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Abstract

Since London underground opened as the world's pioneer underground railway, the network has grown exponentially to over 402km, servicing more than 1.34 billion customers annually. The rail network is over 150 years and is deteriorating, therefore, it is imperative that innovative maintenance techniques are implemented to inspect the condition of the tunnels and to scope for repair works. Innovation can be difficult to implement due to the size of the London Underground. This study evaluates the practical application and performance of the innovative conditional laser tunnel inspection compared to the currently used traditional method. The results show the accuracy of the lasers, along with the software's ability to create the scoring for a Principal Inspection report in accordance with the London Underground Standards. Though the initial cost is higher, this would be regained from the saving in maintenance works carried out during the four years between the Principal Inspections.

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General introduction

London Underground opened the world's first underground railway, between Paddington (then called Bishop's Road) and Farringdon Street in 1863 (Bownes, *et al*., 2012). It could not have been envisioned that the network would grow exponentially to over 402km in length and carry over 1.34 billion customers a year, making it one of the busiest networks in the world (Transport for London, 2016). Now over 150 years after construction, the network is deteriorating and with no way for reconstruction. Therefore, it is imperative that new innovative maintenance techniques are implemented to inspect the condition of the tunnels and to scope for repair works.

London Underground, being a public company needs to be mindful of the current economic issues throughout civil engineering, sustainability and cost saving techniques. These are important factors which London Underground engineers need to implement in order to keep the railway running efficiently, and with as minimal delays as possible. However, working with such an old infrastructure can pose several challenges. London Underground's civil engineering department is responsible for over 4,616 assets across the network, 123 of which are tunnels (Transport for London 2016). However, this number is disproportionate due to the large sizes of the tunnels. The team works together to make sure these assets are in a serviceable condition for trains to run.

The maintenance process employed by London underground is presented in figure 1. The process ensures that the underground London is undisrupted and prevent potential injury or death to its customers or staff. By strengthening the inspection stage, it allows the subsequent processes to act on more substantial, relevant and accurate data which can also reduce overall cost.

London Underground is now the first railway in Britain to test a 3D laser scanning technique to scan for a number of different defects within the tunnels. The subsequent analysis and evaluation of these case studies and trials, carried out within London Underground, have proved the use of laser scanning as a Non-Destructive Test (NDT) could be beneficial in a variety of ways.

This has led to many of the lines on the network being scanned; the data collected, analysed and then reviewed by critical safety engineers. The defect results can then be used to prioritise any repair works that are required to keep the tunnels in working order. This new inspection technique could be advantageous for London Underground, due to the large amount of tunnel works to be inspected. It is also environmentally friendly, sustainable and can be used to analyse the whole life cycle of a tunnel with accurate data and analysis.

The aim of this study is to review the practical application and performance of the innovative laser tunnel conditional inspection technique compared to the traditional method currently employed by London Underground. London Underground has over 260km of its network in tunnels and as per The Road Tunnel Safety Regulations (2007), tunnels with safety implications such as those carrying cars or trains are required to be inspected every five years. Consequently, non-compliant companies face heavy administrative fines. To give London Underground a safeguard, the company's Standards set out the inspection frequency at every four years.

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Review of tunnel inspection developments

Engineering innovation in railway

Civil engineering has always been at the forefront of innovation throughout all industries, with the railway industry always striving to develop new and exciting ideas to save costs, increase productivity and become more sustainable.

The Enabling Innovation Team (EIT) has been set up by the rail industry to accelerate innovation as many senior professional/organisations still belief that an idea must be proven before investment is made (Rail Research Association UK 2012). Clarke (2012), The EIT is the pioneering cross-industry team intended to address the long-term business challenges for innovative solutions including provision of funds where necessary. The current economic climate makes it extremely difficult to acquire the funding to innovate. Hence having a central body for innovation within the rail industry helps give products and ideas a chance to succeed and strive, especially when companies will not fund an idea. The EIT shows that with the funding required to innovate, a challenge can be taken on by the innovators and a potential outcome can be achieved. Without the funding, the project may not even get off the ground, and the idea could be lost along with their potential cost saving or sustainable benefits.

Rail Safety and Standards Board (2012), highlights that innovation is necessary to make life better for not only the customers, but also for the companies running the lines to become more environmentally and financially sustainable for the future. Innovation and introduction of new products can become potentially rewarding to all businesses, especially if the product introduction and innovation is carried out correctly and at the right time for the business.

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The innovation and implementation of three-dimensional (3D) laser Scanners within civil engineering has been available for some years, and is used to create As-Built drawings and 3D models of civil assets (Abmayr *et al.* 2005; Su *et al*. 2006; Park *et al*. 2007; Olsen *et al* 2009). However, the use of laser scanners and software for underground tunnel inspections, (especially brick tunnels) is a relatively new idea which should be tested to evaluate its effectiveness and sustainability.

Inspection rules and regulations

The Department for Transport (DFT) (Department for Transport, 1995) state in their standard for 'Inspection and Records for Road Tunnels, that tunnels must be inspected every five years and specifies four types of inspections that need to be carried out. These inspections include General, Superficial, Special and Principal inspections. This is very similar to London Underground inspection standards (S1060), which also states that there are three inspection types: Principal, General and Special inspections (London Underground 2014). These laid down Standards are extremely important because if a structure is left without regular monitoring and maintenance, it could fail causing injury or death. Especially with a large and busy network such as London Underground this would almost certainly result in catastrophic harm. By enforcing these Standards, the DFT ensures no company absconds from these inspections to save money or extend their inspection frequency past the recommended five years interval. All inspection records are then legally binding documents that would stand in court if an incident did occur.

The London Underground standards state that inspection of a civil asset should be done at a set frequency and should be inspected by a trained, competent and safety critical inspector, adhering to civil engineering standards (London Underground 2014). This means that there are many and different varieties of inspections per calendar year. Reduction of the overall cost, improved inspection productivity and collection of more accurate data of the civil assets (tunnel) within London Underground, could be very beneficial to the financial models of the relevant organisations. Especially as the London Underground is legally obligated to maintain the railway infrastructure which is used by over four million people daily. Hence, inspections are required to all civil assets within London Underground, regardless of the size and usage.

Traditional inspection process

Currently, the traditional method is carried out using a Rotamag scaffold tower fitted onto a track trolley (figure 2) and pushed through the tunnel on foot to carry out the inspection of the asset. The inspector will then create tunnel charts which are hand drawn and scanned into the computer, this usually reduce their quality and makes them difficult to read. The next inspection of the tunnel is subsequently conducted four years later where an inspector will need to be able to read the charts clearly to see if any further defects have occurred.

The traditional method of inspection has limitations and could be improved substantially. From table 2.0 it can be seen the cost of inspection significantly increases depending on the length of the tunnel. With an average tunnel, approximately 400-500m taking 5 engineering hour shifts to inspect, which equates to 24-man hours and at a total cost of £6,700. Additionally, there would be the London Underground inspectors cost to take into consideration, which is approximately £250 a shift. From this information, the inspection of the over 123 tunnels across the network is evidently costly to the company.

Another challenge is accuracy, as each inspector no matter how well trained, is likely to interpret defects differently to the next inspector, especially as physical measurements of the square meterage of defects would make inspection costs to be prohibitive. This potential discrepancy in interpretation can impact on the costing of contracted maintenance work. Consequently, resulting in overcharges or fines from the contractor due to the wrong meterage provided during the inspection process. Although, the London Underground prides itself on having high health and safety standards ensuring that inspectors attend numerous safety training. However, primary causes of accidents are from slips, trips and falls. Walking such a vast meterage of tunnels to carry out the inspections where there are many components on track that can be tripped over, especially when all the inspections need to be carried out in engineering hours at night when trains are not running.

Evidently, the traditional method of tunnel inspection is out of date and by using the 3D laser scanning technology improvements can be made to modernise the inspection process, making the inspections safer, more accurate and eventually less costly.

Laser tunnel scanning system

London Underground uses a Spanish specialist contractor to carry out the laser scanning of the tunnels. The contractor provides the skilled team and the equipment to carry out the inspection. They analyse the data and provide it to London Underground for review by skilled engineers. The laser scanning system employed by the contractor is called Laser Tunnel Scanning System

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(LTSS), which uses multiple high-speed laser scanners to acquire both 2D images and high resolution 3D profiles of tunnel linings. The system can scan a tunnel profile of up to 24m arc, at 1mm resolution for images, with the acquisition of 3D data at a speed up to 20km/h.

Once all the data has been processed and digitalised, the data can be analysed offline by the operator using a 3D viewing software. From the software and input data, the operator can precisely measure any defects to the tunnel lining and collaborate all their findings in the form of graphs or an inspection report, produced by the computer software (Tunnel Viewer). In masonry tunnels the software can detect deformation, fractures to the brickwork, joint loss to the mortar, dampness to an area of the tunnel and face loss (spalling) to the brickwork. In cast iron tunnels, the software can detect missing bolts, seepage, fractures and deformation. Finally, in concrete tunnels spalling, fractures, deformation and honeycombing. Figures 3 and 4 show the LTSS laser train arrangement and Laser train in use respectively.

Pavemetrics (2016), LTSS is 100 times faster and 10 times more accurate than typical Light Detection and Ranging (LIDAR) technology usually employed in most laser scanning systems. The LTSS can acquire 120,000,000 3D and 2D image points per second with an accuracy of 0.5mm compared to standard LIDAR accuracies of 5.0mm for 100,000 points. This accuracy is vital because typical defects on London Underground brick tunnels are smaller than the 5mm which would not be picked up by the standard LIDAR scanners.

Tunnel surfaces with an arc length of less than 12m can be inspected with just one pass of the lasers, however if they are over 12m then the surfaces will be captured through multiple passes (usually forwards then backwards), with the captured images being stitched together to

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get the correct data. Figure 5 presents a typical diagram showing how the scanners captures data from a brick tunnel.

Laser products used in the UK must be checked against The British Safety Standard (BSI) for laser safety which addresses concerns such as; laser classification, permissible exposure levels (MPE), risk assessment and eye protection (British Standard Institution 2014). The lasers used to carry out the 3D scanning on London Underground have been classified by the manufacturers as Class 3b. Therefore, adequate precautions must be taken to avoid direct eye exposure to the laser beam, this informed the placement of permanently affixed aperture warning labels above the laser windows (Pavemetrics, 2010).

Case study

The asset that has been selected to conduct this study is the M168/TL53 which is a brick tunnel located between Edgware Road and Baker Street on the circle line of the London Underground. Comparison of inspection result for this asset done using the traditional method is made against that of the NDT laser tunnel inspection.

For a Principal Inspection on a brick tunnel, an in-depth report needs to be produced in accordance with the London Underground S1060 Inspection standard. This process requires all defects to be noted and compared to the last Principal Inspection report. Any maintenance work that have been carried out to the asset since the last Principal Inspection is noted, along with a tunnel chart documenting all the defects is added to the report. Figure 6 shows an example of a brick tunnel chart which is added to every tunnel Principal Inspection report for the traditional inspection process.

The key in figure 6 shows all the defects which need to be added to the chart if they are identified on the inspection. This tunnel chart then continues for the total length of the asset depending on the extent of the tunnel. Each square on the tunnel chart *(figure 6)* represents a $1m^2$ section of brick tunnel. Finally, all the defects on the tunnel chart are tabulated and included in the Principal Inspection report to show the total quantities of each defect, which is also compared to the previous Principal Inspection results. Subsequently, comparisons can be made on any deteriorations to the asset as there is a trend of either increase in area of defect, no change in area of defect, or decrease in areas of defects. Decrease in defect area occurs when there has been maintenance work carried out to the asset at some point within the years between the principal inspections to remove a section of the defects noted.

Defect measurement in laser tunnel scanning

The computer software, Tunnel Viewer used to process the data captured with the laser tunnel inspection enables zooming into a particular defect to carry out further analysis and evaluations. A measuring tool within the program enables the geometry including the surface width and depth of individual defects to be computed. The measuring tool can be used to calculate joint loss, fractures, spalled areas and the amount of seepage to a specific area. This tool will not only measure one effected area but the whole asset, thereby providing the inspector with a better insight into a particular defect that may be a cause of concern. This feature of the software is particularly good as these types of defects would have had to be measured on site, whereas they can all be carried out off site with higher degree of accuracy. The software also provides cross-sectional view of the asset from all the points collected on site using the laser,

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digital cameras and using the angle of triangulation with computer algorithms to form a grey scaled reconstructed profile of the brick tunnel. *Figure 7* is labelled below identifying what each part of the grayscale image means.

Masonry defects

Joint loss

Joint loss occurs when there is mortar loss in the brick joints. This is a very common defect in old masonry but can also be caused from frost damage. If left unattended, it can result to weakened and loose bricks. The mortar can be easily be replaced by a maintenance process called re-pointing, where new mortar is added to the joints. It is a major concern having loose bricks within a tunnel carrying up to 33 trains per hour. London Underground has a contract to repair any joint loss required for a year, but to do this, it must be correctly identified. The laser train does this, and also identifies the location of the joint loss in the tunnel. This informs the contractor if a rotamag tower is required in the case of highly located repair works. Previously the inspector would have had to identify joint loss using tunnel charts (figure 6) which are often hard to read. The Tunnel Viewer software can identify the exact amount of brick loss in the tunnel and comparison can be made to subsequent scheduled principal inspection run. Therefore, the department can evaluate the exact extent of the tunnel that has been successfully repaired. This is useful for maintenance records and for budget forecasting. Figure 8 shows the Tunnel Viewer software identifying joint loss within a tunnel.

Face loss

Face loss also occurs to old brick work, especially those exposed to weathering. This is when the face of the brickwork breaks away often in large pieces in a large section of brickwork. It can also lead to a serious defect in a tunnel if left unattended, particularly in the crown above the train path. Repairs can be done by cutting out the bricks and replacing them where required, however as before this needs to be identified. The Tunnel Viewer software uses the parameters set to determine the loss of face to the brickwork as shown in *figures 9.*

Fractures

Fractures can present enormous safety hazards within tunnels and have several causes, but it is usually caused by movement within the tunnel. There is often an underlying problem with the tunnel when fractures occur. Fractures can lead to loosen brickwork and equipment that could result in the train service becoming affected. Traverse fractures present a more serious defect than longitudinal fractures as they indicate flattening of the arch and possible rotation of the tunnel. However longitudinal fractures are more common and related to lack of load distribution. The Tunnel Viewer software identifies fractures as shown in figure 10. It provides the length, depth and width of the fracture at the worst point. The Tunnel Viewer software can then be used to measure the fracture at any point required. With the reference function in future scans, the fracture can be overlaid to measure any change.

Water ingress

Water ingress is a common defect within the aging tunnels of the London Underground. Water ingress can be caused by groundwater penetration through the tunnel lining and into the tunnel but the more common ingress is from third party Thames Water pipe leaks, often under mains pressure. The laser identifies water ingress by the slower response time for the lasers to bounce back making the wall look illuminated (figure 11). The data collected is used to rectify the water ingress where possible, otherwise it can be dealt with by using deflector plates or drainage gullies away from the track and electrical equipment. If left unattended, water ingress can cause damage to electrics, signalling equipment and the track infrastructure leading to line shut downs.

Laser tunnel charts & inspection report output

Laser tunnel charts are produced in two formats with greyscale detail identifying the defects along the tunnel and the white background identifies the location of the defects along the tunnel's arch length. These are produced for every tunnel scanned and it replaces the hand drawn charts (figure 6). They are a useful reference to evaluate what repair works have been executed in future comparison and to locate any defects in the crown that could lead to serious problems. These are included in every inspection report for future reference, in-case an incident was to occur.

In compliance to the London Underground Standard S1060 a score sheet must be completed as part of the inspection report. This scores structural items that could affect the integrity of the tunnel. Defects, such as described under Masonry Defects, affect the tunnel's

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score. Therefore, for the laser inspection process to work, these defects must be quantified and put into the relevant score sheet.

The scoring is split into two parts, the first is the extent, which is the percentage of the defect of that element. For instance, if 2% of the tunnel's brickwork has joint loss, this is calculated by the total surface area of the brickwork divided by the defect's square area. This is done automatically by the Tunnel Viewer software. The second section of scoring is the severity, this is also done by the Tunnel Viewer software with the pre-set parameters given to the software by London Underground engineers. These parameters dictate at what severity the defect should be scored under, usually the depth of the defect. The severity results correspond to numbers which are multiplied to get a final number, shown in figure 12. All the numbers for every aspect of the scored tunnel are totalled; a final score is calculated and recorded for further review. Finally, the reviewing inspector completes the report with inputs such as the recommended actions and the priority of this action as this cannot be done by the software.

Discussion of result

Comparison of both inspection processes

Table 3 and figure 13 show the previous inspection results of the brick tunnels between Baker Street and Finchley Road using the traditional NDT method against the results of the software scored in relation to the data obtained from the laser inspection.

It can be observed from figure 13 that the laser inspection data result scores from the software are higher than the traditional scores for all the assets. This shows that many of the brick tunnels are generally in a good condition with few tunnels indicating only minor issues.

None of the assets apart from TL133 and TL137 require maintenance work until at least after the next Principal Inspection due to their high score. If the traditional scores were to be used, nearly all of the brick tunnels would require scheduled maintenance work before the next Principal Inspection at a substantial cost to the maintenance budget. Therefore, the laser tunnel inspection significantly reduces the contractor work shifts. Table 4 presents the London Underground Standard requirement in regard to the scores of an asset and recommended maintenance action.

The main benefits of the laser tunnel inspection can be attributed to the innovative tunnel chart produced by the tunnel viewer software from the site inspection. The tunnel chart produced in portable document format allows the maintenance engineers to work out the area of repairs required for each tunnel, produce accurate repair cost estimates which can be provided to the selected contractor to show the exact location and type of defects they are required to repair. Importantly, the charts provide valuable data that can be overlaid and compared to that of subsequent inspections.

These highlighted benefits result in improved data collection accuracy, improved operational safety (as inspectors are not required on site, consequently removing significant safety risks), cost reduction through improved budgeting and effective monitoring of maintenance carried out.

Cost overview

Three major tasks are involved in conducting the full inspection of the 123 brick tunnels:

- Desk study on every asset to be inspected, where analysis of previous defects, location, possible deterioration and repairs are carried out.

- Inspection to be done by a competent asset inspector along with necessary support staff, pictures and hand drawn sketches of all defects.
- Creation of inspection report from site findings, this process is started on site using a mobile tablet and completed off site on word template sheets.

Traditional inspection method cost

Tables 5 presents costing information for contract staff and equipment while Table 6 presents of London underground inspectors cost per brick tunnel inspection.

The total cost for the traditional method is computed by accounting for the contracting staff/equipment and the inspector cost presented in table 5 and 6 for the entire length of tunnel.

Total cost per brick tunnel (700m) = £8,040 (table 5) + £700 (table 6) = £8,740 …. Eq.1

Laser inspection cost

The cost of completing the survey of the London Underground Circle, Hammersmith & City, District and Metropolitan Lines by the consultant firm is £120,000. Including an additional cost of 150,000 to complete data analysis which takes approximately three months. Thus, the total cost reaches to £270,000 for the consultant's package. But these should be added to the further cost of hiring the engineering train from Transplant which is £25,500 and the cost of the inspector's time to write the 123 inspection reports which is £15,375. Therefore, overall cost reaches to £310,875.

Total cost (123 Nos. Tunnel) = £120,000 + £150,000 + £25,500 + £15,375 = £310,875 ….Eq.2

Cost comparison

The total length of the 123 tunnels to be inspected is 21,000m. With the total cost of a tunnel (700m) being £8,740 the total cost of all 21,000m by the traditional method of inspection is £262,200; making the traditional method £48,675 cheaper than running the laser train. This is due to the large amount of data being collected and analysed which in-turn takes a considerable amount of time for the laser train to process. Hiring of the Transplant train with drivers for the eight laser train shifts is also high due to the complex nature of the booking, and driving of an engineering train during cancelled engineering hours.

As other London Underground workers can work alongside the traditional method of inspection no shifts or works are lost. However, the Laser inspection method requires cancelled engineering hours as precautionary safety measures and to maximise the operation time of the survey process. These cancelled hours have an impact on other workers leading to wasted shifts thus costing the business money. To minimise this, the train paths are published in the Engineering Works schedule well in advance, to enable other departments to work around the planned disruption.

Conclusion

This study evaluated the application of innovative laser tunnel inspection in the London Underground compared to the long-standing traditional tunnel inspection method. This was conducted using a case study brick tunnel section located on the Circle line of the London Underground.

The study result demonstrated that improved accuracy in the overall inspection process is achieved using the laser inspection system evidenced by the improved inspection report scores compared to the traditional inspection method. Consequently, improving the estimation of required maintenance life cycle and budgeting.

Although, the laser inspection method is currently just under £50,000 more expensive, the laser survey data and scores collected is vastly more accurate indicating that the brick tunnel assets are in better condition than previously determined. This shows that less maintenance is required resulting in considerable savings to the civil engineering maintenance cost.

Moreover, the implementation of the laser inspection removes the increased safety risks associated with the traditional inspection method. This significant safety improvement due to the application of laser inspection system also makes it a justifiable investment. Furthermore, the laser inspection system is sustainable as other civil assets including under-bridges, over-bridges and viaducts are being suggested to inspected using the same process with low environmental impact. This can result in potential additional maintenance savings across the civil engineering assets of the London Underground.

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Table 1. London Underground Major Civil Asset Numbers

London Underground Major Civil Assets					
Bridge – Foot	219	Escalator Machine Room	378	Wall – Retaining	985
Bridge – Over Line	145	Girdering	1007	Subway	59
Bridge – Underline	292	Linear Station Staircase	431	**Tunnels**	**123**
Bridge – Viaduct	57	Platform (Station)	361	Covered Way	98
Canopy (Platform)	139	Roof Structure & Support	48	Canopy (Station Entrance)	113
TOTAL:			**4616**		

Table 2. Rotamag Scaffold cost

Length of Tunnel (m)	**Number of shifts required**	**Total Cost (£)**
0-100	1	1,340
100-200	2	2,680
200-300	3	4,020
300-400	4	5,360
400-500	5	6,700
500-600	6	8,040
600-700	7	9,380
700-800	8	10,720

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Table 3. Brick Tunnel Score Comparisons Traditional method vs. Laser Survey NDT Inspections

Tunnel asset number	Traditional score (%)	Laser score (%)
TL127	84.3	87.5
TL128	84.0	95.83
TL129	71	100
TL130	90	100
TL132	91	95.83
TL133	81.1	83.33
TL134	81.1	91.67
TL135	84.0	95.83
TL136	87.5	93.8
TL137	84.0	93.8
TL138	75	91.67
TL140	87.5	100
TL141	84.3	100
TL142	90	100
TL143	77	91.67
TL144	83	95.83

Table 4. Scores per asset and Maintenance procedure (London Underground 2017)

Asset condition	**Score (%)**	**Comment**
Poor	0-40	Immediate fault raised and maintenance work carried out
Marginal	41-64	Potentially fault raised and repairs carried out between 1-12 months
Average	65-85	Repaired between 12-24 months
Good	86-100	Review any defects

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Table 5. Costing for contracting staff and equipment required for an inspection on a brick tunnel inspection

Staff/Equipment	Cost Per Shift (£)	Number of Shift	Cost Per Tunnel (£)
Site Person in Charge	200	6	1200
Protection Master	180	6	1080
Skilled Operatives x 3	450	6	2700
Rotamag	500	6	3000
Tapping Hammer	10	6	60
Total	**1,340**		**8,040**

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Table 6. Showing inspector's man hours per brick tunnel inspection

	Inspection of a Brick Tunnel (London Underground inspector's cost)	
	Traditional Inspection	**Laser Inspection**
	Process Average time (Hours)	**Process** Average time (Hours)
Desk to study	1	1
Inspection	21	0
Report Write up	7	9
Total	**28**	**10**
Cost	***£700***	***£250***

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Figure 1. Flow Chart; London Underground Maintenance

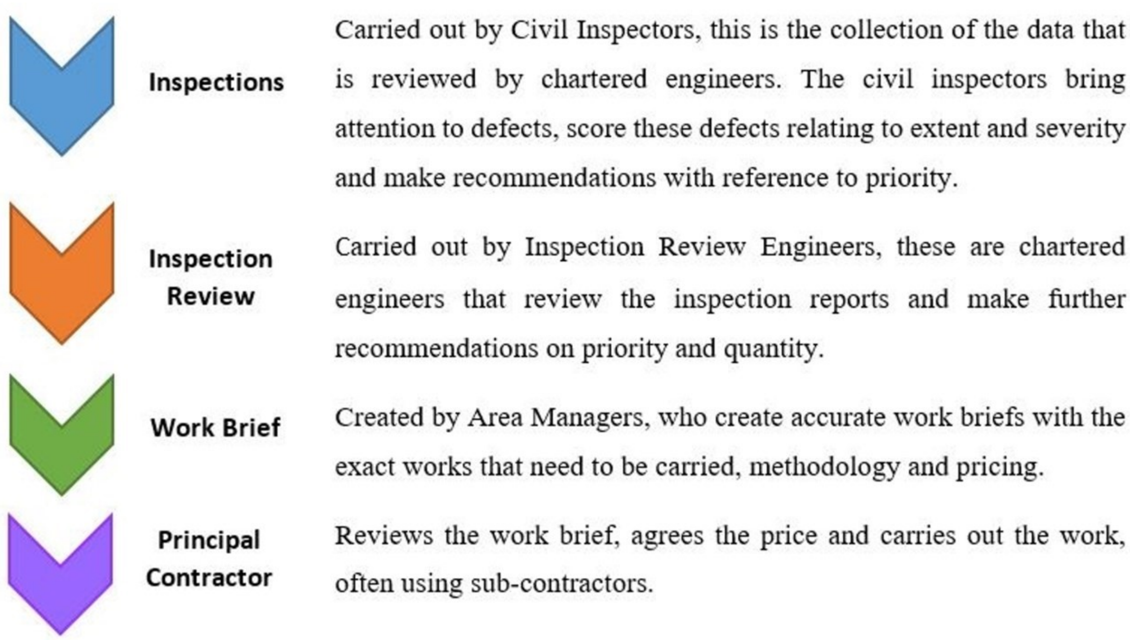

Figure 2. Rotamag tower setup used for traditional NDT method (Permaquip 2016)

Figure 3. LTSS laser train arrangement

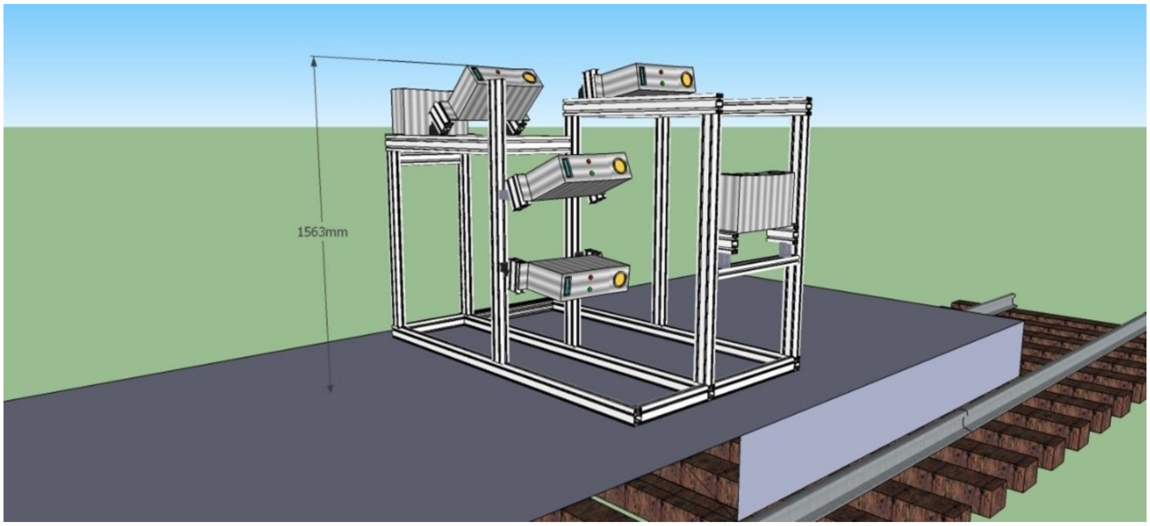

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Figure 4. Laser train in use

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Figure 5. Typical diagram showing scanners used to collect the tunnel profile data (Pavemetrics 2016)

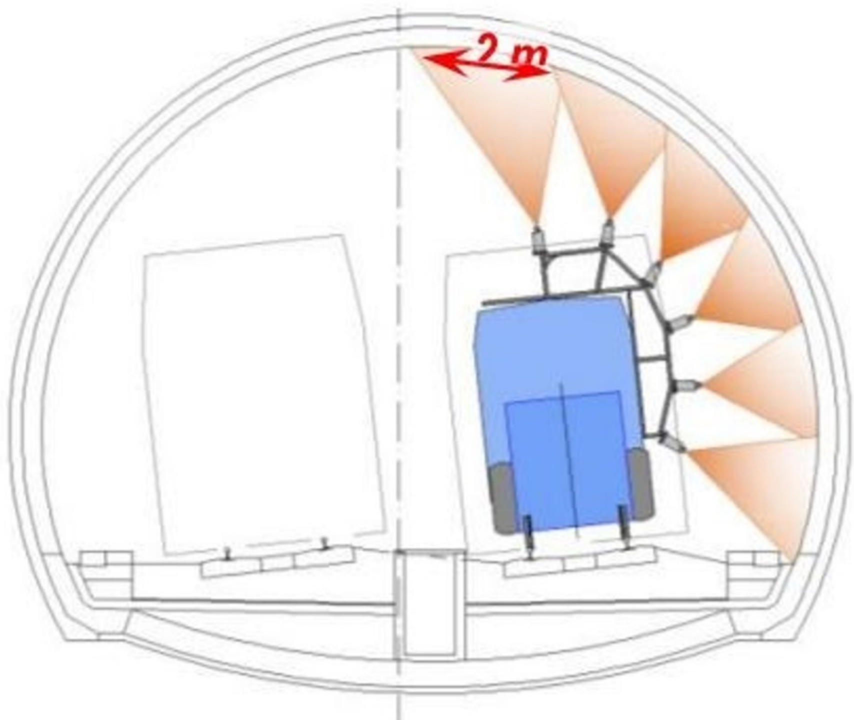

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Figure 6. London Underground Traditional Inspection Tunnel Chart

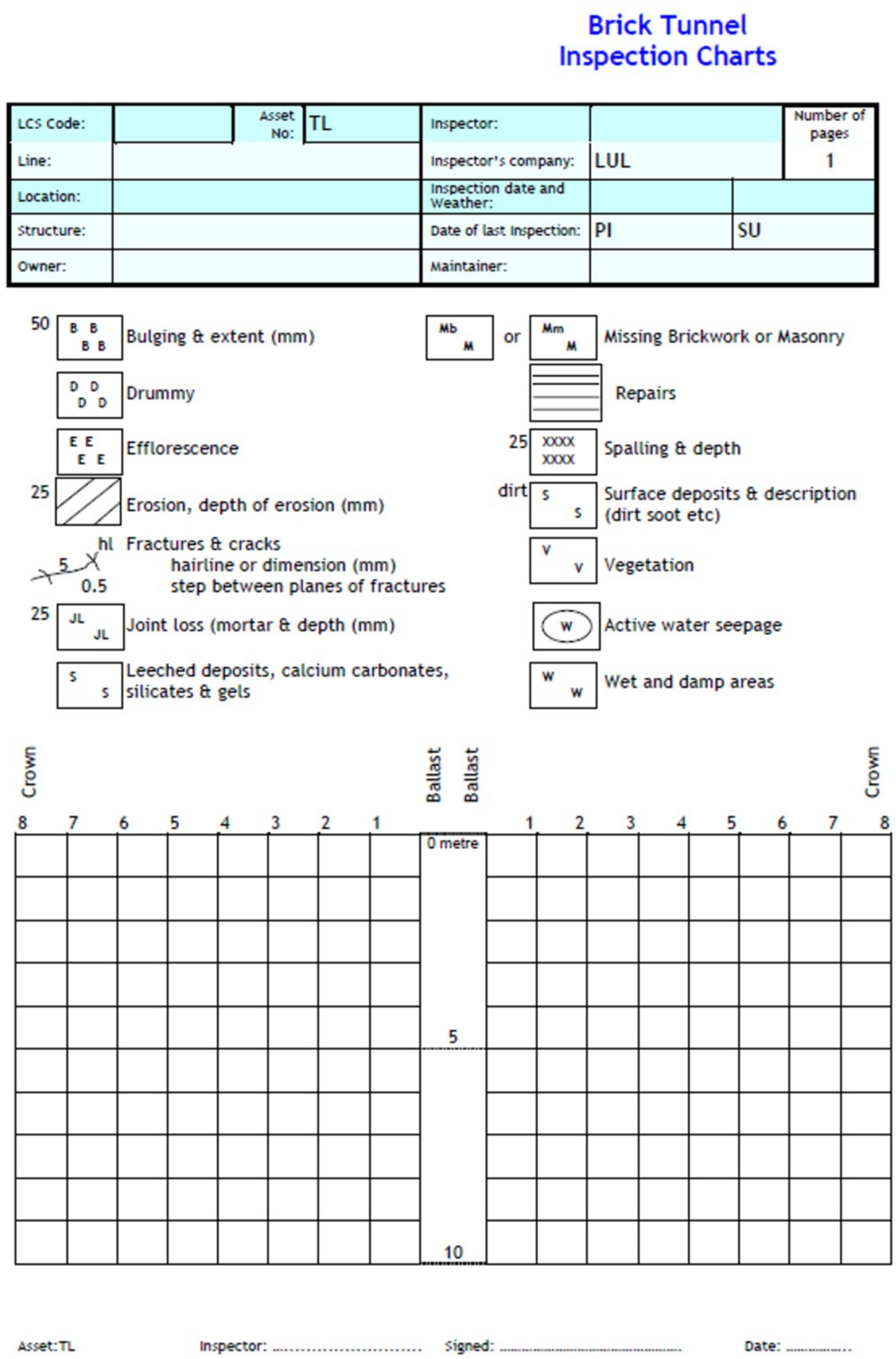

Figure 7. Labelled typical tunnel cross-sectional view (Euroconsult 2017)

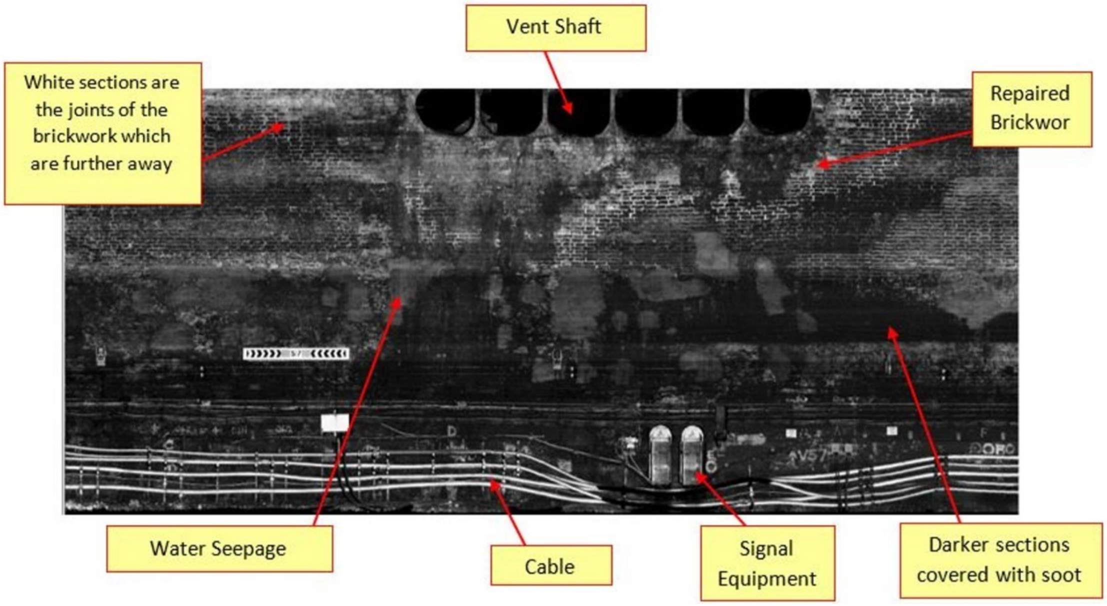

Figure 8. Joint loss identification by Tunnel Viewer software (Euroconsult 2017)

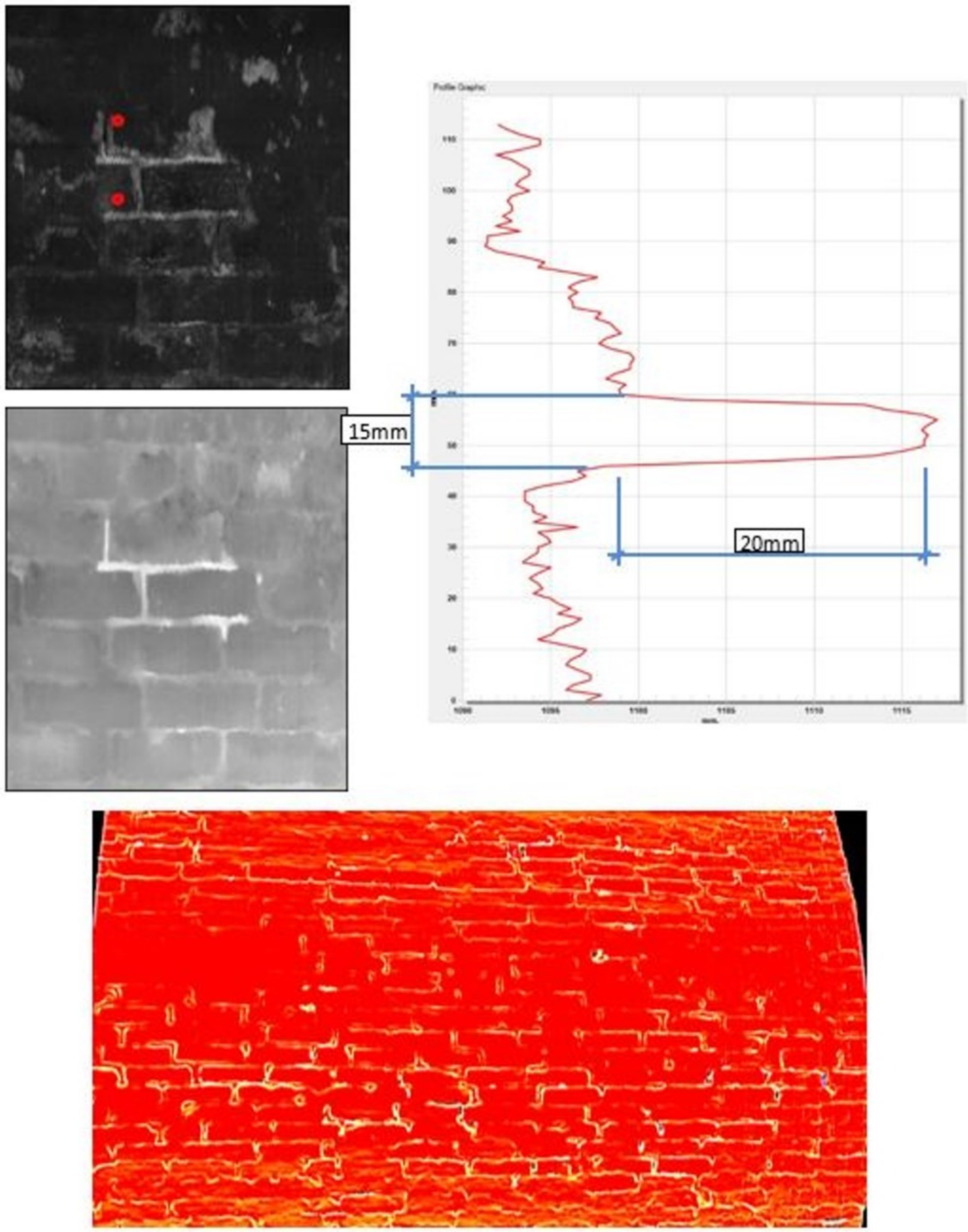

Figure 9. Face loss identification by Tunnel Viewer software (Euroconsult 2017)

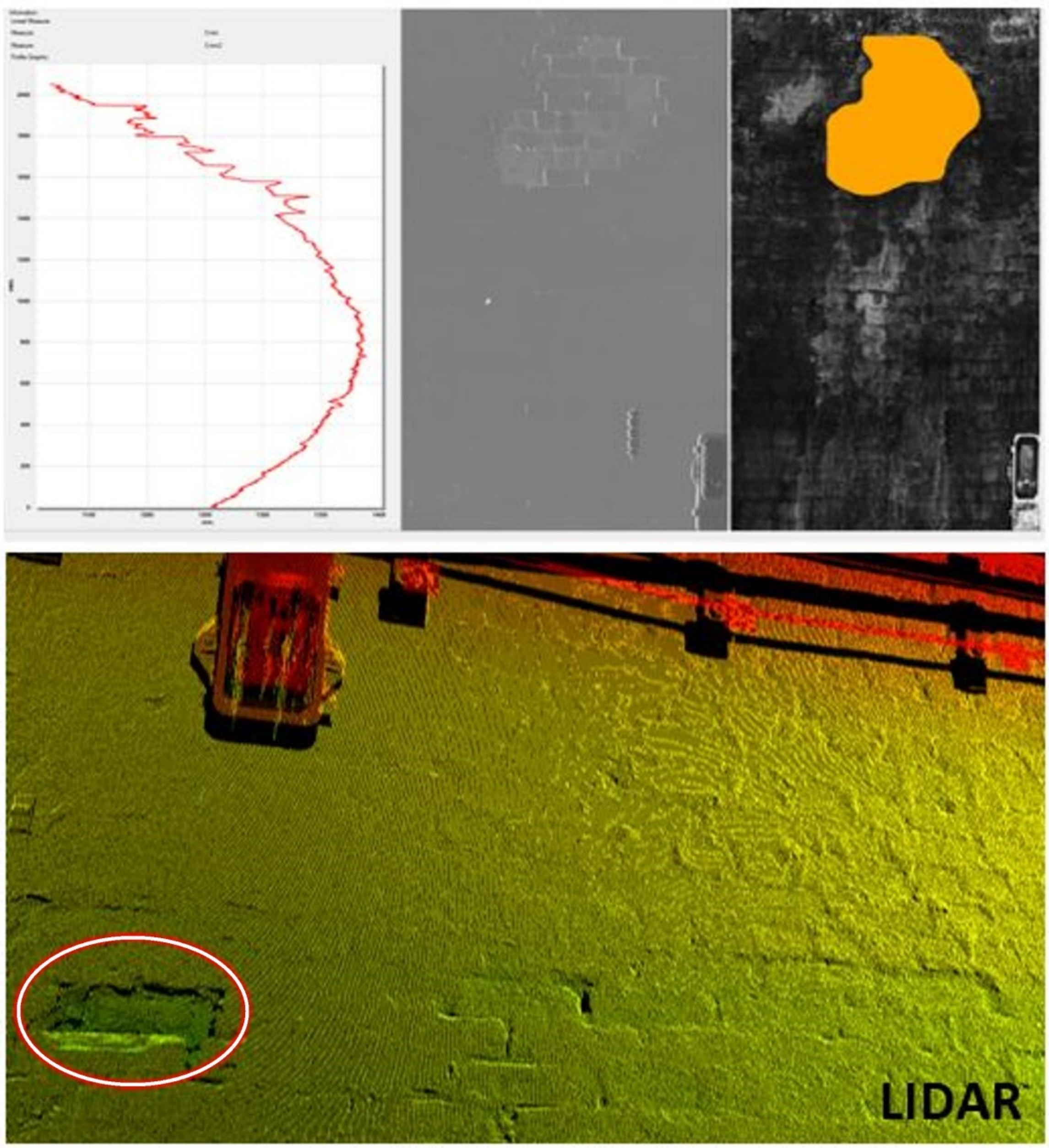

Figure 10. Identification of fracture by Tunnel Viewer software (Euroconsult 2017)

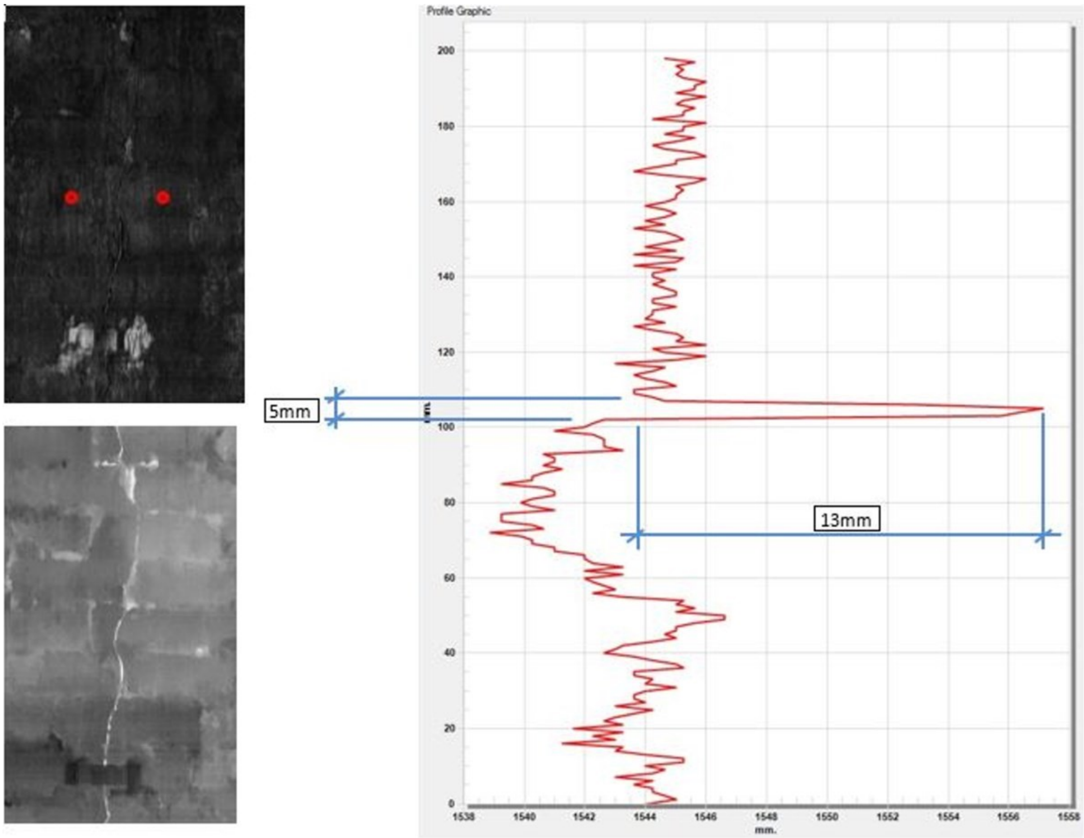

Figure 11. Identification of water ingress by Tunnel Viewer software (Euroconsult 2017)

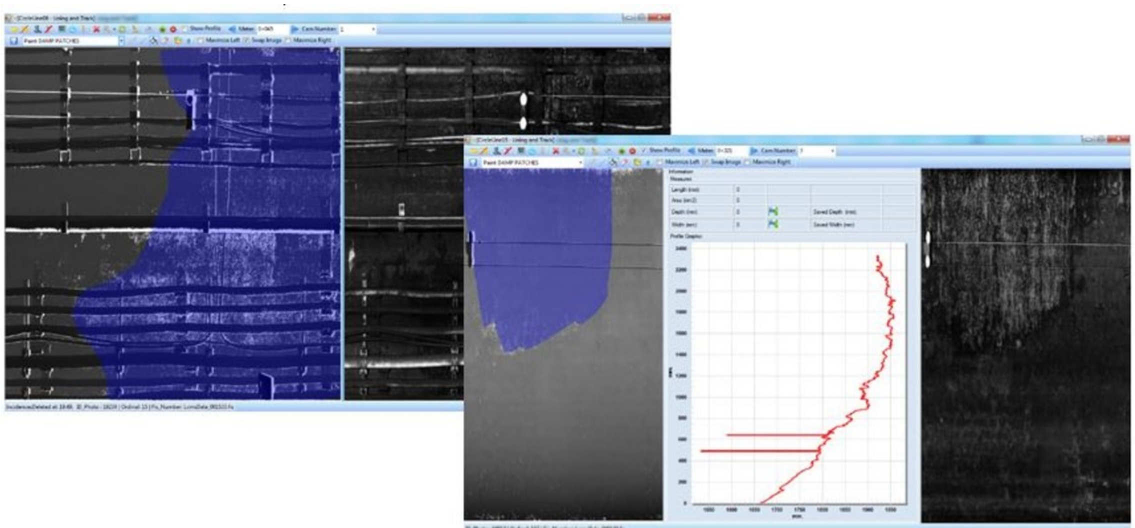

Figure 12. Sample Inspection Report Score Sheet (London Underground 2017)

BRICK TUNNEL

INSPECTION REPORT SUMMARY

Structure No	Inspector's Name
Date of Inspection	Weather/Temp

SUBSTRUCTURE DETAILS

ITEM REF	ARCH, HEADWALLS, PARAPETS, SURFACING AND DRAINAGE	COMMENT AND PRINCIPAL CONSTRUCTION MATERIALS	DEFECTS E	S	R	P	ITEM SCORE
	Brick Arch:						
10	No Rings (square/skew*)						
11	Arch Profile (known/assumed*)						
* 12	Profile Condition/Deformation						
* 13	Material Description/Condition						
* 14	Joint Condition/Width/Depth						
* 15	Cracking (Locate and describe)						
16	Other Comments						
	Headwalls:						
17	Arrangement						
* 18	Alignment						
* 19	Joint Condition/Width/Depth						
* 20	Cracking						
21	Other Comments						
	Parapets:						
22	Arrangement						
* 23	Alignment						
* 24	Joint Condition/Width/Depth						
* 25	Cracking						
26	Other Comments						
	Surfacing:						
27	Carriageway						
28	Footway						
29	Other Comments						
	Drainage:						
30	Arrangement/Support						
31	Condition/Effectiveness						
32	Other Comments						

Indicate items not applicable (N/A) or not visible (N/V)

* Items to receive an 'Item Score' if item is applicable

TOTAL ITEM SCORE (X)	
No. of ITEMS SCORED (Y)	
OVERALL ELEMENT RATING (X ÷ Y) x 12.5 =	%

1.	**EXTENT (E)**	**2.**	**SEVERITY (S)**
A	Less than 5%	1	No 'significant defect'
B	Between 5% and 10%	2	'Minor' - defects of a non-urgent nature
C	Between 10% and 20%	3	'Heavy' - defects of an unacceptable nature which shall be included for attention within the next two annual maintenance programmes
D	Greater than 20%	4	'Severe' - defects where action is needed (these shall be reported immediately to the supervisor). These defects shall require action within the next financial year.
3.	**RECOMMENDED ACTION (R)**	**4.**	**PRIORITY (P)**
C	Replace	I	- Immediate
P	Paint	H	- High (within 12 months)
R	Repair	M	- Medium (within 2 years)
M	Monitor	L	- Low (before next principal inspection)
I	Inspect	R	- Review (for assessment at next principal inspection)

EXTENT/SEVERITY RATING	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4
ITEM SCORE	8	7	5	4	7	6	4	3	6	5	3	2	5	4	2	1

Figure 13. Brick Tunnel Score Comparisons Traditional method vs. Laser Survey NDT Inspections