 13:49:00 *** QVP2967 *** *** 22/12/12 13:49 #QVP2967 *** CREATED 22/12/2012 13:23 5 MPH RE-IMPOSED ON DOWN LINE ONLY DUE TO WATER RISING ONTO RAILHEAD 13:25: 1F30 REPORTS ISSUE WITH AIR LEAK AFTER PASS ING THROUGH AREA. EMT ADVISED. XCT ADVISED. NEW INCIDENT CREATED AS ADVISED BY DERBY TRC. DESCRIPTION*** 23-DEC-2012 15:19:00 *** QGP1212 *** *** 23/12/12 15:19 #QGP1212 *** AMENDED INCIDENT : 338879 5F24 25 LATE OFF SHF DESCRIPTION*** 23-DEC-2012 14:49:00 *** EMG0900 *** * 23/12/12 14:49 #EMG0900 * DISPUTED INCORRECT MANAGER CODE PLEASE MERGE WITH 337024 AS DY2107 DRIVER IS BOOKED PNB AFTER WORKING IN 1F24 BUT DUE TO SCHEDULES BEING CHANGED DUE TO THIS INCIDENT DESCRIPTION*** 24-DEC-2012 07:56:00 *** QVP3122 ***	2286	£111,207

							*** 24/12/12 07:56 #QVP3122 *** AMENDED 24/12/2012 04:40 XC / EMT / DERBY /EMCC /TRENT ALL ADVISED THAT LINE SPEED TO BE RESTORED AND FULL SERVICE TO BE REINSTATED DESCRIPTION*** 04-JAN-2013 14:12:00 *** QGP2781 *** *** 04/01/13 14:12 #QGP2781 *** AMENDED AS PER MIDLAND ROUTE ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2 RESOLUTION*** 04-JAN-2013 14:09:00 *** QVPDQM1 *** * 04/01/13 14:09 #QVPDQM1 * DISPUTED INCORRECT DELAY CODE . RESOLUTION*** 24-DEC-2012 12:18:00 *** QVP0534 *** * 24/12/12 12:18 #QVP0534 * DISPUTED INCORRECT MANAGER CODE DISPUTED PENDING REVIEW OF DELAY RE OPERATOR RUNNING AT 3 MP H VICE 5 MPH		
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 22-DEC-2012 13:49:00 *** QVP2967 *** *** 22/12/12 13:49 #QVP2967 *** CREATED 22/12/2012 13:23 5 MPH RE-IMPOSED ON DOWN LINE ONLY DUE TO WATER RISING ONTO RAILHEAD 13:25: 1F30 REPORTS ISSUE WITH AIR LEAK AFTER PASS ING THROUGH AREA. EMT ADVISED. XCT ADVISED. NEW INCIDENT CREATED AS ADVISED BY DERBY TRC. DESCRIPTION*** 23-DEC-2012 15:19:00 *** QGP1212 *** *** 23/12/12 15:19 #QGP1212 *** AMENDED INCIDENT : 338879 5F24 25 LATE OFF SHF DESCRIPTION*** 23-DEC-2012 14:49:00 *** EMG0900 *** * 23/12/12 14:49 #EMG0900 * DISPUTED INCORRECT MANAGER CODE PLEASE MERGE WITH 337024 AS DY2107 DRIVER IS BOOKED PNB AFTER WORKING IN 1F24 BUT DUE TO SCHEDULES BEING CHANGED DUE TO THIS INCIDENT DESCRIPTION*** 24-DEC-2012 07:56:00 *** QVP3122 *** *** 24/12/12 07:56 #QVP3122 *** AMENDED 24/12/2012 04:40 XC / EMT / DERBY /EMCC /TRENT ALL ADVISED THAT LINE SPEED TO BE RESTORED AND FULL SERVICE TO BE REINSTATED DESCRIPTION*** 04-JAN-2013 14:12:00 *** QGP2781 *** *** 04/01/13 14:12 #QGP2781 *** AMENDED AS PER MIDLAND ROUTE ** RESPONSIBLE MANAGER CODE UPDATED FROM IQVW TO XQVW ** REASON CODE UPDATED FROM JK TO X2 RESOLUTION*** 04-JAN-2013 14:09:00 *** QVPDQM1 *** * 04/01/13 14:09 #QVPDQM1 * DISPUTED INCORRECT DELAY CODE . RESOLUTION*** 24-DEC-2012 12:18:00 *** QVP0534 *** * 24/12/12 12:18 #QVP0534 * DISPUTED INCORRECT MANAGER	200	£8,196

							CODE DISPUTED PENDING REVIEW OF DELAY RE OPERATOR RUNNING AT 3 MP H VICE 5 MPH		
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 27-JAN-2014 03:21:00 *** QGP3129 *** *** 27/01/14 03:21 #QGP3129 *** CREATED NOTES:DVR OF 6M27 REPORTS FLOODING TO THE TOP OF THE RAIL BO TH UP & DN MAINS FROM BR15 - APPROX 440YDS ON APPROACH TO TD 4434 SIG.	0	£0
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 01-FEB-2014 10:43:00 *** QGM0637 *** *** 01/02/14 10:43 #QGM0637 *** CREATED WHEN ASKED EMCC SSM REPORTS 2A27 DELAYED SAWLEY R/A CROSSIN G USER AT SAWLEY LC REPORTS WATER EGRESS AT DRAYCOTT.	8	£212
2012	Draycott	Bridges 12 to 17	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 09-FEB-2016 08:01:00 *** QGM0637 *** *** 09/02/16 08:01 #QGM0637 *** CREATED DETAILS REF DY OTM / DY PW. NOTES: IRT REPORT THAT THEY HAVE BEEN MONITORING ISSUE OVER NIGHT DN LINE NOW HAS WATER COVE RING RAIL CLIPS UP LINE STILL HAS CLIPS SHOWING BUT WATER C OVERING SLEEPERS WATER IS STANDING WATER NOT MOVING AND NOT MOVING BALLAST. FLOODING OVER AROUND 200 YARDS. ACCESS FROM BRIDGE 16 DRAYCOTT ROAD AND WALK TOWARDS DERBY ISSUE IS UND ER VILLA STREET BRIDGE. >>>	9	£494
2012	Draycott	Bridges 12 to 13	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 12-MAR-2018 18:29:00 *** QGP1220 *** *** 12/03/18 18:29 #QGP1220 *** CREATED 18:05SSM ADVISES 1F53 HAS STATED WATER UP TO RAILHEAD AND NO T ABOVE ON DOWN MAIN PAST TD4439 SIGNAL. CURRENTLY CAUTIONIN G AT 5MPH. MOM ETA 18:30 18:19VOICE COMMS CHECKED AND DRIVER ADVISES WATER OF RAILHEA D IN PATCHES THROUGHOUT THE AREA. EMT/XC HST AND 15X STOCK S USPENDED. XC 220/221 STOCK 3MPH CAUTION. EMT MERIDIAN STOCK 5MPH 18:26EMCC SSM ADVISES THAT 2N59 HAS JUST GONE THROUGH ON THE UP AND CONFIRMED NO STANDING WATER ON THE UP AND THE RAILHE AD IS VISIBLE ON THE DOWN. 1F55 CURRENTLY BEING CAUTIONED ON THE DOWN AND SITUATION TO BE RE-EVALUATED AFTER THIS. DESCRIPTION*** 12-MAR-2018 23:25:00 *** QGP1220 *** *** 12/03/18 23:25 #QGP1220 *** AMENDED RESOLUTION*** 12-MAR-2018 22:20:00 *** QGP1146 *** * 12/03/18 22:20 #QGP1146 * DISPUTED PARTIAL ACCEPTANCE DELAYS TO EMT SERVICES WHERE CAUTIONED AS PER THEIR INSTRUCTIONS WHICH IS CONTRARY TO RULE BOOK INSTRUCTIONS SHOULD BE ATTRIBUTED TO EMT. DELAYS REQUIRE TO BE SPLIT.	406	£20,413

2012	Draycott	Bridges 12 to 13	SPC6	120.1144	122.1494	I.03	DESCRIPTION*** 02-APR-2018 17:17:00 *** QGP1220 *** *** 02/04/18 17:17 #QGP1220 *** CREATED : DVR OF 1M68 REPORTS FLOOD-WATER IN THE 4FT OF BOTH THE UP & DN MAINS CURRENTLY NOT TO THE BOTTOM OF THE RAIL BUT COVE RING THE BALLAST IN THE AREA OF THE OLD MARLBOROUGH FOOT/BAR ROW-X-ING. WATER SEEMS TO BE MOVING VERY SLIGHTLY & "RIPPLI NG". SSM HAS DECIDED TO CAUTION 1F48 DN MAIN DUE TO THE REPORT O F THE THE "RIPPLING" / WATER MOVING SLIGHTLY. DESCRIPTION*** 02-APR-2018 17:23:00 *** QGP1220 *** *** 02/04/18 17:23 #QGP1220 *** AMENDED DESCRIPTION*** 02-APR-2018 21:34:00 *** QGE0001 *** *** 02/04/18 21:34 #QGE0001 *** AMENDED	148	£9,861

APPENDIX 5 Technical parameters for pipe drains

Appendix 0.2 Pipe gradient (Network Rail, 2010)

Pipe dia	150mm D	150mm V	225mm D	225mm V	300mm D	300mm V	375mm D	375mm V	450mm D	450mm V	525mm D	525mm V
Gradient 1 in	Nominally self-cleaning										Damaging	
50	23.3	1.32	68.8	1.73	148.2	2.10	268.6	2.43	436.8	2.75	658.9	3.04
100	16.5	0.93	48.6	1.22	104.8	1.48	189.9	1.72	308.9	1.94	465.9	2.15
150	13.5	0.76	39.7	1.00	85.5	1.21	155.1	1.40	252.2	1.59	380.4	1.76
200	11.7	0.66	34.4	0.87	74.1	1.05	134.3	1.22	218.4	1.37	329.4	1.52
250	-	-	31.4	0.79	67.6	0.96	122.6	1.11	199.4	1.25	300.7	1.39
300	-	-	28.1	0.71	60.5	0.86	109.7	0.99	178.3	1.12	269.0	1.24
350	-	-	26.0	0.65	56.0	0.79	101.5	0.92	165.1	1.04	249.0	1.15
400	-	-	-	-	52.4	0.74	95.0	0.86	154.4	0.97	232.9	1.08
450	-	-	-	-	49.4	0.70	89.5	0.81	145.6	0.92	219.6	1.01
500	-	-	-	-	46.8	0.66	84.9	0.77	138.1	0.87	208.4	0.96
600	-	-	-	-	42.8	0.61	77.5	0.70	126.1	0.79	190.2	0.88
700	-	-	-	-	-	-	-	-	116.7	0.73	176.1	0.81
	Nominally silting											

Appendix 0.3 Recommended hydraulic roughness values (Network Rail, 2010)

Material	Roughness, k (mm)
Plastic	0.03
Concrete	0.06 - 1.5
Vitrified clay/earthenwate/clayware	0.06
Brick - well pointed	4
Ductile/cast iron	0.06 / 0.015
Spiral wound steel/ uncoated steel	0,03
Pitch fibre	0,03
Asbestos cement	0,03
Spun bitumen or concrete lined	0,03
Grass reinforced plastic as lining material	0,03

Appendix 0.1 Coefficient for part-full pipes (Network Rail, 2010)

Proportional Depth	Coefficient
0.10	0.019
0.20	0.085
0.30	0.193
0.40	0.336
0.50	0.500
0.60	0.673
0.70	0.840
0.75	0.916
0.80	0.982
0.85	1.035
0.90	1.070
0.95	1.078

APPENDIX 6 Contributing Factors: Risks Related to C3 Drainage Assets

a. Contributing factors: risks related to C3 drainage assets

In this section, the risks, which have been categorised into various contributing factors associated with defective or failed drainage assets (C3), are discussed with respect to the likelihood of their occurrence. The contributing factors are related to the subgrade, environment, land use, maintenance, components, design and installation.

b. Contributing factor: subgrade

In this category, the risks are related to weak soil (X5) and excessive soil pressure (X8)

i. Weak soil (X5)

In terms of the railway track's substructure, subgrade soils, especially fine grained such as clays and silts whose strength is likely to be affected by water ingress are termed weak soils herein. A large deflection of a considerable depth may indicate a weak soil (Ghataora and Rushton, 2012; LI *et al*., 2016). When excessive water infiltrates a weak soil layer underneath a channel drain or ditch ditches, a softening event below this drain level can occur, which can then lead to settlement may lead to a change in gradient Excessive soil pressure (X8. Excessive soil pressure can lead to bank instability (Network Rail, 2011). This can occur when soil moisture is raised significantly, which generates pressures on the bank of the C3 (channel drains and ditches) assets and may lead to collapse of its structure.

c. Contributing factor: environmental

The risks in this category correspond to flood risk from: surface water (e.g. from heavy rainfall) (X6); river flooding (X7a); inundation from the sea (X7b); reservoirs (X7c); weathering (chemical) (X10); and prolonged, extreme hot weather (X44)

i. Flood risk from surface water (heavy rainfall) (X6)

Flood risks from surface water can occur during heavy rainfall events (Li *et al.*, 2016). These events, where they exceed the capacity of the drainage system, may lead to excessive surface water run-off, which can then lead to excessive water infiltration in the track bed and damage or block with debris drainage assets, such as channel drains and ditches (C3).

ii. Flood risk from rivers (X7a)

Flood risk from rivers adjacent to railway track substructures has been reported in the literature (Penning-Roswell, 2013; McBain *et al*. 2010). Typically flooding from rivers can occur when rivers break their banks or breach flood defence systems (McBain *et al* , 2010)). Although the C3 drainage assets may remain clear, they can be overwhelmed by flood water due to an inadequate capacity to cater for the flood. Otherwise, they can be blocked by debris carried by the flood water which may lead to an increase in the amount of water infiltrating the track bed.

iii. Flood risk from the sea (X7b)

The Dawlish rail incident in 2014 (DfT, 2014) showed that there is a risk from flooding to railway lines which are close to the sea or in coastal area. Sea water may infiltrate the track bed the Dawlish incident. At Dawlish the impacts were severe and included washed out a railway line, collapsed drainage assets which caused additional damage to the line. In direct impacts were associated with the line being closed for a period of time whilst the affected part was reconstructed and the rebuilding of the adjacent sea wall defences.

iv. Flood risk from reservoirs (X7c)

Although there has been no substantial record of flooding from reservoirs in the UK since 1925 (Environment Agency, 2018), there is still a risk to drainage assets (i.e. C3) of ballasted railway track built close to a reservoir or canal system.

v. Weathering (chemical) (X10)

According to Selig and Waters (1994), a weathering (or chemical) event may affect the track support system (i.e. ballast degradation), which is exposed directly to the atmosphere. Similarly, this also can occur with C3 assets that are installed on the side of or surrounding the track. The weathering risk may lead to a deterioration of C3 material.

vi. Scouring around channel drains and ditches (X29)

Scouring of the C3 assets may lead to bank instability (Network Rail, 2018).

vii. Prolonged extreme hot weather (X44)

Prolonged extreme hot weather may lead to settlement that may lead to a change in a gradient. This can be caused by cracks (Willway *et al.*, 2008) in the subgrade below the C3 assets, induced by the extreme event.

d. Contributing factor: land use

Other contributing factors include: changes to land use (catchment areas) (X11); changes to drainage upstream (X12); and damage caused by other/3rd party assets (X40)

i. Change to land use (catchment area) (X11)

As consequences of the rapid land development that has taken place adjacent to the UK's railway network over the last few decades (Mohammad *et al*., 2013; Du and Mulley, 2007) the catchment area might be reduced or may have changed. This may disrupt its main function, to retain and dissipate water adequately before it enters the drainage asset. i.e. the rate of surface runoff has been increased.

ii. Changes to drainage upstream (X12)

Changes to drainage upstream is associated with drainage systems that are not as those on the section of railway track considered and which can potentially have a negative affect the networks as excessive water run off to the surrounding track and may overwhelmed the track

iii. Damage caused by other/3rd party assets (X40)

According to Sihota (2016), damage caused by assets owned by others (i.e. 3rd party assets) may affect the condition of channel drains and diches. For example, piling or foundation works in a housing development adjacent to the railway line may cause a change in gradient of the specific section in which channel drains exists, which may in turn lead to substantial settlement.

e. Contributing factor: maintenance

Inadequate routine drainage maintenance is associated with the following risk:

i. Failure to clean out debris (X19)

A failure to clean out debris may lead to debris accumulation in C3 assets, which then become partially or fully blocked.

ii. Non-ballast material infiltration (X20)

C3 assets are mostly built as open structures, without covers. Therefore, non-ballast material may infiltrate these assets, which in turn increases the debris infiltration risk (DE1). This material can come from a number of sources, including waste or spillage from passing trains and fly tipping.

iii. Poor ballasting practices (X21)

Poor ballasting practices may lead to blocked C3 assets. This risk can be triggered by a failure to adequately perform blast maintenance activities, including tamping, stone blowing or blast renewal. This risk inhibits the ability of C3 assets to adequately drain water.

iv. Vegetation overgrowth (X25)

According to Network Rail (2010; 2018), vegetation overgrowth can partially or fully block channel drains and ditches, reducing their overall drainage capacity.

v. Spoil tipping (X26)

Spoil tipping occurs when the upper parts of earthworks (i.e. cutting) are degraded and spoiled, affecting the C3 assets. This risk may lead to a blockage, and subsequent failure, of the asset (D8).

vi. Damage caused by burrowing animals (X41)

Damage caused by burrowing animals has been discussed in Network Rail's Drainage Standard (Network Rail, 2010). This risk may contribute to blocked channel drains and ditches.

vii. Lack of silt clean out (channel drains) or excavate (ditches) (X42)

Routine siltation maintenance of the C3 assets plays an essential role in ensuring their adequate functioning. Insufficient maintenance may lead to a silting event, which may reduce the capacity of the drainage asset to drain water adequately.

f. Contributing factor: component

The components of aging channel drains and ditches can be at risk of failure if they have not been adequately maintained (X28).

i. Aging channel drains and ditches (X28)

Aging channel drains and diches may lead to unexpected deterioration rate of associated assets; this means the asset can be collapsed in any time

g. Contributing factor: design

Poor design of drainage assets can pose a risk, through for instance inadequate gradients of channel drains and ditches (X30):

i. Inadequate gradient of channel drains and ditches (X30)

Poor design can lead to inadequate gradients in drains and ditches. When that occurs, these assets may not dissipate water adequately, which in turn may mean they have inadequate capacity. This means that the drainage asset, although clear and free of debris, may be overwhelmed with water.

h. Contributing factor: Installation

Damage caused by poor installation (X43) may lead to the silting of C3 assets.

APPENDIX 7 Excel Tables for Risk Impact Estimation

Excel tables for estimating total impact (costs) of defective or failed drainage asset C3 (channel drains and ditches) at the selected sites

Appendix 7.1 Summary of the impact of risks associated with collapsed of channel drains and ditches at Ardsley Tunnel

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Cost (min) (£)	Cost (mid) (£)	Cost (max) (£)	Cost (mean) (£)	Data Source
1	2	3	4	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (i.e. wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12		1	Clearing drainage asset and pumping floodwater. 5%*(I111+I21+I22)				5,742.06	6,420.00	9,230.89	£6,775	Environment Agency (2018)
I13	m	200	Damage to drainage component				38,272.00	54,832.00	71,392.00	£54,832	
I14	m	200	Damage to signalling								
I2			Delay costs								
I21	minutes	574.88	Delay costs without speed restrictions and cancel	27.57	40.26	90.11	15,850.82	23,142.00	51,801.51	£26,703	NR's record (Appendix 4)
I22	minutes	422	Delay costs with speed restrictions (5 MPH)	42.86	47.62	52.38	18,085.76	20,095.29	22,104.82	£20,095	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		0	Residential cost								
I52		0	Non residential cost								
I6		0	Farming land damage costs								
It			Total Costs Impact							£197,117	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impact with 90% confidence (It90)							£210,768	

Appendix 7.2 Summary of the impact of risks associated with inadequate capacity of channel drains and ditches at Ardsley Tunnel

a.

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Cost (min) (£)	Cost (mid) (£)	Cost (max) (£)	Cost (mean) (£)	Data Source
1	2	3	4	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12'	Incident	1	Pumping floodwater.				4,593.65	5,136.00	7,384.71	£5,420	Environment Agency (2018)
			5%*(I111+I21+I22)*80%								
I13	m	200	Damage to drainage component								
I14	m	200	Damage to signalling								
I2			Total Delay costs								
I21	minutes	574.88	Delay costs without speed restrictions and cancela	27.57	40.26	90.11	15,850.82	23,142.00	51,801.51	£26,703	NR's record (Appendix 4)
I22	minutes	422	Delay costs with speed restrictions (5 MPH)	42.86	47.62	52.38	18,085.76	20,095.29	22,104.82	£20,095	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		0	Residential cost								
I52		0	Non residential cost								
I6		0	Farming land damage costs								
It			Total Costs Impact							£140,930	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impact with 90% confidence (It90)							£151,777	

Appendix *7.3* Summary of the impact of risks associated with collapsed channel drains and ditches at Clay Cross Tunnel

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Cost (min) (£)	Cost (mid) (£)	Cost (max) (£)	Cost (mean) (£)	Data Source
1	2	3	4	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (i.e. wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12	Incident	1	Clearing draiange asset and pumping floodwater. 5% *(I111 + I21 + I22)				6,672.59	7,595.88	9,853.53	£7,818	Environment Agency (2018)
I13	m	200	Damage to drainage component				38,272.00	54,832.00	71,392.00	£54,832	Sihota (2016)
I14	m	200	Damage to signalling								
I2			Delay costs								
I21	minutes	603.29	Delay costs without speed restrictions or cancellations	40.15	70.64	102.61	24,222.31	42,617.03	61,901.47	£42,765	NR's record (Appendix 4)
I22	minutes	643	Delay costs with speed restrictions (5 MPH)	37.46	37.57	38.07	24,066.77	24,137.95	24,457.67	£24,179	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		0	Residential cost								
	m2	4,537.20	Non residential cost								
I52	m2	224.30	Electricity sub station		193.9268		44,215.49	46,542.63	53,989.45	£47,396	Penning-Rowsell *et al.*(2013)
I53	m2	4,312.90	Depot		87.4404		383,344.21	403,520.22	468,083.46	£410,918	
I6		0	Farming land damage costs								
It			Total Costs Impact							£676,620	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impacts with 90% confidence (It90)							£701,700	

Appendix 7.4 Summary of the impact of risks associated with inadequate capacity channel drains and ditches at Clay Cross Tunnel

Code	**Unit**	**Quantity**	**Impact**	**Unit Cost (min) (£)**	**Unit Cost (mid) (£)**	**Unit Cost (max) (£)**	**Cost (min) (£)**	**Cost (mid) (£)**	**Cost (max) (£)**	**Cost (mean) (£)**	**Data Source**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
I1			Unplanned maintenance costs								
I11	m	200	Damage to track substructure (i.e. wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12	Incident	1	Pumping floodwater. 5% *(I111 + I21 + I22)*80%				5,338.07	6,076.71	7,882.83	£6,255	Environment Agency (2018)
I13	m	200	Damage to drainage component								
I14	m	200	Damage to signalling								
I2			Delay costs								
I21	minutes	603.29	Delay costs without speed restrictions or cancellations	40.15	70.64	102.61	24,222.31	42,617.03	61,901.47	£42,765	NR's record (Appendix 4)
I22	minutes	643	Delay costs with speed restrictions (5 MPH)	37.46	37.57	38.07	24,066.77	24,137.95	24,457.67	£24,179	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		0	Residential cost								
	m2	4,537.20	Non residential cost								
I52	m2	224.30	Electricity sub station		193.9268		44,215.49	46,542.63	53,989.45	£47,396	Penning-Rowsell *et al.* (2013)
I53	m2	4,312.90	Depot		87.4404		383,344.21	403,520.22	468,083.46	£410,918	
I6		0	Farming land damage costs								
It			Total Costs Impact							£620,224	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impacts with 90% confidence (It90)							£643,722	

Appendix 7.5 Summary of impact of risks associated with collapsed channel drains and ditches at Draycott

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Min (min) (£)	Mid (mid) (£)	Max (max) (£)	Cost (mean) (£)	Data Source
1	2	4	3	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (i.e. wet bed)								
I12	Incident	1	Clearing drainage asset and pumping floodwater.	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
			5%*(I1a1+I2a+I2b)				7,627.15	9,024.74	11,061.09	£9,131	Environment Agency (2018
I13	m	200	Damage to drainage component				38,272.00	54,832.00	71,392.00	£54,832	Sihota (2016)
I14	m	200	Damage to signalling								
I2			Total Delay costs								
I21	minutes	87.29	Delay costs	27.46	52.53	63.15	2,397.19	4,585.06	5,512.32	£4,375	NR's record (Appendix 4)
I22	minutes	1652	Delay costs with speed restrictions (5 MPH)	41.90	54.92	63.54	69,241.30	90,747.07	104,997.95	£89,538	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		6566.1	Residential cost		69.55		433,838.64	456,672.26	529,739.82	£465,045	
		0	Non residential cost								
I6		0	Farming land damage costs								
It			Total Costs Impact							£711,632	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impacts with 90% confidence (It90)							£738,524	

Appendix 7.6 Summary of impact of risks associated with inadequate capacity channel drains and ditches at Draycott

Code	Unit	Quantity	Impact	Unit Cost (min) (£)	Unit Cost (mid) (£)	Unit Cost (max) (£)	Min (min) (£)	Mid (mid) (£)	Max (max) (£)	Cost (mean) (£)	Data Source
1	2	3	4	5	6	7	8	9	10	11	12
I1			Unplanned maintenace costs								
I11	m	200	Damage to track substructure (i.e. wet bed)	404.52	425.81	553.56	80,904.57	85,162.70	110,711.51	£88,711	ORR (2013)
I12	Incident	1	Clearing drainage asset and pumping floodwater. 5%*(I1a1+I2a+I2b)*80%				6,101.72	7,219.79	8,848.87	£7,305	Environment Agency (2018)
I13	m	200	Damage to drainage component								
I14	m	200	Damage to signalling								
I2			Total Delay costs								
I21	minutes	87.29	Delay costs	27.46	52.53	63.15	2,397.19	4,585.06	5,512.32	£4,375	NR's record (Appendix 4)
I22	minutes	1652	Delay costs with speed restrictions (5 MPH)	41.90	54.92	63.54	69,241.30	90,747.07	104,997.95	£89,538	NR's record (Appendix 4)
I23	minutes	0	Delay costs with cancellations								
I3		0	Additional passenger travel costs								
I4		0	Bus transfer cost								
I5			Property damage costs								
I51		6566.1	Residential cost		69.55		433,838.64	456,672.26	529,739.82	£465,045	Penning-Rowsell *et al.*(2013
I52		0	Non residential cost								
I6		0	Farming land damage costs								
It			Total Costs Impact							£654,974	
			Results of Monte Carlo Simulation (MCS)								
-			Total costs impacts with 90% confidence (It90)							£680,762	

APPENDIX 8 Notes of the Results VerificationMeeting

Notes of Meeting

Agenda : Results verification/ validation subject to the development of a risk-Informed framework for the appraisal of drainage maintenance of ballasted railway track

Date : Tuesday, 10th December 2019

Duration : 1.5 hours (10.00 – 11.30 am)

Place : Network Rail Office, Baskerville House, Birmingham

Participants : Track Bed Team-Network Rail, Kristianto Usman

Session 1: Verification of the estimation results of likelihood of railway drainage risk (± 40 minutes)

Firstly, the researcher presented a brief of his research and the aim of the meeting. Thereafter, the results of the likelihood estimation were distributed to the experts to obtain some feedback. The experts asked about assumptions that were made to estimate the likelihood and data (input) for the model. Following the questions, the researcher answered that the probability of risk was estimated based on some assumptions as follows:

- The assessed site was a homogeneous 200 m section in part of the UK's rail network
- There are three failure modes which could potentially occurr on C3 (channel drains and ditches) drainage asset; the failure modes are blocked, collapsed, and inadequate capacity.
- The likelihood of the failure modes (risks) were presented by the range of percentage with 90% confidence along with an estimation point with 90% percentile (P90).

Based on the results of analysis and discussion during this session, the experts opinion are as follows:

- The likelihood of the blocked C3 at the cutting section (i.e. Ardsley, Clay Cross Tunnel) higher than at the plain section (Draycott); experts confirmed the finding cope with the current condition in the UK rail network.

- Considering the results of the likelihood estimation, the blocked needs to be firstly maintained. When the budget is available, the experts advised the undertaking of another failure simultaneously, i.e. blocked and collapsed maintenance.
- Based on the above findings, they confirmed that the results are sensible and justified.

Session 2: Verification of the estimation results of impact of railway drainage risk (± 20 minutes)

In this session, experts scrutinised the results of the risk impact based on a practitioner's point of view. The experts confirmed the results and suggested some thought as follows:

- A separate allocation for unplanned maintenance (direct cost) and delay cost as compensation to TOC with other types of impact that might have higher uncertainty, e.g. impact to property
- To refine the estimation, determine the unit cost for unplanned maintenance based on the quotation record from the contractor or the owner's estimate.

Session 3: Verification of the estimation results of risk value and the maintenance appraisal (± 30 minutes)

In this session, the link between risk values and maintenance decision was scrutinised by the experts. Based on their experiences and current practice, it is evident that the maintenance decision rely on the degree of importance of the assessed lines; there is a trade-off of consequences and likelihood of risks. If the routes have an equal degree of importance, the higher likelihood will be prioritised. This means that a site with a relatively lower likelihood may have a substantial impact if the failure occurs.

Therefore, the concept of risk value incorporating maintenance appraisal is suitable for the railway industry. Hence, the experts confirmed that the risk results are suitable and its feature (link between risk values-maintenance appraisal) can be considered for adoption.. In addition, some further insights were discussed as follows:

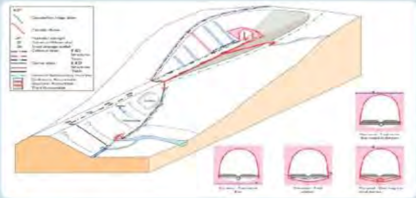
- The framework is suitable to perform the logic of the physical condition of drainage assets.
- The results are sensible and helpful for the maintenance decision-making process

- Potentially to be adopted in industry, it was suggested proposing it to the drainage route asset manager (RAM) for further development
- A failure database can be beneficial to improve this framework

APPENDIX 9 Concept of Improving Drainage Asset Management Decision Making – Network Rail

Improving Drainage Asset Management Decision Making

What is the situation?



The effective control of water is essential to the safe and economic management of railway infrastructure.

Drainage has an important role in reducing the degradation mechanisms caused by water; such as the long-term softening of materials that form the track support system and earthworks.

Neglect of the drainage system can have significant cost and safety implications for the parent asset; such as delay minutes, poor track geometry, line closures and a likelihood of earthwork failures.

Analysis of causes

Priority problems

Specific priority problems

- Lack of models including a top-down whole life modelling tool.
- Insufficient decision support tools.
- Insufficient tools and datasets to manage, view, map drainage as a system including a workflow management system.

Related goals

- To produce a top-down whole life cycle and cost model for drainage by CP7.
- To produce a bottom-up decision support work-bank tool by CP6.
- Drainage systems identified, connected, linked to system and mapped by CP6.
- Models to support planning via intervention scenarios at the system level.

Benefits

- This will enable more efficient and effective decision making that will provide both cost and safety benefits.
- Asset management underpins the whole life cycle of an asset base. Fit for purpose decision support tools, models and datasets will allow for informed decisions to be made that will improve life extension, safety, performance, resilience.

NetworkRail

Scope


fig. 1


fig. 2

The ability to make timely and effective decisions is a key factor in managing the assets in accordance with policy and strategy. Better decision making can help target drainage interventions and manage the system at an optimum whole life cost. Efficient, accurate and traceable decision making can also provide significant safety benefits by improving the condition of the parent assets and reducing the likelihood of failure.

The enablers to supporting better decision making are:

- Data Management.
- Decision Support Tools.
- Modelling.
- Systems Approach.
- Competency.

Providing a solution to the issues highlighted for each individual enabler (see below) will allow for safer, more reliable and efficient drainage systems.

Specific research needs

To address these challenges it is expected that R&D actions will need to address the following aspects:

1. **Models and top-down whole life modelling tool**

   How can top-down whole life cost modelling of drainage be achieved? What new models need to be developed and combined with existing models to account for factors such as degradation, capability analysis, flood risks due to land use change, climate change, weather resilience etc.?

2. **Decision support tools**

   How can current and new processes be managed better with decision support tools? What is required to develop a live bottom-up work-bank tool and how would this integrate with existing systems? How can intervention scenarios be modelled at a system level in order to support business planning?

3. **Tools and datasets to manage, view, map drainage as a system**

   How can we map and view drainage as a system? Tools and datasets are required for the management of drainage from a holistic systems approach. The developed tools should support the decision-making process and allow for timely interventions providing both whole life cost and safety benefits.

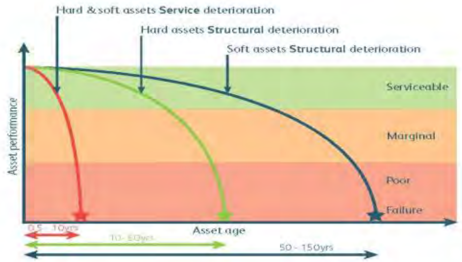


Table 7.1: Cross asset interaction risk matrix

Drainage performance	Track, earthworks or asset condition (related to drainage)		
	Serviceable	Marginal	Poor
Serviceable	Lowest risk	Slight risk	High Risk
Marginal	Slight risk	Moderate risk	High Risk
Poor (including under capacity)	Moderate risk	High Risk	Highest risk
Serviceable	Slight risk	Moderate risk	Highest risk