PhD Dissertation of Engineering

Integrated Risk Management Framework for Preventing Losses from Landslide, Flood and its Compound Disasters

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Integrated Risk Management Framework for Preventing Losses from Landslide, Flood and its Compound Disasters

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Abstract

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In recent years, it has been reported that climate change is leading to increased damage and losses caused by natural hazards. Moreover, reports of compound disasters caused by multiple hazards in extreme weather events are becoming more frequent. Efforts have been made to improve risk management for natural hazards; however, there has been little discussion about providing an integrated framework supported by technical tools to establish an efficient and effective management plan based on quantitative analyses. Meanwhile, risk management tools and frameworks have been developed intensively in the industrial sector for decades. Applying risk management practices proven in the industrial sector can assist in systematic hazard identification and quantitative risk analysis for natural hazards, thereby potentially helping to reduce unwanted losses and to promote interactive risk communication. The objective of this study is to introduce methods of studying risk commonly used in the process industry, and to suggest how such methods can be applied to manage natural disasters, providing an integrated risk management framework. In particular, the hazard and operability (HAZOP), safety integrated level (SIL), and quantitative risk assessment (QRA) methods were investigated for the parts of the risk management process, which are risk identification, risk analysis, risk treatment, risk evaluation, and risk acceptance, as these methods are used to conduct key risk studies in industry. Herein, a literature review regarding those key risk studies and their application in various fields is briefly presented, together with an overview of risk management for natural hazards and multi-hazard risks. Next, common ways of implementing these risk studies for managing natural hazards are presented, with a focus on methodological considerations. First, a case

study is presented in which HAZOP is applied to identify climate-related natural hazards in an organization using a worksheet that lists and evaluates natural hazards. Second, a study applying SIL is presented, in which the probability of landslide and rockfall occurrence is estimated based on the concept of reliability, indicating how probability values can be used for landslide risk management. In the third part, a simplified QRA for landslide hazard is exemplified through the case of site planning for a resort facility on a mountain hill, with the purpose of illustrating how stakeholders can make decisions on spatial planning regarding risk acceptance. In addition, this part presents the result of impact assessments conducted using physically-based models for cases involving multiple hazards, such as a post-wildfire landslide and complex flooding resulting from dam collapse. The technical approaches used in this study—systematic hazard identification, time-dependent reliability, and quantitative risk assessment for single or compound disasters using physically-based models—provide the methods to resolve the difficulty of establishing tools for managing the risk from natural hazards. The analysis presented in this study also provides a useful framework for improving the risk management of natural hazards

through establishing a more systematic context and facilitating risk communication between decision-makers and the public.

- *Keywords: risk communication; multi-hazard risk; physically-based model; time-dependent reliability; climate change adaptation; spatial planning*
- *Student number: 2015-30698*

Publications

Please note that parts of this dissertation were published as peer-reviewed journal papers (see below), and there is some repetition in the methods and results.

1. Lee, J. and Lee, D., (2018). Application of Industrial Risk Management Practices to Control Natural Hazards, Facilitating Risk Communication. *ISPRS International Journal of Geo-Information*, 7(9), p.377.

2. Lee, J. and Lee, D.K., (2018). Risk management for natural hazards based on reliability analysis: A case study of landslides. In *Safety and Reliability–Safe Societies in a Changing World*, CRC Press, p.2797-2803.

3. Lee, J., Lee D. K., Song Y. I., (2019). Analysis of the potential landslide hazard after wildfire considering compound disaster effect. *Journal of the Korea Society of Environmental Restoration Technology*, 22(1), p.33-45. (in Korean)

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1. Introduction

1.1 Study background and objective

In recent years, it has been reported that climate change is leading to increased damage and losses caused by natural hazards (IPCC, 2013). The worldwide data on the number of deaths and economic damage caused by natural disasters indicate that such losses continuously occur. When the number of natural disasters worldwide is evaluated over a long period of time, it can be seen that natural disasters are gradually becoming more common (Ritchie & Roser, 2019). Furthermore, reports of compound disasters caused by multiple hazards in extreme weather events are becoming more frequent in recent years, and unexpected damage to people and properties has occurred.

For instance, a mudslide occurred after heavy rainfall in Montecito, California in the U.S.A. in January 2018, which was a composition type of the compound disaster because it occurred at a lower rainfall threshold due to an intense wildfire the previous month (Aghakouchak et al., 2018). The wildfire had severely damaged the forest land cover and changed properties of the soil texture, and many casualties occurred in neighboring settlements as a result of the amplified damage. The Senamnoi dam in Laos and the irrigation reservoir in the Swar region of Myanmar collapsed and caused numerous casualties in the summer of 2018 (BBC, 2018; YTN, 2018). These are typical examples of the cascading effect of multi-hazard risk, in which complex flooding caused by inundation due to heavy rainfall and an overflow due to dam collapse occurred simultaneously.

In order to minimize the losses and damages caused by natural disasters, presumably amplified by climate change, it is of paramount importance to prepare preventive activities proactively following a planned schedule rather than to respond reactively after a hazardous event happens. An integrated risk management framework that includes all steps required for the effective implementation of preventive action can help avoid the occurrence of unwanted losses of people, property, and the environment. As an integrated framework for natural disaster risk reduction, the Sendai framework has been adopted by the United Nations (UN) world conference (UNISDR, 2015); however, it only contains declarations at the policy level, and does not provide technical modules or management practices.

In order to find good examples of risk management applied to natural hazards, it is useful to explore local practices conducted to mitigate natural disasters. A common approach to risk management for natural hazards is to employ a strategy following the project life cycle, and it has been suggested that adequate processes should be applied in the steps of hazard identification, risk assessment, and mitigating damages (Hanewinkel et al., 2011; Hooijer et al., 2004; Lateltin et al., 2005; Plate, 2002). So far, however, there has been little discussion about providing an integrated framework supported by technical tools to establish an efficient and effective management plan for natural hazards based on a quantitative analysis. Meanwhile, risk management tools and frameworks have been developed intensively in the industrial sector for decades. Systematically analyzing and adopting such tools for the management of natural disasters may help to reduce the unwanted loss of life, property, and environment caused by natural hazards.

In the process industry, the hazard and operability (HAZOP), safety integrated level (SIL), and quantitative risk assessment (QRA) methods are used to conduct key studies, and they can be organically connected to form an integrated risk management framework extending from risk identification and analysis to risk evaluation. HAZOP is a semi-quantitative method that is helpful for identifying cause-and-effect scenarios following changes in the guide words for each physical parameter (Dunjo et al., 2010). HAZOP is a highly-disciplined procedure meant to identify how a process may deviate from its design intent. This method is especially constructive for detecting potential multi-hazard risks for natural harm to impact a targeted entity that might be otherwise unidentified. SIL provides probability measurements of the performance required for a safety-related system to achieve a targeted risk reduction (I.E.C., 1998). SIL can be applied as a basis for planning periodic inspection activities to reduce the risk below an acceptable level (Høyland & Pettersen, 2017), and it can also be used to check flaws in engineering mitigation measures (Stewart, 2001). QRA is a systematic quantitative approach used to estimate and evaluate the risk to which a study area is exposed (Freeman, 1990). Spatial criteria can be determined to avoid exposing people and properties to a higher than tolerable risk level during site planning.

These risk studies can be employed to construct a risk management cycle more systematically, moving from risk identification, risk analysis, risk evaluation, and risk treatment to risk acceptance, which is introduced in ISO 31000 (Purdy, 2010). The results of each analysis are often used as input data for the other studies that comprise the risk management cycle. For example, credible cause-and-effect scenarios from a HAZOP study can serve as a basis for conducting SIL and QRA, and results from QRA can lead to new findings for HAZOP and provide evidence for risk assessment during SIL. The well-established methods and result formats of these industrial risk management practices can enhance the cascading of risk information at each stage of the project life cycle.

The objective of this study is to analyze methods of studying risk that are commonly used in the process industry, and to identify how they can be converted and applied as technical tools providing an integrated risk management framework. The technical methods used in this study—systematic hazard identification, the time-dependent risk analysis, and quantitative risk assessment for single or compound disasters using a physically based model—can resolve the difficulty of establishing tools for the management of risk from natural hazards.

Various discussions have sought to interpret losses and damage as a third pillar of climate regimes that is distinct from mitigation and adaptation since the Paris agreement in 2015 (Mechler, 2017). In order to use loss and damage as leverage in driving climate change policy, reliable risk information derived from proven methods will be highly advantageous. More accurate predictions and warnings regarding the potential impacts of natural disasters on human societies will become available based on physical models. In addition, QRA can provide an estimation of exposed risk indices for people, environmental settings, and property, supporting decision-making on disaster risk reduction.

In terms of risk communication, the integrated risk management framework suggested in this study can improve the cascading of risk information. Communication between decision-makers and the public is important for managing the risk posed by natural disasters (Albano et al., 2015), and propagation of risk information through a well-constructed risk management framework can increase public awareness and provide better opportunities to reduce the exposed risk. Straightforward and forceful tools are also in demand to implement actions leading to substantial changes (Michielsen et al., 2016), and a series of efforts to align exposed risks below tolerable levels through the suggested method can help to satisfy this need. Applying risk management practices that have been proven in the industrial sector may contribute to establishing a practical approach for risk communication and decision-making.

This thesis begins by introducing the study, and then it continues to present a literature review on risk management for natural hazards, the key risk studies in the process industry and their application in various fields, and types of multi-hazard risk. Next, the case study part is composed of three thematic sections: risk identification for climate change issues, risk analysis and treatment for natural hazards, and risk evaluation and acceptance for compound disasters. Each section is composed following the sequence of methods, results, and discussion. The first section presents the method used for risk identification and a case study in which this method is applied to climate-related hazards. The second section begins with a case study of landslide risk analysis and treatment, and explores the same framework for the case of rockfall. The third section is concerned with QRA using a physically-based landslide model, the impact assessment of post-wildfire landslide, and the impact assessment of complex flooding caused by a dam collapse. The remaining part of the thesis presents a discussion of the overall findings and areas for further research. Finally, the conclusion presents a summary of the thesis and a brief discussion of the significance of this study. The resulting analysis and the cases presented in this study may help improve the risk management of natural hazards through establishing a more systematic context and facilitating risk communication.

1.2 Study scope

The broad process of risk management framework includes not only the steps for risk assessment and treatment but also for the process of establishing the context such as the policies, organizational structures, governance, arrangements, improving the process (Purdy, 2010). However, the integrated risk management framework suggested in this study has focused on the scope of the risk assessment and treatment part addressed in ISO 31000, and its approach oriented more on the technical point of view. Especially, the natural hazards analyzed for the case of this study are focused on landsides, floods and its compound disasters that has relatively higher probability of occurrence compared to the other natural disasters in South Korea.

The scope of this study consists of three thematic parts from the steps of risk management: risk identification, risk analysis and treatment, risk evaluation and acceptance. The first part is risk identification for climate change issues developed from HAZOP study, which shows the result as a form of worksheet identifying and enlisting hazards that can be exposed to an institution or a local government, and it may help to follow up action items for climate change adaptation until close. A brainstorming approach participated by multi-disciplinary teams for hazard identification is suggested. In addition, the factors to be found at the time of workshop and the way to apply semi-quantitative method of measuring risk in cause and consequence scenarios is discussed. The results are used as input data for subsequent risk management steps and served as the first step for cascading risk information.

The second part corresponds to the stage of risk analysis and risk treatment in the suggested integrated risk management, which was utilized the method from SIL. This part shows how to analyze the risk of a target area exposed, how to determine the required safety target and how to verify whether or not the target met by calculating reliability of safety functions. As input data, inventory data on the occurrence of past disasters and weather data were used to calculate the frequency of subjected natural disasters. The process of finding effective management scheme is discussed to treat exposed risk considering a maintenance plan. The case studies included landslide and rockfall cases in South Korea.

The third part is for the risk evaluation and risk acceptance in the risk management steps, which was adopted the QRA method. This process is required because unexpected loss and damage can be occurred by natural disasters even if risk is analyzed properly and the risk treated sufficiently. Provided that a concerned disaster occurs, potential areas of affected and the risk exposed to people are examined by using a quantitative risk assessment. In order to supplement the statistical approach based on probability, a physically-based models were applied to simulate landslides and floods for performing consequence analysis. The process to use quantitative risk information for spatial planning was shown comparing to individual and societal risk criteria. In addition, the impact assessment of compound disasters were conducted by using physically-based models to address the significance of multi-hazard risk in case of post-wildfire landslide and complex flooding.

Overall, this study is concerned with how to implement the integrated risk management framework to cope with natural disasters caused by climate change through the flow of risk identification, risk analysis, risk treatment, risk evaluation and risk acceptance, which is addressed by ISO 31000, an international standard for risk management. The following Figure 1 shows schematic diagram of the suggested management process and the components of detailed studies conducted for the thesis.

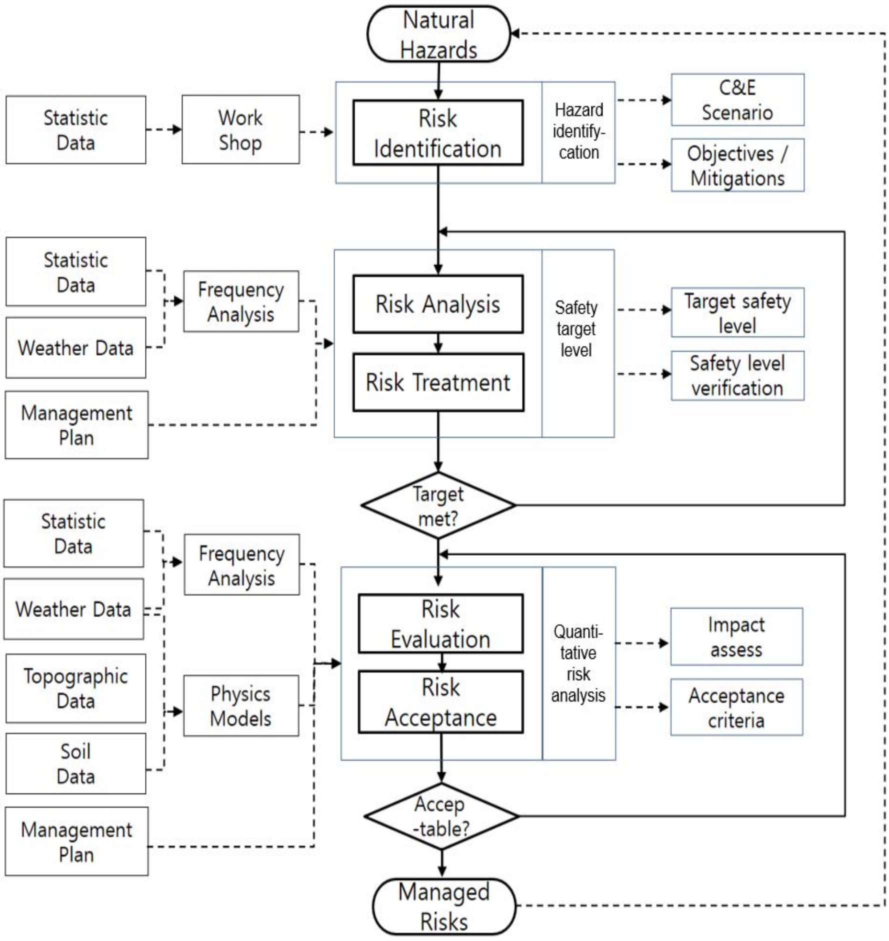


Figure 1. Schematic diagram of the integrated risk management process

2. Theoretical paradigm and literature review

2.1 Natural hazard management and communication

2.1.1 The status of natural disaster occurrence

In South Korea, natural disasters statistics that have occurred for last 20 years show that casualties and property damage due to natural disasters tend to decrease as Figure 2 (M.I.S., 2018). This can be seen as a tendency of overall damage reduced because of improved weather forecasting system and strengthened efforts for disaster prevention. However, the worldwide data about the number of people deaths and economic damage by natural disaster indicate that losses by natural disaster is occurring as shown in Figure 3, and it causes the damages to the human society continuously. When the number of natural disasters recorded worldwide is presented in longtime period, it can be identified that the natural disaster affects to the society is increasing gradually as shown in Figure 4, and natural disaster is occurring steadily over the past two decades as shown in Figure 5. Of course, the increased awareness regarding the natural disasters and population growth may result in increased statistic recording. However, when the natural disasters are understood as interactions between human activities and the nature on the planet earth in

Anthropocene (Sivapalan, 2015), the increase of recording due to recognition by mankind could be accepted as increase of natural disaster, which is causing losses of people and property due to expansion of infrastructure and human activities.

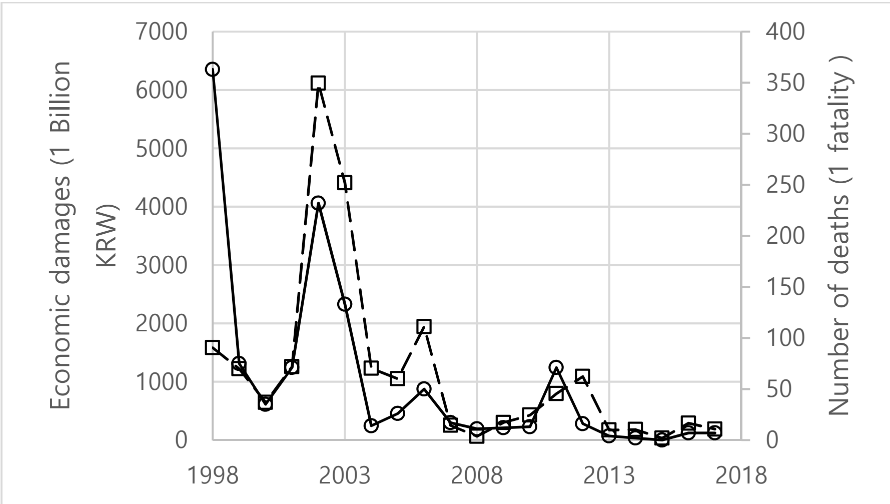


Figure 2. Economic damages and Number of people deaths by natural disaster in South Korea (M.I.S., 2018).

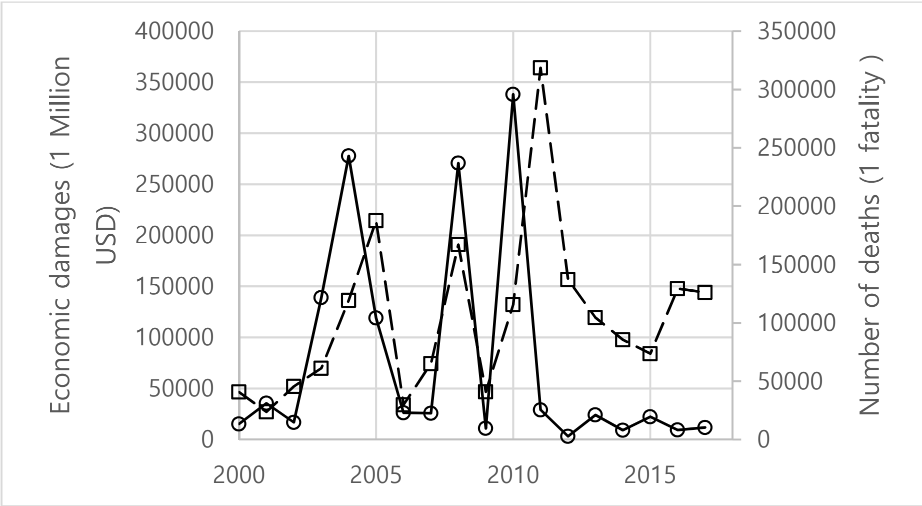


Figure 3. Economic damages and Number of people deaths by natural disaster in worldwide (Ritchie & Roser, 2019)

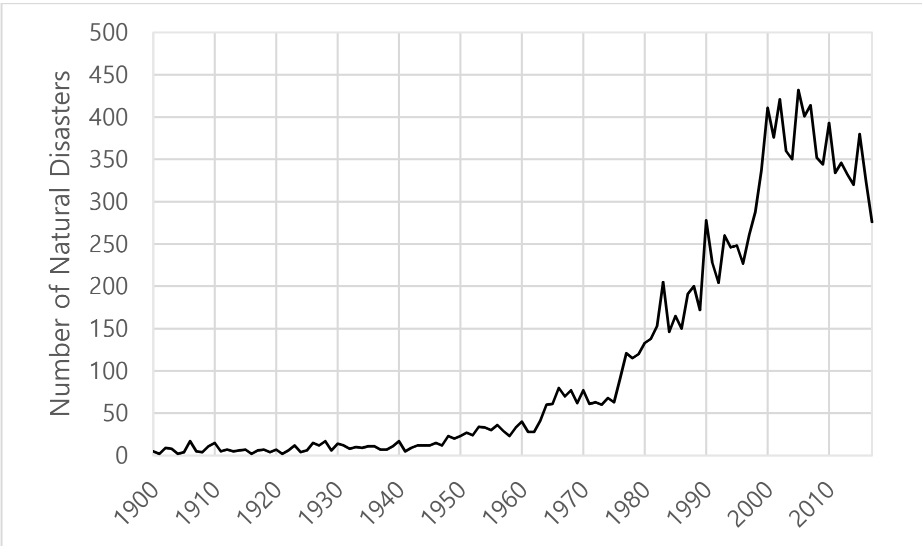


Figure 4. Number of disasters occurrence worldwide from 1900 to the present (Ritchie & Roser, 2019)

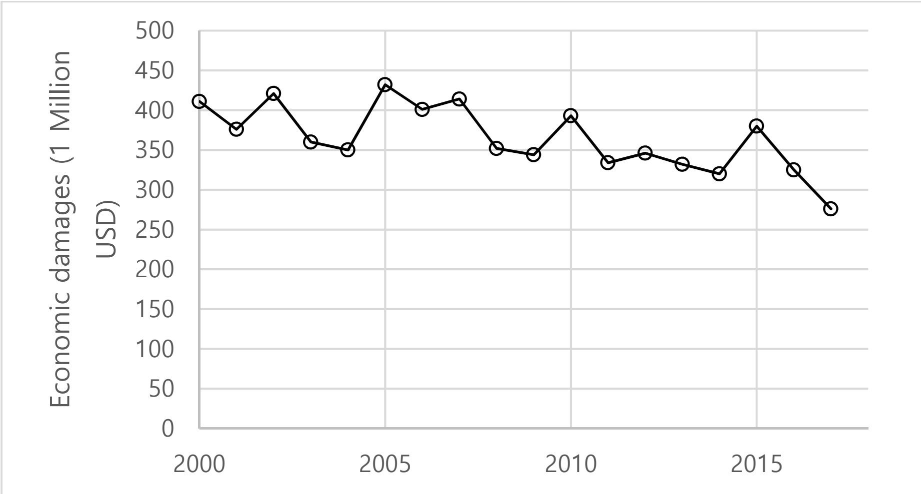


Figure 5. Number of disasters occurrence worldwide from 2000 to the present (Ritchie & Roser, 2019)

2.1.2 Risk management for natural hazard

In order to minimize the losses and damages by natural disasters, presumably due to climate change, it is paramount important to prepare preventive activities proactive following a planned schedule rather than to respond reactively after the hazardous event happened. An integrated risk management framework that includes all steps required for effective implementation of preventive action can help to avoid occurrence of unwanted losses of people, properties and environments. The Sendai Framework for Disaster Risk Reduction established to be implemented between 2015-2030 declare seven targets to reduce loss and damage and to increase information and strategies for disaster reduction, and it includes four priorities as actions to decrease disaster risks: understanding risk, strengthen the governance for managing risk, investing to enhance resilience and encourage disaster response readiness (UNISDR, 2015). The Sendai framework adopted in UN world conference for disaster risk reduction in 2015; however, it does not provide technical modules or management practices that can be specifically implemented on local scale although it contains overall direction of approach and declaration in policy level.

In order to find good examples for risk management applied to natural hazards, it is useful to look at local practices conducted against natural disasters such as flooding, landslides or wild fire. Applying risk management to mitigate natural disasters has been discussed without distinction of the processes at the beginning (UNDRO, 1991), or limited to the engineering stage to conduct risk assessment for man-maid infrastructure (Vrijling et al., 1995). However, for the flood management, setting up a framework following different process has been discussed by dividing it into three stages; the operational level, project planning level and project design level (Plate, 2002). Especially, at the project planning level, the process of participating in decision making from politicians to those directly influenced by floods has been addressed to be included in the flood risk management. The flood risk management has been also defined as implementing mitigation measures to reduce the flood risk most efficiently, and types of the measures were classified in detail from precautious preventions to post flooding measures including preventive flood control such as land-use and channel management, preparatory measure such as forecasting and warning, and measures during floods like emergency evacuation (Hooijer et al., 2004). This approach to flood risk management suggested that the flood risk could be reduced further with control measures in sustainable manner through the management stages to limit damages, rather than merely rely on hydrological technology.

In case of landslide risk management, landslide hazard maps has been made for zoning to restrict development on landslide prone area and to reduce the unwanted losses, which became a requirement based on regulations (Lateltin et al., 2005). This natural risk management has included the four elements; hazard assessment, defining protection requirements, planning mitigation measure and emergency planning, which has the similar cycle as the risk management of flooding above. For the wildfire hazard, an effort have been made to integrate risk assessment into forest management against to main hazards such as storm and wildfire, and the four steps has been suggested to integrate risk into decision making; analysis of framework, probabilities for hazards, estimation of cost and choice of action. The approach for the forest risk management has also overall similarity to make decision for management from identifying probabilities for hazards and select appropriate mitigation (Hanewinkel et al., 2011). A common approach following the project stages rather than searching for engineered solutions just in the initial design stage can be found in applying risk management for natural hazards, which are the steps of hazards identification, applying risk assessment and mitigating damages.

2.1.3 Communication on risk information

The problems of restriction of data accessibility, inappropriate cross-sector communication, lack of risk information dissemination, non-standard or outdated data, additional cost requirement for raw data process and etc. are not sufficiently resolved for natural risk management despite presentation of hazards, vulnerabilities, and risks management has been more easily available through new IT solutions and geo-information platforms (UNISDR, 2004). Since nonstructural management such as early warning and emergency response is recognized as essential part of risk management, seamless communication and propagation of risk information is becoming very important for effective risk management and disaster risk reduction (Albano et al., 2013). In addition, risk communication based on more precise quantitative evidence provides an indicator for early warning and other criteria for risk management. Those quantitative risk information can also provide a reference to establish spatial planning incorporating emergency response plan against natural disasters.

On this perspective, risk-informed regulation has been emerged and challenges for communicating risk-informed decision to the public including the process of setting has been discussed (Bier, 2001). The goals of risk communication has been identified (Rowan, 1991), and it includes establish trust between communicator, raising awareness, education and reaching agreement. Most importantly, motivating people to reduce the exposed risk to their own area of living should be achieved by risk communication. To achieve the goals, risk information from historical data will help stimulating people's experience regarding natural hazards, and building trust in authorities by using empirical data can help increasing perception on risk (Wachinger et al., 2013). Eventually, public participation can be the most effective way to establish trust and promote awareness, which can enhance people's readiness for disaster risk reduction.

The integrated risk management framework suggested in this thesis requires stakeholders' participation and collecting opinions for the completion of the overall process with feedback at each stage. Systematically analyzing on exposed risk to the community and endeavor to close the disparities between experts group, policy maker and the general public presented in this study may help to minimize losses and damages by natural hazards.

2.2 Industrial risk management practices

2.2.1 Risk identification

Risk identification is the first step and the most essential part of risk management to ensure safe operations, avoiding unintended failure in a system (Dunjo et al., 2010). HAZOP aims to identify sets of cause-consequence scenarios considering the system response when deviations are generated from design intent or from ordinary operating conditions (Rossing et al., 2010). HAZOP, in which "hazard analysis" and "operability study" were initially separate components, originated at Imperial Chemical Industries Ltd in the UK in the late 1960s and spread to Europe and elsewhere (Knowlton, 1979; Swann & Preston, 1995). Early studies were based on the supposition that process problems can occur when there are deviations from a normal state, and it was used as a tool to analyze hazards in complex systems (Lawley, 1974). Since then, Klertz (Kletz, 1991; Kletz, 1997; Kletz, 1999) researched the HAZOP technique in detail in studies that have gained widespread recognition, and addressed practical issues of hazard identification and analysis through case studies. Nolan (Nolan, 1994; Nolan, 2014) has discussed HAZOP and what-if studies, and tried to extend the concept to the security field of the process industry, introducing methodology and documentation.

In recent decades, HAZOP has been applied to various fields besides the process industry. It was shown that HAZOP could successfully be applied to computers and transportation systems in addition to mechanical systems (Robinson, 1995). In addition, HAZOP was successfully used to predict traffic problems, and it was also reported to be advantageous for finding newly occurring deviations in a road system in response to adoption of a new technology (Jagtman et al., 2005). Analogous attempts have also been applied to detect problems caused by human errors. For instance, the implementation of HAZOP was discussed to analyze human factors by interpreting guide words as human mistakes and by adding parameters for human behavior (Aspinall, 2006). Kletz (2006) discussed the necessity of expanding the factor of human errors for HAZOP, and exemplified the various types of incidents induced by human mistakes. The application of HAZOP can also be extended to climate change issues.

For example, a similar approach to identify previous weather events affected to organization as HAZOP does can be found in the UK Climate Impacts Program (UKCIP) project. The adaptation wizard of UKCIP have been provided the process to support organizations' adaptation to climate change, and using a worksheet for hazard identification was proposed at the stage of vulnerability assessment (UKCIP, 2018). However, the approach and frame suggested in this study has specialty in that the acceptance of the level of risk can be conducted semi-quantitatively following logical flow of cause-consequence scenarios. It may be possible for entities such as local governments or general service companies, which may suffer losses from natural disasters, to use the customized HAZOP approach to identify specific climate change related natural hazards.

2.2.2 Risk analysis and treatment

SIL was presented in IEC 61508 by the International Electro-Technical Commission as a measure of the probability that a safety function in a certain system performs a desired action properly (I.E.C., 1998). SIL literally refers to the discrete level of safety integrity requirements that is expected to be met by a safety function. It consists of four levels in the IEC standard, from the lowest level of SIL 1 to the most stringent level of SIL 4 to be assigned in a safety-related system. In order to apply the concept to random natural disasters with a low frequency of occurrence, the measures proposed for the low-demand mode can be referred to. The targeted failure measures of average probability are shown in Table 1.

Table 1. Target failure measures for SILs of safety function (in low-demand mode)

Safety Integrated Level (SIL)	Average probability of failure to perform a desired function
SIL 4	$\geq 10^{-5}$ to $< 10^{-4}$
SIL 3	$\geq 10^{-4}$ to $< 10^{-3}$
SIL 2	$\geq 10^{-3}$ to $< 10^{-2}$
SIL 1	$\geq 10^{-2}$ to $< 10^{-1}$

The SIL was originally developed for safety-related systems embedded in an electrical, electronic, or programmable electronic device. SIL studies are used in the process industry to prevent losses of life, environment, or assets by accidents, such as fires, explosions, toxic material releases, or mechanical failures. This approach to functional safety is widely used in various industries to protect humans, the environment, and material assets against hazardous events, as after the inception of SIL, its use spread to system integrators and to manufacturers (Gall, 2008). However, it is possible to use the concept for managing risk by natural hazards if we consider a safety function as a barrier to minimize any damage by a natural disaster.

To apply the SIL concept for natural disasters, the safety function to prevent losses by natural hazards should be defined first. For landslides, prevention of a landslide through monitoring activities followed by warranted mitigation measures was considered as a safety function in this study. By applying the SIL concept to natural hazards, it is possible to obtain probability measurements of the performance required for safety function, which enables the quantitative calculation of risk to meet a targeted risk reduction factor (I.E.C., 1998). Prior to conducting SIL, it is necessary to review a hazard identification report such as HAZOP to determine additional safety barriers (Bhimavarapu & Stavrianidis, 2000).

2.2.3 Risk evaluation and acceptance

There is always the possibility of disasters, even if we identify natural hazards and take steps for risk management based on an analysis of the probability of occurrence using the HAZOP and SIL approaches. Therefore, to minimize losses from disasters, more precise prediction is needed through simulations based on physical models to determine the extent of damage that can occur in various areas under various weather conditions. QRA provides a methodology to estimate the magnitude of the consequences of hazardous events considering the likelihood of their occurrence, and presents quantitative risk indices for the elements at risk, which could be people, environments, property, or even reputation.

The definitions of QRA vary, Freeman (1990) introduced QRA as a methodology for risk assessment with the goal of developing cost-effective strategies for risk reduction. QRA originated in the early 1970s in the nuclear power industry (Apostolakis, 2004). QRA is also widely used for chemical process risk assessment, and it is a regulatory requirement in many countries for planning new facilities and for operational changes (Frank & Jones, 2010). QRA has also been extensively adopted for analyzing construction safety, the fire safety of buildings, food safety, and so on (Guanquan & Jinhua, 2008; Hoornstra et al., 2001; Meng et al. , 2011).

QRA has been actively applied in the field of natural disasters, and various studies have discussed applying QRA to natural hazards affecting people and assets. Guzzetti (2000) discussed applying the risk analysis to landslides, and Dai et al. (2002) discussed the use of the F-N curve by UK-HSE for analyzing the potential societal risk posed by landslide hazards. Zêzere et al. (2008) and Remondo et al. (2008) sought to introduce more accurate quantitative measures in landslide risk analysis, and Jaiswal et al. (2011) detailed the magnitude of landslide consequences in risk calculation by considering the run-out distance with volumes estimated based on empirical data. van Westen et al. (2006) addressed the difficulties in quantitative landslide risk analysis due to a lack of landslide inventory data and limitations in runout modeling and estimating landslide vulnerability. However, more accurate quantitative analyses have recently been made possible by physical modeling based on hydrology.

The use of a physical model, which represents a major advance from the previous practice of frequency estimation through incomplete historic data, indicates whether damages will be actually caused by natural hazards in given topographic, geologic, and meteorological conditions. The model result can provide technical guidance to estimate the possibility that an element at risk will be damaged in a certain location at a specific time. In the case study, QRA was conducted to analyze the extent of the areas affected by potential landslide based on a physically-based model for landslide hazard, the Transient Rainfall Infiltration and Grid-based Regional Slope-stability analysis (TRIGRS) model (Baum et al., 2008). In addition, potential impact by complex flood was assessed by using a physically-based model for flood hazard, the recently revised Limburg Soil Erosion (openLISEM Hazard) model (ITC, 2018).

2.3 Type and impact of multi-hazard risk

Multi-hazard risk cause a compound disaster affected by more than single risk factor. The content of multi-hazard risk has been discussed in the early documents on sustainable development such as Agenda 2 1 and the Johannesburg plan (UNCED, 1992), and research and readiness to reduce the unexpected damage by multi-hazard risk has been being requested.

The term for complex disasters in the form of natural disasters seems to be used in various ways. Kappes et al. (2012) reported that awareness of multi-hazard risk or compound disasters are increased, but they are not consistently used and rather explanatory of various types of compound disasters. The relationship between the multi-hazard risk factors that cause compound disasters has been organized systematically in the Caribbean Handbook on Risk Management project (C.H.A.R.I.M., 2018). The relationship between multi-hazard risk that cause compound disasters can be categorized by type as shown in Table 2 and Figure 6 below (Liu et al., 2016).

Table 2. Type of compound disaster and description

Types of compound disaster	Descriptions of types
Independent events type	Accumulated risk caused by single hazard events that a damage is caused by exposure to A or B event.
Deposition events type	A precedent event changes the susceptibility and increases the probability and magnitude of damage caused by next event.
Domino or cascading hazards	Sequential occurrence of hazard events causes a complex disaster in the form of a chain effect.
Coupled events	Risk associated with the same triggering event that generates different hazard types and increases magnitude

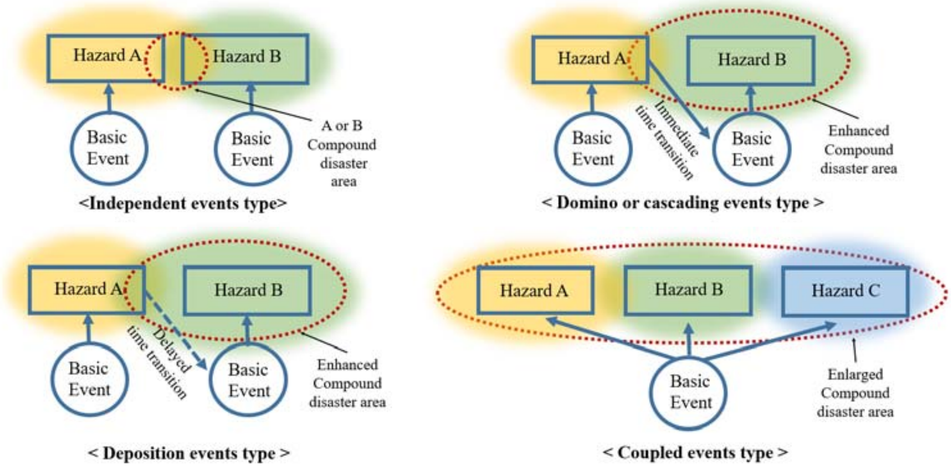


Figure 6. Types and structure of multi-hazard risk

For example, in the case of compound disaster which are debris-flows of landslides followed by forest fires, the impact of landslide due to rainfall can be amplified more easily after a certain period of time after the forest fire has occurred. This is the deposition type of compound disaster. In South Korea, the effects of post wildfire landslide compound disaster may occur due to summer heavy rainfall after the forest fires occurred in dry spring season, and landslide due to surface soil loss can be continued until restoration of vegetation and soil.

For the study of post-wildfire landslide and debris-flow, Nyman et al. (2011) conducted an on-site research of the increase in the amount of soil erosion after the forest fire in southeastern Australia, and analyzed the characteristics of the collected soil samples to clarify the cause of the increase. Parise and Cannon (2012) studied the occurrence and effects of shallow landslides by infiltration of storm rain and debris flows by soil erosion. Cannon et al. (2008) conducted a study on the thresholds of rainfall intensity and duration for landslides in southern California and Colorado border areas, and Staley et al. (2013) have been taken further studies to improve the prediction accuracy of landslide rainfall thresholds for wildfires in southern California. Lainas et al. (2016) studied rainfall thresholds that trigger landslides after wildfire in West Greece, and it has been shown that landslides occurred at 20-30% less rainfall intensity compared to the case before forest fires.

As a study on the effects of post-wildfire landslide with numerical modeling, Ren et al. (2011) analyzed characteristics of soil erosion in southern California using SEGMENT, a geo-fluid model. However, the intensity of the forest fire impact is not based on the actual soil test results but is divided into empirical severity categories, reflecting the change in soil characteristics. Based on the previous researches, this study analyzed the effect of post-wildfire landslide complex disaster scenario considering the effect of water repellency effect.

In case of flooding, collapsing of a reservoir in a catchment during heavy rainfall can cause more severe damage to a community than by a fresh flooding. This type of compound disaster corresponds to a cascading hazards, which shows sequential occurrence of hazard events at the same time amplifying the magnitude of the consequence. Multi-hazard risk by flooding can affect in complex way increasing the severity of damages even though it has relatively low probability of occurrence. To cope with these unforeseen potential impacts, scenarios of compound disaster in case of flooding must be identified and evaluated. This study analyzed the cascading effect by flooding with physically-based model and provide an information for spatial planning and setting mitigation measures.

2.4 Comparison of risk assessment methodologies

There are plenty of risk assessment methodologies used for natural hazards and climate change issues. Among them, the methods used in this study and the previous researches related to the subjects are briefly listed in this session. Table 3 is the summary of risk assessment methods comparison to show advantages and limitations of the reviewed studies. In general, the advantage of risk identification study in HAZOP method is its systematic approach to identify the site-specific hazards in semi-quantitative format following logical order, while previous studies used a fixed form of checklist or missing a frequency estimation part. The advantiges of risk anlysis and treatment methods used in this study are the use of time-dependent reliability concept that makes possible to analysis time-varying dynamic risk and the inclusion of maintenance factors. Wheareas, there are previous studies assessing landslide hazard by using risk matrix method which did not reflect time-varing probability of landslide occurrence, and assessing rockfall hazard without considering change of risk by periodic maintenance or additional mitigation measures.

In the category of risk evaluation and acceptance, the advantage of this study’s approach is that considering the exposed individual risk or societal risk from natural hazards in QRA can support spartial planing and estabilishing mitigation measures. In addition, the physically-based models are used in this study, TRIGRS for landslide hazard and openLISEM for flood hazard, include more detailed physical variables and are succesfully applied to assess the potential impact by compound disasters. Although there are previous studies using numeric modelling, limited use of physical variables existed.

Table 3. Comparison of risk assessment methods

	Title	Hazard	Methodology	Advantage(s)	Limitation(s)	Author/Organization
Risk identification	HAZOP*	All	Worksheet	Semi-quantitative risk assessment	Time-consuming	Lee & Lee (2018a)
	Adaptation wizard	All	Worksheet	Cause and consequence base.	Event frequency missing	Willows et al. (2003) /UKCIP
	Check list for Adaptation	All	Checklist	Quick assessment Weight factor	risk evaluation missing	Olazabal et al. (2017) /BC3
Risk analysis and treatment	Safety Integrated level (SIL) *	Landslide and Rockfall	Time dependent reliability & functional safety	Including Time-varying probability, Including maintenance factor	Limited to frequency analysis Limited to frequency analysis	Lee & Lee (2018b), Lee & Lee (2018c)-Conference proceeding
	Landslide hazard map	Landslide	Risk matrix	Including Element at risk	No Time-varying probability	Lateltin et al. (2005)
	RoMa	Rockfall	Event tree analysis	Including Element at risk & mitigation measure	Not including maintenance factor	Mignelli et al. (2012) Peila & uardini (2008)
Risk evaluation and acceptance	QRA*	Landslide	TRIGRS (by USGS) & QRA	Including Individual & societal risk assessment	No runout model	Lee & Lee (2018a)
	Post wildfire landslide*	Landslide	TRIGRIS (by USGS)	Including multi-hazard risk, Detailed physical variables	no field inventory full data	Lee et al. (2019)
	Mudslide modeling	Landslide	SEGMENT, Geo-fluid model	Including multi-hazard risk,	Use empirical severity category	Ren et al. (2011)
	Complex flood*	Flooding	OpenLISEM (by ITC), Catchment model	Including multi-hazard risk, Detailed physical variables	no field inventory full data	Lee et al (2019)-Conference proceeding
	2D dam-break flood	Flooding	r.damflood, GIS-embedded	Hydrology model on topography	Dam-failure model only, No variables, related to soil	Cannata & arzocchi (2012)

* Suggested methodology in this study.

3. Risk identification for climate change issues

3.1 Method for risk identification

The procedure of HAZOP can be presented based on IEC 61882 (Macdonald, 2004), as summarized below. The first step in conducting HAZOP is to divide systems to define the scope of the study. The study can start with a description of the system to inform the team before proceeding with a node-by-node examination. Next, a deviation needs to be generated, considering a combination of parameters and guide words. Parameters are also known as elements, keywords, or properties. Guide words are the words used to identify and state a particular deviation from a design intent. The combination of parameters with guide words results in meaning and generates applicable deviations. An illustrative arranged blend of parameters with guide words is displayed as a matrix in Table 4(a), which is a typical set of applicable deviations.

Alternatively, the combinations shown in Table 4(a) can be converted to those shown in Table 4(b) when we consider climate change issues to identify deviations with suitable combinations of guidewords and parameters. To generate deviations caused by climate-related natural hazards, parameters of climate exposure, such as temperature, rain, and wind, can be used to replace the physical parameters of a typical process. Combined with suitable guide words, deviations that lead to damage by natural hazards can be derived, such as heavy rain, drought, storm, flooding, landslides, sea level rise, abnormally high temperatures, and etc.

Table 4. (a) Meaningful combinations of guide words for process parameters, (b) Deviations that lead to damage by natural hazards.

(a)	
Parameters	**Meaningful combination of guidewords**
Flow	No, more of, less of, reverse, else where, as well as
Temperature	Higher, lower
Pressure	Higher, lower, reverse
Level	No, higher, lower, reverse
Mixing	No, more less
Reaction	Higher, lower (rate of), no, reverse, as well as
Phase	Other, reverse, as well as
Composition	Part of, as well as
Communication	No, part of, more of, less of, other, as well as
(b)	
Climate exposure Parameters	**Deviation by climate change**
Temperature	Hot, cold, boiling, freezing
Rain	Heavy rain, flooding, drought, wildfire
Snow	Heavy snow, frost
Wind	String wind, Tornado, Typhoon
Topography	Landslides, land subsidence
Inundation	Sea level rise, coastal river flood
Flora/Fauna	Withering, vermin, infectious disease
Lightening	Lighting injury, asset damage

After setting up parameter-guideword combinations, a study can be conducted following the flow shown in Figure 7. Once it is decided whether a deviation makes causes, possible causes are established through a multi-disciplinary team discussion. The expected frequency of initiating causes need to be addressed, but without considering existing safeguards.

Consequences should be considered to complete the cause-consequence scenario, and the severity of consequences need to be stated under the categories of loss of life, property, environment, or reputation of an entity. Before risk evaluation, existing safeguards in a plan, design, or operating condition should be considered as mitigating measures in order to avoid overestimating the level of risk.

At the stage of risk estimation and evaluation, a risk matrix can be used to decide acceptability. Risk scenarios above the acceptable risk criteria are identified as high-risk items and screened for possible recommendations. The acceptable risk criteria on the risk matrix may be developed in variable sets depending on the nature of entities and the environment. Finally, recommendations are provided to correct deficiencies of design or omission of operational planning to reduce risk to below an acceptable level. Importantly, recommendations should be presented to a party that shall carry out an action to resolve the raised issues. This series of steps is used as a procedure for finding a credible cause-consequence relationship that results from a deviation. A HAZOP study can be conducted quantitatively if the frequency of the initial cause and the magnitude of consequences are estimated numerically.

Figure 7. The steps used in hazard identification from derived deviations (adapted from Macdonald, 2004).

The sequence of a HAZOP study can be presented in the order shown in the worksheets in Table 6 for the HAZOP case study, as such a system enables the systematic reporting of causes and consequences. It contains columns to be filled with content established during a HAZOP session, including deviations from parameter-guideword combinations, cause-consequence scenarios estimated in a quantitative manner, and recommendations together with an indication of the party designated to carry out actions before the due date. This worksheet should be filled out for each node. In the context of controlling natural hazards, the nodes can consist of services, infrastructure, or facilities of an entity, such as transportation, electricity, water supply, and sewerage networks. The specific content of the nodes is expected to vary in accordance with land use patterns in residential, commercial, industrial, rural, and forest areas.

3.2 Result of risk identification

3.2.1 Climate change risk identification

The following checklist in Table 5 and HAZOP worksheet on Table 6 are the part of a sample case study for an enterprise that we have developed to identify various incident scenarios when exposed to natural hazards by extreme weather events. The checklist was designed to reflect the likelihood and severity of risk factors for the company caused by abnormal weather conditions on a qualitative scale. In contrast, the HAZOP worksheet shows how the risks identified using the checklist can be analyzed more specifically and documented in a logical order.

Table 5. The sample checklist for identify risks caused by heavy rain

Risk category	Risk factor	Occurrence frequency	Impact category	Impact severity
		Low high	People,/Property/Env.,	Low high
Emplo-yee	Injury caused by equipment collapsing due to heavy rainfall	[1] [√] [3] [4] [5]	[√] / [ ] / [ ]	[1] [2] [3][√] [5]
	Injury caused by electric shock due to humid conditions	[√] [2] [3] [4] [5]	[√] / [ ] / [ ]	[1] [2] [3] [4][√]
	Commuting delays due to traffic system downtime	[1] [2] [3] [√] [5]	[√] / [ ] / [ ]	[√][2] [3] [4] [5]
Logistics	Transportation network disconnected by flooding due to heavy rain	[1] [√] [3] [4] [5]	[ ] / [√] / [ ]	[1] [2][√] [4] [5]
	Shipping and aviation disruption caused by heavy rain	[√] [2] [3] [4] [5]	[ ] / [√] / [ ]	[1] [2] [3][√] [5]
	Inundation of logistics storage due to heavy rains	[1] [√] [3] [4] [5]	[ ] / [√] / [ ]	[1] [2][√] [4] [5]
	Raw material or final product damage or quality deterioration due to heavy rain	[1] [√] [3] [4] [5]	[ ] / [√] / [ ]	[1] [√][3] [4] [5]
Location	Slope collapse near worksite, soil discharge, or landslide	[√] [2] [3] [4] [5]	[√] / [ ] / [ ]	[1] [2] [3] [4][√]
	Inundation of rivers and lakes near the workplace due to heavy rainfall	[√] [2] [3] [4] [5]	[√] / [ ] / [ ]	[1] [2] [3][√] [5]
Utilities	Damage of electrical equipment (substation, transmission tower, etc.)	[1] [√] [3] [4] [5]	[ ] / [√] / [ ]	[1] [2] [3][√] [5]
	Damage of water supply network due to heavy rain	[√] [2] [3] [4] [5]	[ ] / [√] / [ ]	[1] [2][√] [4] [5]
	Damage of waste treatment facility due to heavy rain	[√] [2] [3] [4] [5]	[ ] / [√] / [ ]	[1] [2][√] [4] [5]

** Note: The checklist was filled out arbitrarily, and the intention of presenting the checklist is to provide a comparison with the HAZOP worksheet.

Table 6. Sample HAZOP worksheet to identify risks associated with the parameter of rain for the service node of logistics

Guide word	Devi-ation	Cause	Freq.	Consequence	Expected damage	Existing safeguard	Risk level (H/M/L)	Recommended action	Action to be taken by
More	Heavy rain	Traffic system downtime and disconnection	5 yr	Possible production disruption caused by raw material supply instability	People: Assets: H Environ.:	Extreme weather operation guideline	High	Increasing capacity of raw material storage	Dept. of Training
More	Heavy rain	River flooding near the worksite	10 yr	Production downturn due to potential inundation damage of the facilities (Tag-xxx) for maintenance	People: Assets: M Environ.:	Drainage network	Medium	Emergency pumping	Dept. of Mainten-ance
More	Heavy rain	River flooding near the worksite	10 yr	Damage of the final products stored in station B at the north yard	People: Asset: L Environ.	Drainage network	Low	Embankment work	Dept. of Logistics

** Note: The levels of risks are decided through a comparison using a risk matrix reflecting the frequency of the initiating cause and the expected damage estimated by the HAZOP team.

3.3 Discussion on risk identification

The advantages of the HAZOP technique for identifying natural hazards are as follows. It reduces the chances of omitting crucial causes of natural harms that may result in losses. HAZOP provides numerical estimates of the frequency of causes and the amount of losses, and it enables a determination of the acceptability of risk through a comparison with risk tolerance criteria. The estimated amount of loss found during HAZOP can be used as a basis for cost-benefit analysis, so that organizations appropriately allocate resources for mitigating natural hazards. In addition, HAZOP allows hazard identification to be customized for a given entity better than an experience-based checklist format, which limits the scope of questioning deviations from design intent (Shafaghi & Cook, 1988). In the cause-consequence scenarios derived from a HAZOP study, location-specific damage scenarios can be included, considering the geo-spatial features of natural hazards. Moreover, HAZOP addresses the possibility of compound deviations due to potential multiple failures (Baybutt, 2015). Most importantly, HAZOP facilitates risk communication between decision-makers and the public through multi-disciplinary participation.

Despite its advantages, HAZOP has some drawbacks for hazard identification. Baybutt (2015) discussed the weaknesses of HAZOP. First, disadvantages can arise since HAZOP studies rely on discovery based on previous experiences, rather than by applying certain rules. The outcome of HAZOP can be subjective and can omit important scenarios by mistake if a leader lacks experience or the involvement of team members is not well balanced. HAZOP studies may fail to consider various external factors or deviations due to issues other than system design, because it generates deviations by choosing parameters within the design intent. During HAZOP studies, the repetitive presence of deviations can lead to the duplication of cause and consequence scenarios, which may hamper team performance in hazard identification and reduce the readability of the study report. In addition, a method that follows the guide words can lead to exaggerated scenarios through HAZOP, or a team may fail to find a critical deviation by misunderstanding the combination of the guide word and the parameter. Lastly, it may fail to address transitional events between an initial cause and consequences, which might be important for understanding the complete sequence of cause and effect in scenarios.

In order to complement these shortcomings, experienced team members from a multidisciplinary department should participate in the study, with good communication and cooperation (McKelvey, 1988). The problems that most HAZOP findings are typical and that the report contents are often repetitive can be overcame by executing a safety review in a shortened form that is equivalent to the HAZOP procedure (Grossmann & Fromm, 1991). HAZOP studies should be updated periodically to reflect the identification of new hazards and to maintain validation (Baybutt, 2015). The frequency and impact of disaster occurrence as a result of natural hazards due to climate change can vary over time. In particular, periodic updates for the management of infrastructure or changes in facilities should be conducted because the vulnerability of people living in the affected area can be impacted by changes in circumstances. The HAZOP study is not only an end in itself, but it is also a starting point for various risk communications and provides input data for other risk analysis methods. The contents of HAZOP can inform hazardous natural disaster scenarios in subsequent risk analyses, such as SIL and QRA, and can facilitate risk communication with the public throughout the decision-making process.

4. Risk analysis and treatment for natural hazards

4.1 Method for risk analysis and treatment

IEC 61508 states that a SIL study should be implemented following the overall safety lifecycle introduced in the standard as a technical framework (I.E.C., 1998). The overall safety lifecycle in IEC 61508 includes the steps from planning to retirement, and it consists of design, realization, validation, maintenance, and decommissioning stages. The overall safety lifecycle is constructed to achieve a desired safety integrity level of the safety-related system based on a more systematic approach.

The purpose of the safety life cycle can be comprehended as a sequential process of analyzing a safety-related problem, designing a solution, and verifying that the problem is substantially resolved as intended (Van Beurden & Amkreutz, 2001). This study is limited to SIL within the scope of the design stage. To comply with the standards, a SIL study at the design stage is divided into SIL classification to determine safety requirements and SIL verification to calculate the reliability of a safety function (Stavrianidis & Bhimavarapu, 1998).

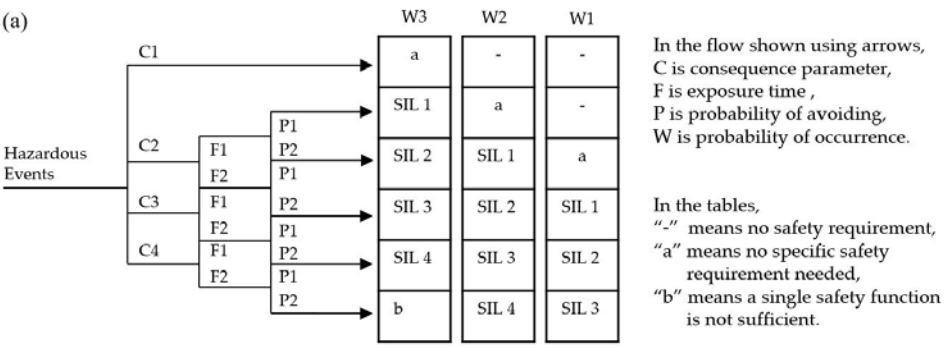
SIL classification aims to determine the target SIL for an individual safety function in a system, whereas SIL verification is a way to ensure whether the targeted SIL can be satisfied by calculating the probability of failure on demand (PFD) afterward. The numeric calculation of reliability with the PFD is a common technique used to design safety interlock in process systems (Freeman & Summers, 2016), and this risk-based approach is widely implemented in the process industry and structural safety management as part of adopting reliability engineering (Bertolini et al., 2009; Selvik & Aven, 2011; Stewart, 2001). The PFD calculation is conducted by using the failure rates of devices that comprise a safety-related system, and it normally involves a communicating connection of sensors, programmable logic solver, and final actuating elements (Gabriel et al., 2018).

To apply SIL to control natural hazards, the frequency of occurrence of natural disasters, which corresponds to the failure rate of mechanical components, needs to be identified. The probability of disaster occurrence should be also calculated in the same manner as the PFD calculation. Furthermore, a systematic classification of natural hazards, as in a SIL study, is required to assign safety requirements. Below, SIL classification and SIL verification methods are presented separately, examining how SIL studies can be applied for landslide prevention.

SIL classification

A SIL classification study can be conducted using the risk graph, risk matrices, or Layer of Protection Analysis (LOPA) methods (Gabriel et al., 2018). The common purpose of these methods is to specify the targeted SILs for safety functions. The procedures contain a scheme of risk-based analysis, in which a numerical level of the safety requirement is selected. The risk graph method includes four parameters for selecting a risk level: consequences of the event, frequency of exposed time, possibility of avoidance, and probability of unwanted occurrence (I.E.C., 1998). The risk matrices method includes two parameters of risk, severity of consequences and likelihood of the event; however, it can be used as a more quantitative method than the risk graph method. When values and ranges are quantitatively developed to describe adverse impact on life, environment and property, the matrices type of risk ranking can provide criteria to determine SILs numerically (Baybutt, 2014). In this regard, the risk matrices method is more quantitative than the risk graph method (Langeron et al., 2008). Considering the efficiency and complexity needed for a given case, entities can choose the method that best suits their purposes. Examples of risk graph and risk matrices models are shown in Figure 8. Through the LOPA method, which is more quantitative, various safety barriers, including existing safety devices and procedural control measures such as inspections are assessed, and the requirement for additional independent protective layers is determined based on a targeted risk tolerance level (Freeman, 2007).

(a)



(b)

Frequency of hazardous events (yr^{-1})	Severity of consequence			
	1 – First aid	2 – Moderate injury	3 – Serious injury	4 - Fatality
$<10^{-5}$	-	-	-	-
$\geq 10^{-5}$ to $<10^{-4}$	-	-	-	SIL 1
$\geq 10^{-3}$ to $<10^{-4}$	-	-	SIL 1	SIL 2
$\geq 10^{-2}$ to $<10^{-3}$	-	SIL 1	SIL 2	SIL 3
$\geq 10^{-1}$ to $<10^{-2}$	SIL 1	SIL 2	SIL 3	SIL 4
≥ 1.0 to $<10^{-1}$	SIL 2	SIL 3	SIL 4	SIL 4

Figure 8. (a) An example of the SIL graph method for determining the required risk reduction, (b) An example of the SIL matrices method for determining the required risk reduction (adapted from Baybutt, 2014).

The SIL classification method can be used in various ways to establish safety requirements that protect against natural hazards. For landslides, which selected as a case study, it was possible to use a landslide susceptibility map to determine the desired safety integrity levels. A landslide susceptibility map can be produced through logistic regression or other methodologies to show the landslide hazard grades, and it can be interpreted as a process for determining a targeted safety requirement. If a hazardous landslide grade is identified in a certain location, stringent management and robust mitigation measures are required to achieve a higher risk reduction effect than is possible for the other areas, provided that the same conditions of vulnerability for elements as described in Varnes's risk formula are assigned (Varnes, 1984).

SIL verification

After the determining desired safety level, a verification process should be performed to ensure that the safety function meets the targeted safety requirements. SIL verification is a process for proving that a safety function satisfies the required SIL by calculating the average probability of failure on demand (PFDavg), and it can be performed through a reliability analysis or Markov analysis (Shu & Zhao, 2014). The reliability analysis method was used for this case study, and the PFDavg calculation showed the degree to which a safety function reliably fulfilled the requirements. Reliability is commonly defined as the probability that an item performs its purpose adequately during the desired time period under certain operating conditions (Billinton & Allan, 1992). It is possible to identify the variables that are needed to describe probability of natural disaster occurrence from the context of reliability definition.

The probability of landslide occurrence can be derived from the concept of reliability. Reliability R(t) and unreliability F(t) can be expressed mathematically as shown below (Goble, 2005) :

$$R(t) = Ns(t) / N \quad (1)$$

$$F(t) = 1 - R(t) = 1 - e^{-\lambda t} \quad (2)$$

where Ns is the number of surviving items,

N is the number of total items,

λ is the failure rate,

t is the specific time.

When the number of surviving items Ns is regarded as the number of locations where landslides have not happened, the value of N minus Ns can be considered as the number of locations where landslides have occurred. If the specific time (t) is regarded as the period of time for observing landslides, the failure rate (λ) can be deemed as the frequency of landslide occurrence, which is used to denote the probability of landslide occurrences. According to the ISA-TR84 (I.S.A., 2002), PFDavg is expressed by the equation below, and a graphical illustration of the equation is shown in Figure 9:

$$\mathrm{PFDavg} = \frac{1}{\mathrm{TI}} \int_0^{\mathrm{TI}} 1 - e^{-\lambda t}\, dt \tag{3}$$

where TI is the time interval between the proof tests.

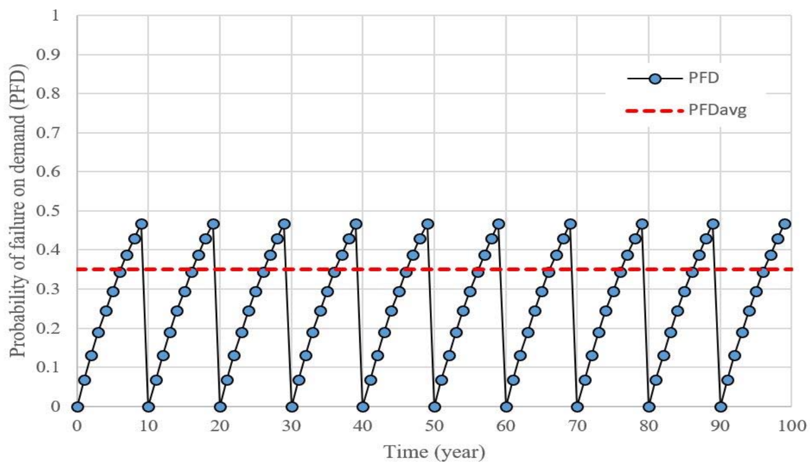


Figure 9. Changes in probability of failure on demand (PFD) across a year, and the average probability of failure on demand (PFDavg) (adapted from Goble, 2005).

This explains how the average unreliability can be managed below the desired level of risk, which corresponds to the probability of landslide occurrence in our case study. Provided that the safety function for preventing landslides is performed well by the authorities, the average probability of landslides can be managed in static conditions with periodic monitoring activities followed by proper mitigation measures. It is possible to estimate the controlled risk levels by calculating PFDavg, and the resulting measures enable a judgement to be made regarding whether safety requirements have been met.

Frequency of landslide occurrence

Landslide risk can be briefly expressed by an equation in which the probability of a hazardous event is multiplied by the probability of loss of life or property (A.G.S, 2000). For risk analysis, the frequency of landslide occurrence must be identified prior to calculating the probability of landslide occurrence. To estimate the frequency of landslide occurrence, a unit pixel of key studies was considered as a component item to denote the unit for the frequency of landside occurrence. The frequency of landside occurrence can be interpreted as the instantaneous failure rate, presented in terms of the number of failures per unit time, and it is based on measurements of the quantity of components exposed to a stressful environment.

Based on the assumption above, the frequency of landslide occurrence can be derived from the concept of the failure rate as below:

$$\lambda = (N - Ns) / (Ns \times \Delta t) \quad (4)$$

where λ is the failure rate of the pixel components, which corresponds to the frequency of landslide occurrence,

N is the number of total items;

Ns is the number of surviving items,

Δt is the time between landslide occurrences.

Given that Ns is defined as the number of pixel components with no landslide initiation, subtracting Ns from N in Formula 4 can be considered as a measure of the number of landslide events because the point locations of landslide initiated were regarded as the failed components. Time to fail, which refers to the time to landslide reoccurrence, is given by Δt in Formula 4, and it expresses the probabilistic period between landslides. It can be estimated by establishing the rainfall threshold. More information is provided below regarding the rainfall threshold for landslide initiation.

As per Formula 4, the units for the frequency of landslides can be expressed quantitatively as below, provided that the unit pixel (10 m ×10 m) is obtained from the data of a landslide hazard map:

$$FL = \text{landslide event} \times \text{pixel}^{-1} \times \text{year}^{-1} \quad (5)$$

where FL is the frequency of landslide occurrence and the area of a unit pixel corresponds to 100 m^2.

Meanwhile, Corominas and Moya (2008) described two separate approaches to the spatial probability and temporal probability of landslide occurrence. The relative frequency is the ratio of the number of landslides recorded to the unit area, which allows multiple regional landslide events to be described. The units for the relative temporal frequency are the same as those given in Formula 5. The relative temporal frequency of landslides could be identified in this study because the landslide inventory data included multiple landslide events in the province region that were triggered by a heavy rain event.

The overall procedure for analyzing the frequency of landslide occurrence based on the concept of the failure rate in the reliability study and the differentiated frequency according to landslide hazard grades is shown in Figure 10.

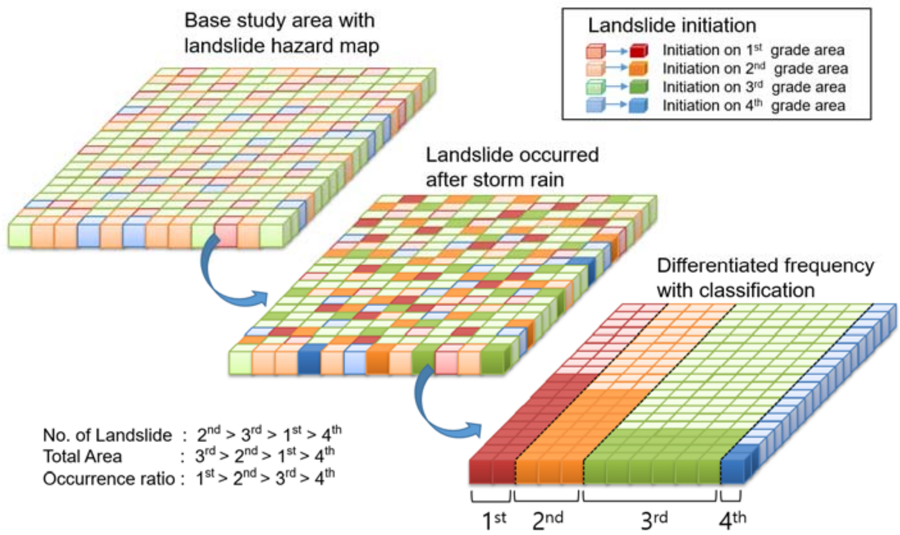


Figure 10. The frequency of landslide occurrence based on the concept of the failure rate.

Notably, when the number of landslide events is classified by the landslide hazard grade, the maximum landslide hazard grade was assigned to each landslide event with an overlay of the inventory polygon data and landslide hazard map on the GIS platform. Moreover, in a conservative approach to risk analysis, the area where landslides did not occur was measured when determining the total area corresponding to each landslide hazard grade. It should also be noted that the estimated value of the frequency varies depending on the size of the area. The frequency units for this study are only representative of Gangwon Province.

Probability of landslide occurrence

To estimate the probability of random disastrous events caused by natural hazards over time, a Poisson distribution is often employed. Crovelli (2000) presented a Poisson distribution model to express the probability of landslide occurrence in continuous time in natural environments, as below:

$$P[N(t) = n] = e^{-\lambda t} \frac{(-\lambda t)^{n}}{n!} \qquad (6)$$

where n is 1, 2, 3…

λ is the rate of occurrence of landslides,

t is the specified time,

N(t) is the number of landslides that occurred during time t.

The probability of one or more landslides occurring in time t, which is referred to as the exceedance probability, is expressed as below, when λ is much less than one (λ<<1):

$$P[N(t) \geq 1] = 1 - e^{-\lambda t} \tag{7}$$

This model of the probability of landslide occurrence can also be presented using the definition of reliability. The definition of reliability usually contains four basic elements: probability, adequate performance, time, and operating conditions (Billinton & Allan, 1992), and one of the definitions in general terms can be introduced as follows: the probability that an item will perform a required function without failure under stated conditions for a stated period of time (O'Connor & Kleyner, 2012). The reliability function R(t) in mathematical terms is expressed as follows (Kapur & Pecht, 2014):

$$R(t) = \frac{Ns(t)}{N} \tag{8}$$

where Ns is the number of surviving items,

N is the number of total items.

Unreliability, F(t) is given as:

$$F(t) = 1 - R(t) = \frac{N - Ns(t)}{N} \tag{9}$$

$$f(t) = \frac{dF(t)}{dt} = -\frac{1}{N}\frac{dNs(t)}{dt} \tag{10}$$

When the hazard rate h(t) is normalized with its surviving items Ns(t) instead of the total number of items N from the unreliability rate f(t) equation, we obtain the hazard rate h(t), as shown below, with a more conservative meaning:

$$h(t) = \frac{f(t)}{R(t)} \tag{11}$$

The integral of the hazard rate h(t) over the time from 0 to t is:

$$\int_0^t h(\tau)\ d\tau = -\ln R(t) \tag{12}$$

Then, R(t) is:

$$R(t) = e^{-H(t)} \tag{13}$$

where H(t) is the number of hazards in time t, and can be expressed as $H(t) = \lambda t$.

Finally, we obtain F(t) as:

$$F(t) = 1 - R(t) = 1 - e^{-H(t)} = 1 - e^{-\lambda t} \tag{14}$$

By using Formula 14 above, the probability of landslide occurrence can be calculated using the frequency of landslide occurrence estimated from the concept of the failure rate, as expressed in Formula 5.

4.2 Results of risk analysis and treatment

4.2.1 Risk analysis and treatment for landslide hazard

Returnable time period estimation by rainfall threshold

In order to estimate the returnable time period between landslide occurrences, a rainfall threshold was established, since the mechanism of landslide occurrence is triggered by the increase in pore water pressure and rain water seepage forces (Cullen et al., 2016). Since Caine's research (1980) examined the relationship between the minimum rainfall duration and intensity required to cause a landslide, a number of methodologies to identify the rainfall threshold have been examined, with the goal of finding the most suitable correlation with landslide initiation (Aleotti, 2004).

However, the examined proposals are valid only with the local geo-spatial properties (Jakob et al., 2006; Martelloni et al., 2012). Thus, domestic research results were applied to reflect the features of local geology, vegetation, and topography. Kim and Chae (2009) reported that landslides tend to occur in South Korea when the consecutive rainfall is over 200 mm for 48 hours. Based on their results, cumulative precipitation of more than 200 mm for 48 hours was adopted as a criterion for the rainfall threshold.

To determine the daily rainfall intensity, which was another factor used to determine the threshold, daily precipitation records were reviewed from when Typhoon Ewiniar caused heavy rainfall in July 2006. This decision was based on the assumption that landslides are likely to occur in the future in similar environmental conditions. Despite the lack of continuous landslide inventory data, this method provides a basis for estimating the frequency of landslide occurrence. Rainfall data from the Automatic Weather Station (AWS) located in the center of Gangwon Province were adopted as a representative sample to estimate landslide frequency, considering the geographic location and the high severity of damage caused by the typhoon.

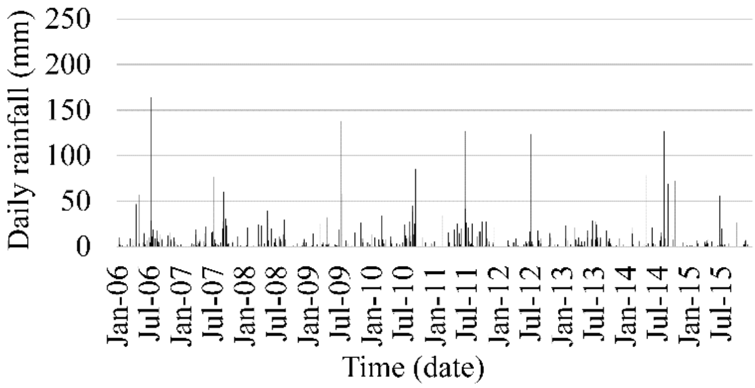


Figure 11. Sampled daily rainfall in Gangwon Province for 10 years (2006 – 2015)

The daily rainfall records in the region for the last 10 years are plotted in Figure 11. The graph shows that daily precipitation exceeded 150 mm on both July 15 and July 16, 2006, and it is possible to assume that landslides occurred after the rainstorms on those dates. Therefore, a daily rainfall of more than 150 mm was set as another factor contributing to the rainfall threshold. As a result, the rainfall threshold was established as including both 48-hour cumulative precipitation over 200 mm and daily precipitation over 150 mm.

By screening using the rainfall threshold, as shown in Figure 12, the average landslide occurrence interval was estimated by counting the dates that satisfied these criteria, which resulted in three events during the reviewed 10-year period. Thus, the probabilistic period of landslide occurrence was estimated as 3.3 years for the analysis of the probability of landslide occurrence in this study.

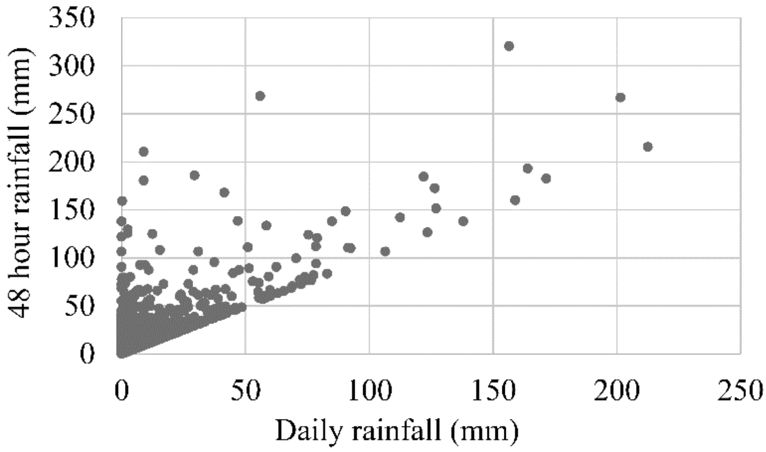


Figure 12. Scatter diagram of daily rainfall and 48-hour cumulative rainfall showing that 3 events exceeded the rainfall threshold in 10 years (2006-2015).

Estimation of landslide frequency

The locations in the inventory data where landslides have occurred in Gangwon Province are presented in Figure 13.

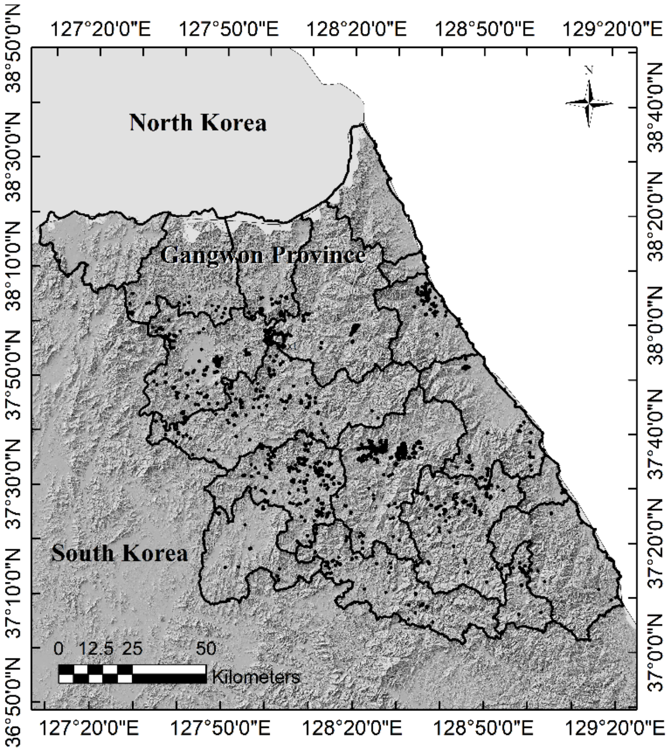


Figure 13. Locations of landslide occurrence in the study area

An analysis of the landslide hazard map of Gangwon Province shows that grades 2 and 3 predominated throughout the study region, while grade 1 areas were sparsely scattered near mountainous areas. The resulting estimation of the frequency of landslide occurrence is summarized in Table 7. The total areas of the each landslide hazard grade are shown, except for grade 5, which had null data, and it is shown that grade 3 occupied the largest area of 5815.2 km^2, followed by grade 2 (4611.6 km^2), grade 4 (250.0 km^2), and grade 1 (186.5 km^2).

When the number of landslide events was counted and classified along with the landslide hazard grades, a total of 72 landslide events were found in grade 1 areas, followed by 700 landslides in grade 2 areas, 433 in grade 3 areas, and 8 landslides in grade 4 areas. The most landslides occurred in grade 2 areas because they accounted for the most area. However, if we examine the occurrence ratio, which is defined as the number of landslide events divided by the total area, it can be seen that the highest number of landslide events per area occurred in grade 1 areas.

Thus, our results indicate that areas with a landslide hazard of grade 1 had the highest value of landslide occurrence frequency (1.17E-05 landslide events × pixel $^{-1}$ × year $^{-1}$). The frequency decreased from grade 2 to grade 4, which had the lowest value of landslide occurrence frequency (9.70E-07 landslide events × pixel $^{-1}$ × year $^{-1}$). It should, however, be kept in mind that the estimated landslide occurrence frequencies are only valid for Gangwon Province area.

Table 7. The analyzed frequency of landslide occurrence

Landslide hazard grade	No. of Landslides	Total area * (km^2)	Landslide occurrence frequency (λ) **
1	72	186.5	1.17E-05
2	700	4611.6	4.60E-06
3	433	5815.2	2.27E-06
4	8	250.0	9.70E-07

* The unit pixel (10m × 10m) is used for frequency estimation.
** The unit of landslide occurrence rate (λ) is landslide event × pixel $^{-1}$ × year $^{-1}$

The probability of landslide occurrence

Given the estimated frequency of landslide occurrence along with the landslide hazard grades, the probability of landslide occurrence was calculated following Formula 14 and plotted with a logarithmic scale on the Y-axis. The graph in Figure 14 shows an increase in the overall probability of landslide occurrence over time, as well as presenting discrete curves according to the landslide hazard grade. The resulting graph indicates that grade 1 areas had the highest value of probability of landslide occurrence, followed by grade 2 areas, grade 3 areas, and grade 4 areas, sequentially.

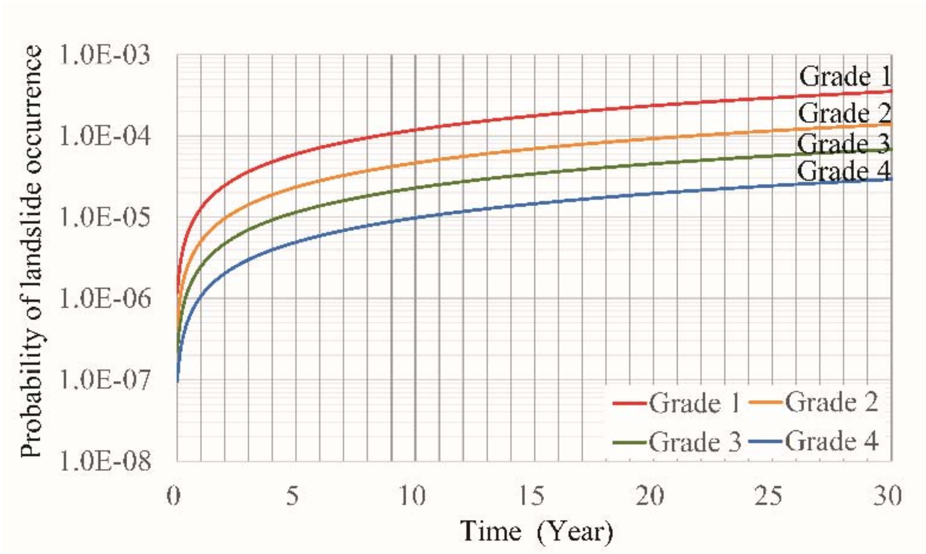


Figure 14. Increases in the probability of landslide occurrence depending on the landslide hazard grade.

Our results indicate that locations with different grades of landslide hazard are exposed to different risk levels, which can be analyzed by calculating the probability of landslide occurrence. The probability of a landslide, which is a disaster caused by a natural hazard, can be estimated based on the concept of reliability. The calculated probability value can be used as a basis for landslide risk management

4.2.2 Risk analysis and treatment for rockfall hazard

Analysis of rockfall frequency with inventory data

A case study was conducted to apply risk analysis and treatment for rockfall hazard. Rockfall occurrence data was classified according to the degree of danger that damages a safety function, and frequency of rockfall occurrence was analyzed looking for efficient risk reduction with mitigation measures. This case study shows how to classify the occurrence rate of rockfall hazards systematically and how to reduce the risk below the acceptable level by considering additional mitigation measures as well as to calculate risk reduction effect quantitatively based on the concept of functional safety. For the case study, the rockfall data of artificial cut slopes on the highway networks in South Korea was used, which is provided by Korea Expressway Corporation.

By using the rockfall data collected for more or less 20 years depending on each highway lines, the occurrence rate was distinguished in detail as used in a functional safety study. Figure 15 below shows a classification structure of occurrence data which divide into four groups: λdu as dangerous undetected fail, λdd as dangerous detected fail, λsu safe undetected fail, and λsd safe detected fail. In this study, classification of λsu and λsd was not carried due to no clear information on data set to distinguish between two groups. The classification category is based on the approach by the IEC 61508 standard by the International Electro-Technical Commission.

Safe or dangerous in fail-to-function state		Detected or undetected by diagnostics	Description	Examples of rockfall inventory data
λ total	λd	λdu	Dangerous undetected fail	Rockfall material reached the road surface
		λdd	Dangerous detected fail	Rockfall material was stopped by rockfall protection barriers
	λs	λsu	Safe undetected fail	A fracture that could cause a rockfall was identified on a slope
		λsd	Safe detected fail	

Figure 15. Classification structure of rockfall occurrence data

According to the classification of rockfall occurrence data, frequency of rockfall was analyzed. As a result, the Figure 16 below shows that there are more slopes on the side of low frequency of rockfall occurrence, and the number of slopes decrease as frequency increase; however, distribution of histogram and scatter diagram over failure rate is different depends on the classification groups.

Rockfalls that all include fracture, stopped by fence and reaching road, so called λtotal has zero value in the lowest rockfall frequency range. λd which is the failure rate that excludes the rate of fracture or collapse sign from λtotal shows higher number on lower frequency. λdu which is the rockfall break the protection fence and run down to road surfaces shows increased number on the lowest range. For estimating the risk that actually damage the function of road traffic, frequency of λdu that the rock fall material run down to the road surface need to be considered.

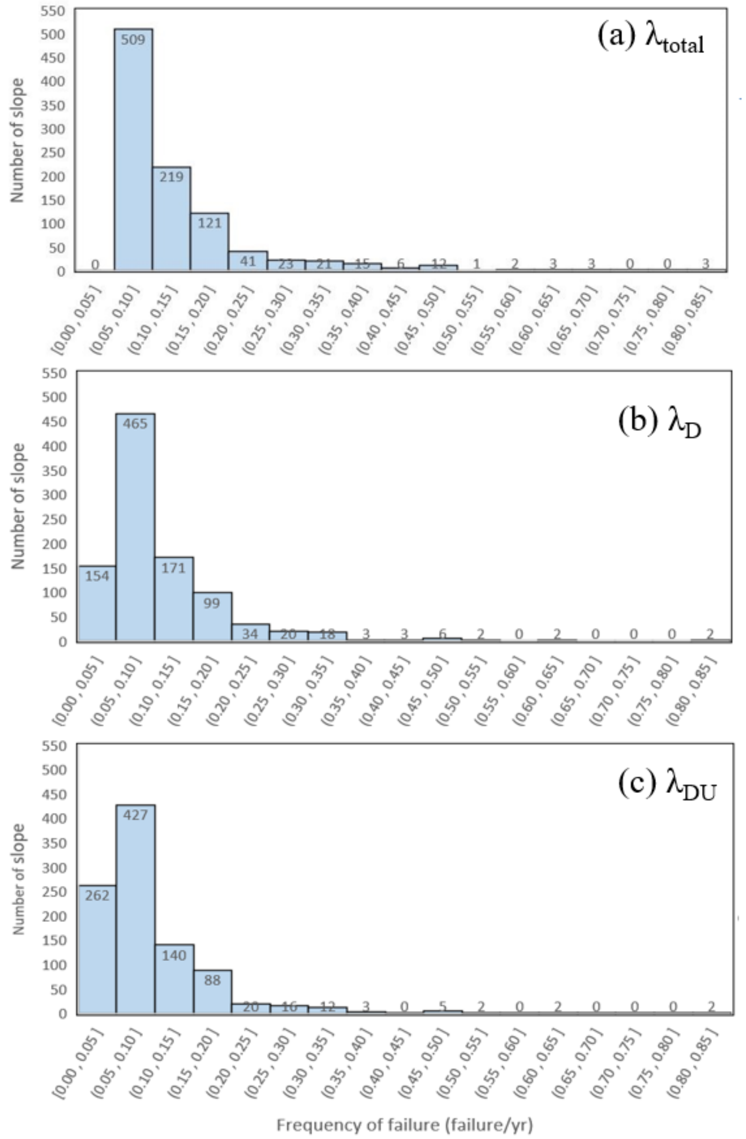
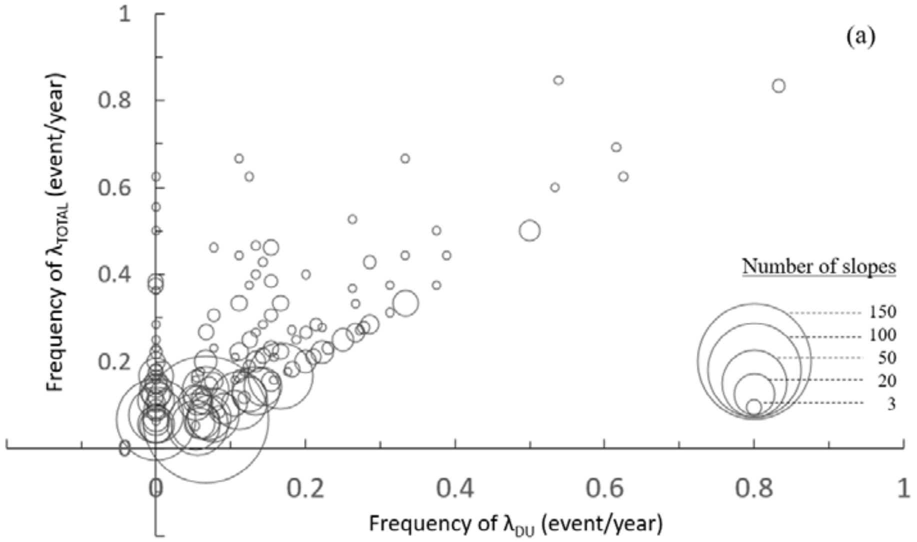


Figure 16. Histogram of λdu, λd and λtotal showing number of slope with failure rate

In addition, scatter diagrams were plotted between λtotal and λdu. Figure 17 below shows that the value of λdu can be separately displayed from λtotal, and more attention should be paid to λdu, to identify the outliers that has relatively higher occurrence rates than others. Figure 17(b) shows that λd and λdu are more related comparing to λtotal and λdu, and it partially proves the validity of the data set.



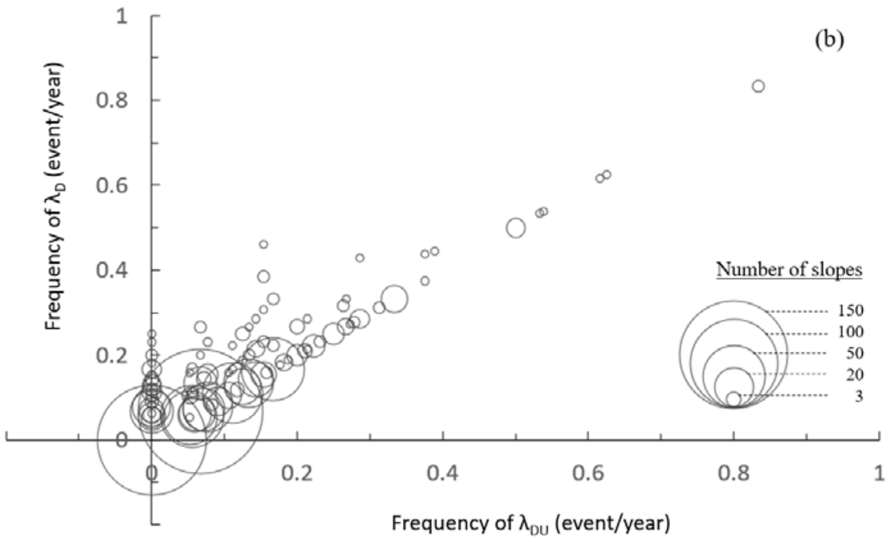
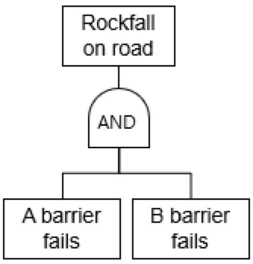


Figure 17. (a) Scatter diagram of λdu and λtotal, (b) Scatter diagram of λdu and λd.

Probability of rockfall occurrence

Next, the unstable slopes were screened, which shows outstanding values of rockfall events occurrence from the result of frequency analysis, and the probability of occurrence was calculated to estimate the risk reduction effect with additional mitigation measures. As an additional mitigation measure, redundancy of protection barrier was considered. As shown in Figure 18 below, composition of fault tree analysis, A and B barrier fail then rockfall damage to traffic, was used and applied to the equation of average probability of failure on demand.



$$\mathrm{PFDavg} = \frac{1}{\mathrm{TI}}\int_0^{\mathrm{TI}} \left(1 - e^{-\lambda t}\right)^2 dt \qquad (15)$$

Figure 18. Composition of fault tree analysis for redundancy

As a result, six slope groups that have relatively higher frequency of rockfall events were screened, which recorded higher rates of substantial damages to traffic on the highway networks. Finally, the expected risk reduction effects with additional mitigation measures were calculated as shown in Figure 19 below.

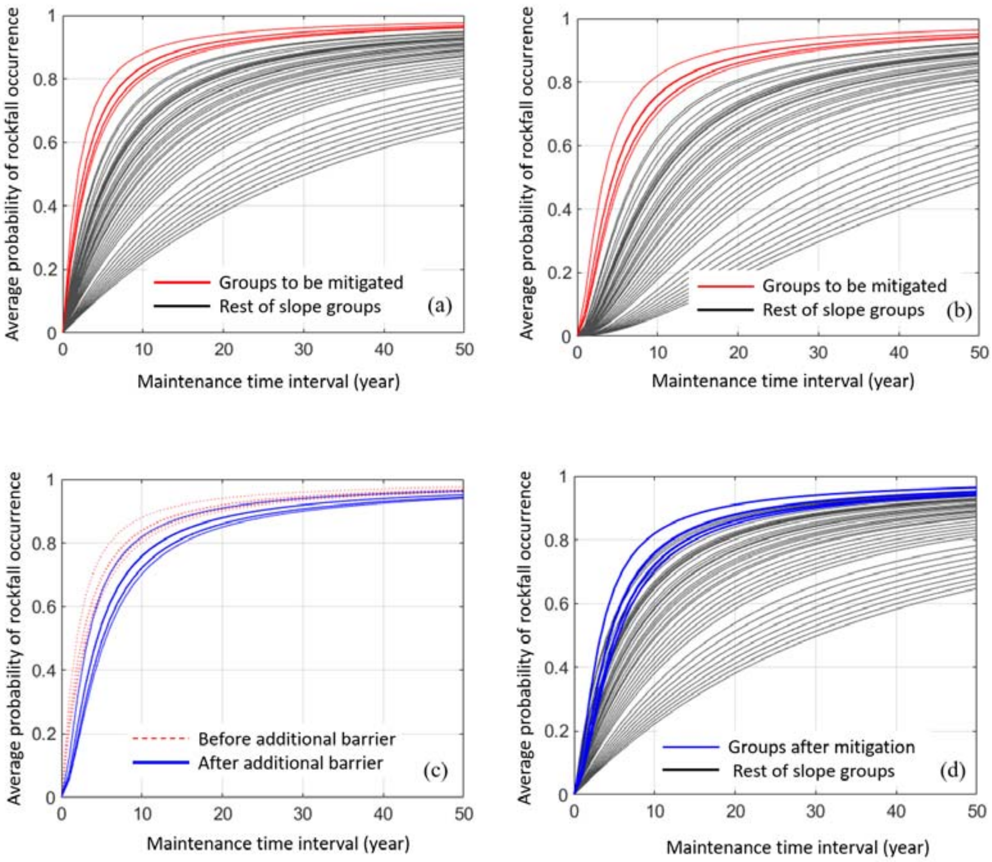


Figure 19. Decreased probability after installation of additional protection barrier, (a) Average probability of rockfall with single mitigation (single fence), (b) Average probability of rockfall additional protection barrier, (c) Decreased probability with additional protection barrier for six outstanding groups, (d) Improved average probability of rockfall occurrence.

When probability of rockfall occurrence is projected over life time, a decision-maker can identify which slopes shows higher probability of failure, and can consider to install an additional mitigation. For example, if a redundant barrier is placed to block rockfall, probability of rockfall occurrence of six outstanding groups, consisting of 11 separate slopes, will be decreased like Figure 19(c) shows. This numeric calculation of reduced risk can be done with fault tree analysis. Finally, improved average probability of rockfall occurrence can be achieved after treatment of risk for those six outstanding groups as shown in Figure 19(d). Figure 19(b) shows improved overall probability profiles of rockfall occurrence when a redundant mitigation measure is placed for all slopes, however risk treatment might be focused to limited locations due to budget constraint.

Revised model with maintenance factors and common cause failure

In reality, constant average probability of rockfall occurrence with periodic maintenance is not achievable, and the average probability will be increased over time. There are flaws that cannot be detected with maintenance process due to imperfect inspection and also limitations of its maintenance itself. For example, degraded parts of rockfall protection fences or nets above ground such as beam, wire can be covered by visual inspection easily but degraded underground foundation or anchor bolt cannot be checked without specific non-destructive inspection devices. The limitations and characteristics of such maintenance can be reflected in the rockfall probability model as a diagnostic coverage. The portion of flaw that is not fixed by periodic maintenance activities will contribute to an increase in the probability of rockfall occurrence over time. In addition, the probability of being damaged by a rockfall accident which can occur during the repair time for maintenance can be included to the rockfall probability model. If a protection barrier is dismantled for maintenance purpose during repair times, the function of safe operation for a highway cannot be ensured when small-scale of rockfalls occur, even though those rockfall may correspond to the category of dangerous detected (λdd). The increment of the rockfall probability by the repair time factor can be expressed as the multiplication of λdd and repair time, and it can be included in the revised equation.

On the other hand, there might be larger scale of rockfall events that make both barriers fail. It is also necessary to include the factor that increases the rockfall probability breaking multiple barriers, although it has lower probability. This factor is known as the common cause failure which means the events result in coincident failures of a multiple channel of safety system, and it is called in as beta factor in IEC 61508 (I.E.C, 2003). In case of rockfall, the common cause failure will be the falling of large volume earth materials running down over protection barriers, such as a toppling of fractured rock column or a catastrophic slope failure from a deep sheet. Occurrence rates of those common cause failures can be separately counted from dangerous undetected fails (λdu) and an increase of probability can be incorporated in the modified equation. The modified equation including the effect factor by diagnostic coverage, repair time and common cause failure can be expressed as follow, and the sample graph is shown in Figure 20 below.

$$
\begin{aligned}
\mathrm{PFDavg} = {} & \mathrm{DC} \cdot \frac{1}{\mathrm{TI}} \int_0^{\mathrm{TI}} 1 - e^{-\beta \cdot \lambda \mathrm{du} \cdot t}\, dt + (1 - \mathrm{DC}) \cdot \frac{1}{\mathrm{LT}} \int_0^{\mathrm{LT}} 1 - e^{-\beta \cdot \lambda \mathrm{du} \cdot t}\, dt \qquad (16) \\
& + \left(1 - e^{-\beta \cdot \lambda \mathrm{dd} \cdot \mathrm{MRT}}\right) + \left\{1 - e^{-(1-\beta) \cdot \lambda \mathrm{dd} \cdot \mathrm{MRT}}\right\}^2 \\
& + \mathrm{DC} \cdot 2\{(1 - \beta) \cdot \lambda \mathrm{dd} \cdot \mathrm{MRT}\} \cdot \frac{1}{\mathrm{TI}} \int_0^{\mathrm{TI}} 1 - e^{-(1-\beta) \cdot \lambda \mathrm{du} \cdot t}\, dt \\
& + (1 - \mathrm{DC}) \cdot 2\{(1 - \beta) \cdot \lambda \mathrm{dd} \cdot \mathrm{MRT}\} \cdot \frac{1}{\mathrm{LT}} \int_0^{\mathrm{LT}} 1 - e^{-(1-\beta) \cdot \lambda \mathrm{du} \cdot t}\, dt \\
& + \mathrm{DC} \cdot \frac{1}{\mathrm{TI}} \int_0^{\mathrm{TI}} \left(1 - e^{-(1-\beta) \cdot \lambda \mathrm{du} \cdot t}\right)^2 dt \\
& + (1 - \mathrm{DC}) \cdot \frac{1}{\mathrm{LT}} \int_0^{\mathrm{LT}} \left(1 - e^{-(1-\beta) \cdot \lambda \mathrm{du} \cdot t}\right)^2 dt
\end{aligned}
$$

where β is a beta factor (common cause failure),

DC is diagnostic coverage,

LT is a life time of safety system,

MRT is a mean repair time,

TI is a periodic maintenance interval.

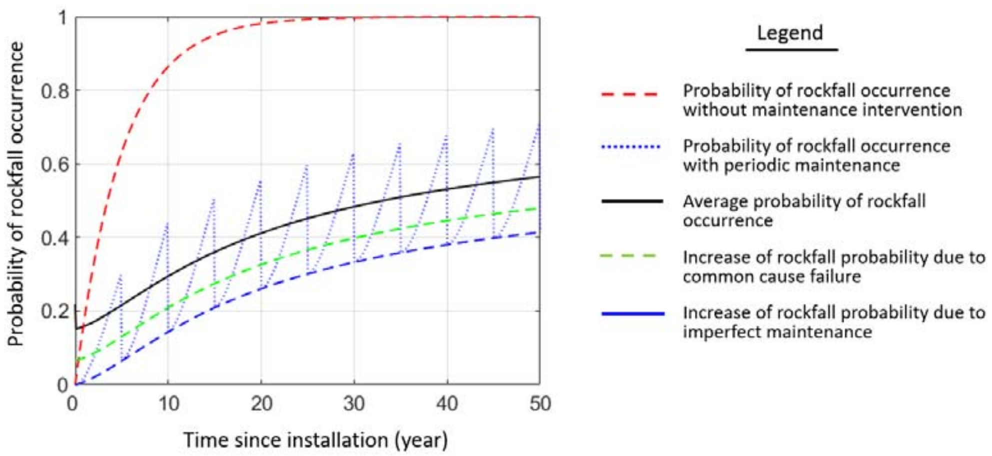


Figure 20. Increase of the probability of rockfall occurrence including the effect by diagnostic coverage, repair time and common cause failure

Unfortunately, the data set used in this study did not include any information to decide the diagnostic coverage or mean repair time that can be variable depending on the characteristics of the maintenance activities. If the information accumulated from maintenance experiences is available later, a more precise rockfall probability modeling will be possible using the modified equation.

4.3 Discussion on risk analysis and treatment

Risk analysis and treatment for landslide

The advantages of SIL are that it provides a systematic method to determine desired safety requirements, and that it enables verification of whether the safety function meets the target with numerical criteria. When it is applied to manage the risk from natural hazards, a decision-maker can follow a logical sequence to determine the desired safety level, and can verify its suitability for planning. In addition, the technical guidance given by applying SIL to natural hazards can help stakeholders to reach an agreement through risk communication enhanced by numerical guidance.

Notably, it is not recommended to depend on an unconvincing safety-related system with strict management only by satisfying a PFD calculation result (Van Beurden & Amkreutz, 2001). In the IEC 61508 standard, there is additional restriction, referred to as architectural constraints (I.E.C., 1998). The design process must involve selecting a sufficiently robust architectural configuration of safety to guide the selection of safer equipment and to ensure that redundancy is considered. Examples of such measures, regardless of the PFD calculation, would be a sufficient and fast enough beacon to detect potential landslides in a community, or a sufficiently well-constructed check-dam to prevent debris and sediment reaching a town located at the down flow of a catchment.

In addition, considering human factors is also important when utilizing the concept of SIL to control natural hazards. In the IEC standard, little attention is paid to human interventions in organizational matters during the operation stage; however, specific safety functions may require human-operated actions, and they might be more sensitive to human factors than other safety functions (Melo & Nele, 2013). In case of natural hazards, planned safety system reliability at the design stage can deteriorate due to mismanagement and human errors during the operation stage of an entity.

Some additional shortcomings should be considered before applying an SIL study to control natural disasters. As with other risk studies, subjective interventions can lead to greater uncertainty, even if the SIL analysis is quantitative in nature. While applying SIL to natural hazards, the fact that risk discriminators can be applied in an unbalanced way is also a problem. When the SIL graph method is used, the magnitude of potential consequences is consolidated into a single parameter of the probability of unwanted occurrence (Baybutt, 2007). If the range of the risk parameter is not subdivided appropriately, it may not be possible to set a reasonable risk target.

To resolve these problems, the construction of an expert team with interested parties not biased toward a single field is important for establishing reasonable safety requirements. It is also necessary to select risk parameters carefully to achieve safety objectives, and when doing so it is important to understand the entire process, ranging from the setting of target safety levels to the verification of fulfilment on quantitative grounds. SIL executors should set the range of risk parameters prudently for proper risk discrimination, and the frequency of natural disasters must be based on empirical data to achieve credible verification results.

Risk analysis and treatment for rockfall

Since rockfall is generally considered an infrequent cause of fatal accidents, management efforts to reduce rockfall risk could be seen as relatively less significant than efforts for other natural disasters, such as landslides or flooding. However, initial failure of unstable slopes, thereby increasing rockfall, may precede a massive rock slope failure (Evans et al., 2006). Therefore, monitoring and management activities to prevent further collapse are required once a precursory phenomenon such as rockfall or fracture on an unstable slope is detected. The suggested model can estimate the probability of rockfall occurrence including the effect by periodic maintenance with the concept of reliability after the detailed frequency analysis for the rockfall hazard, and the model can provide the information for developing an indicator to implement efficient management to reduce the potential damage by rockfall hazard.

As a different type of rockfall protection barrier, Foresting can be an alternative mitigation measure to reduce the possible damage by rockfall. Despite the constraint that there must be sufficient space from the infrastructure to the unstable slopes to be protected, this natural type of protection is the most environmentally friendly solution. It has been reported that a forest with the purpose of damping rockfall energy costs less than other solutions, is more sustainable, and works well as a rockfall barrier (Kienholz & Mani, 1994). When a new construction of highway creates artificial slopes, planning a planting space as a buffer area to be used as an independent protective barrier could be very helpful for reducing the probability of losses due to rockfall damage. Meanwhile, a new type of highly flexible rockfall mitigation measure, comprising a hybrid barrier and attenuator, has been attracting attention recently (Dhakal et al., 2011). The attenuator system is a dynamic barrier for absorbing rockfall energy, in which an upper part captures falling rocks and the lower part is draped down to release rocks to the lower skirts of slopes. The hybrid barrier system is to capture falling rocks and drive them to a targeted area, while attenuating their energy by up to 90%. They consist of an interception part to catch falling rocks and a transition part to guide rocks toward the designated area (Cerro et al., 2016). These systems will also have specific failure rates during operation and maintenance characteristics. If statistical data regarding the failure rate and diagnostic coverage are obtained for those alternative mitigation measures after installation on cut slopes, the rockfall probability model suggested in this study can be used to estimate the time-varying probability of rockfall occurrence, including a risk reduction factor accounting for periodic maintenances.

Although this study focused on the frequency analysis to see how it affects to the functional safety on the highway networks without consideration of the elements at risk or vulnerability, rockfall risk assessment will be possible later with additional data. Highway user information regarding the average speed of vehicles, traffic volume, and types of passenger vehicles could be used to conduct a more detailed rockfall risk assessment (Budetta, 2004). Furthermore, improving recording procedures and establishing a rockfall hazard rating system will be an important starting point for applying quantitative risk assessment (Bunce et al., 1997). Introducing a three-dimensional (3D) trajectory simulation model would increase the precision and reliability of rockfall hazard assessment systems (Guzzetti et al., 2003); however, more accurate descriptions of the point of origin and measurements of rockfall volume must be recorded in the inventory data for the 3D simulation. After appropriate rockfall risk assessment, including an analysis of the damage severity on the element at risk and a consideration of its vulnerability, shifting of land-use zoning or the use of engineering solutions to protect infrastructure could be suggested as alternative mitigation measures to reduce the rockfall hazard for areas estimated to exceed a tolerable risk level (Copons et al., 2005). An integrated framework, including a systematic rockfall inventory, rockfall hazard rating, and rockfall risk assessment supported by a physically-based model, needs to be implemented with periodic maintenance planned on the basis of risk indicators. This management effort will be an effective and efficient approach to prevent unwanted losses caused by rockfall

5. Risk evaluation and acceptance for compound disasters

5.1 Method for risk evaluation and acceptance

Quantitative risk assessment

The methodology of quantitative risk assessment (QRA) can be summarized in the steps shown in Figure 21. The overall process of QRA consists of two parts: risk analysis and risk assessment. The first step, risk analysis, involves defining potential events and incidents. This step is related with hazard identification, and HAZOP results can provide insights into hazardous scenarios. The next step is to construct the risk analysis, including an evaluation of consequences and an estimation of frequencies.

Consequence Analysis (CA) is commonly implemented to reflect the results of modeling fires, explosions, or toxic releases in the process industry, and the use of physical modeling to simulate the outcomes of landslide incidents can be considered as an example of CA. For the frequency analysis, the likelihood of hazardous events can be estimated systematically by employing event tree analyses (ETA) and fault tree analyses (FTA), assuming that the events are independent of each other (Ferdous et al., 2011). After the analysis of consequences and frequencies, the adverse impact on elements at risk must be estimated. If the consequences of natural events are found to pose no hazard to people or properties at any frequency, the risk can be considered negligible. Otherwise, further analysis of frequency is required to evaluate the risk, combining the potential consequences with the frequency of events.

In the risk assessment process, the risk should be reviewed first in light of acceptable criteria. If the risk exposed to the elements is considered to be excessive, a risk reduction measure needs to be found and prioritized cost-effectively. When applying the QRA method to natural hazards, the selection of components and techniques in the QRA steps can be flexible, as long as the natural disaster scenarios are well defined and the results of the risk evaluation are sufficiently analyzed.

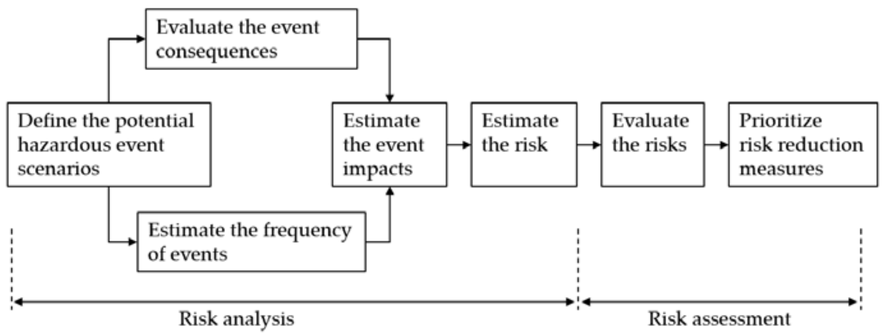


Figure 21. The steps of QRA, modified from chemical process QRA (adapted from Freeman, 1990)

The definition of risk is frequently referred from the risk formula provided by Varnes (1984) in his study of landslide hazard zonation. The proposed definition of total risk (Rt) is the expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a particular natural phenomenon, has been expressed as:

$$Rt = E \times Rs = E \times (H \times V) \qquad (17)$$

where, natural hazard (H) refers to the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon, vulnerability (V) denotes the degree of loss to a given element at risk resulting from the occurrence of a natural phenomenon of a given magnitude, specific risk (Rs) refers to the expected degree of loss due to a particular natural phenomenon (the product of H times V), and element at risk (E) denotes the population, properties, and economic activities, including public services, that are at risk.

In addition to the risk formula above, the risk of climate-related impact is described as a result from the interaction of climate-related hazards, vulnerability and exposure of human including ability of adaptation in IPCC 5th assessment report. However, the risk in this study was analyzed as the probability of future loss which is the combination of the probable frequency and probable severity of the concerned events. The reason is that the analysis of vulnerability could be a separate study scope requiring consideration of social factors. This thesis rather focuses on the detailed frequency analysis and the accurate consequence analysis based on the physically-based model.

Physically-based landslide model

TRIGRS is a model for evaluating the possibility of landslide occurrence due to rainfall, consisting of a hydrologic model of pressure head and groundwater analysis by rainfall infiltration, and a slope stability model for analysis of slope stability (Baum et al., 2008). This model computes the transient pore-pressure changes using input variables of the rainfall infiltration, hydraulic properties, and slope stability, and displays results for the factor of safety over the grid area.

In addition to the TRIGRS model, there are physically-based models for assessing the effects of landslides, such as the SHALLSTAB (Shallow Slope Stability Model), the dSLAM (Distributed Shallow Landslide Analysis), the SHETRAN (System Hydrology European TRANsport), and the SINMAP (Stability Index Mapping) (Park, 2013). TRIGRS was used for this study because of the relatively large number of verification data and the convenience of applying on a wide study area.

The TRIGRS hydrological model is based on the modified formula proposed by (Iverson, 2000), including the static and transient factors, to simulate the water movement in the unsaturated soil layer over time. This hydrologic model provides the solution to analysis the groundwater pressure head by dividing it into finite soil boundary condition and infinite soil boundary condition, and the general formula is expressed as follows:

$$\psi(Z,t)) = (Z-d)\beta + 2\sum_{n=1}^{N}\frac{I_{nz}}{K_s}\left\{H(t-t_n)[D_1(t-t_n)]^{\frac{1}{2}}\ \mathrm{ierfc}\left[\frac{Z}{2[D_1(t-t_n)]^{\frac{1}{2}}}\right]\right\} - 2\sum_{n=1}^{N}\frac{I_{nz}}{K_s}\left\{H(t-t_{n+1})[D_1(t-t_{n+1})]^{\frac{1}{2}}\mathrm{ierfc}\left[\frac{Z}{2[D_1(t-t_{n+1})]^{\frac{1}{2}}}\right]\right\} \quad (18)$$

where

ψ = ground water pressure head (m),

t = time (sec),

Z = soil depth(m),

d = water table(m),

β = cos2θ - (IZLT / Ks),

Ks = saturated hydraulic conductivity(m/s),

IZLT = steady, pre-storm infiltration

InZ = infiltration rate in unit time,

D1 = D0 / cos2θ,

D0= Saturated diffusion coefficient (m^2/s),

θ = slope degree(°),

N = number of time step,

H(t-tn) = Heaviside step function,

ierfc = integral error function

The TRIGRS slope stability model is based on infinite slope stability analysis and shows the safety factor by the ratio of shear and shear stress expressed by the Mohr-Coulomb equation. The results of the model are derived from the Factor of Safety (FS) and the probability of landslides occurring at the location where the simulation result is FS <1 is interpreted as high landslide hazard area. The equation for calculating the safety factor is as follows:

$$\mathrm{Fs}(\mathrm{Z},\mathrm{t}) = \frac{\tan\varphi'}{\tan\theta} + \frac{c' - \psi(\mathrm{Z},\mathrm{t})\gamma w \tan\varphi'}{\gamma s Z \sin\theta \cos\theta} \qquad (19)$$

where

FS = Factor of safety

Z = soil depth (m),

t = time (s),

c' = soil cohesion (kPa),

γs = wet-soil unit weight (kN/m^3),

θ = slope degree(°),

ψ = ground water pressure head(m),

γw = water unit weight(kN/m^3),

ϕ' = Internal friction angle(°)

Physically-based flooding model

The openLISEM Hazard model developed by ITC (2018) was used for flooding simulation with cascading effect of dam collapse. Initially, Limburg Soil Erosion Model (LISEM), a single-event physically based model for hydrology and soil erosion model, was developed by De Roo et al. (1996). Later, openLISEM Hazard model has been developed adding more input variables and flow approximations on the original model with the purpose of modelling flood, sediment flow, and shallow slope failure on a catchment scale. The model uses grid cell to solve the governing fluid flow differential equation. The main characteristics of openLISEM Hazard model are, runoff flow, channel flow, channel flooding, splash & flow detachment erosion and Sediment transport. Figure 22 shows the overall flow of Open LISEM Hazard model process, and Figure 23 shows the physical variables used for the modelling that is collected from rainfall, land use, soil, and terrain data.

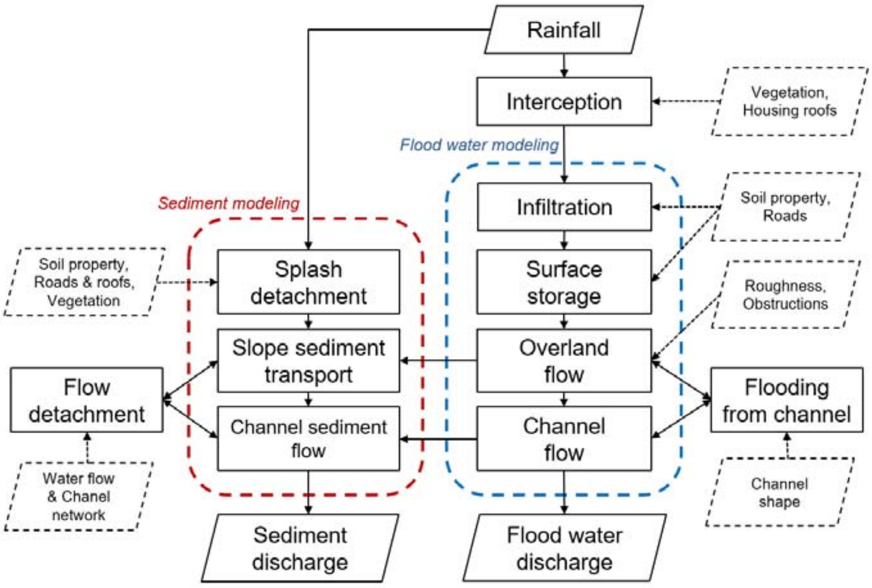


Figure 22. Schematic diagram of open LISEM Hazard model process (adapted from open LISEM user manual, 2018)

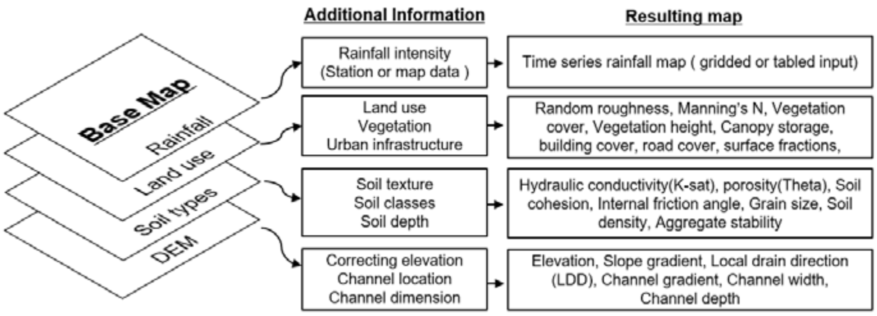


Figure 23. Input data for the physically-based flood modelling

The model consist of the process for the flood water flow and sediment flow to incorporate the two-phase solid fluid equations that can simulate the actual damage by the flooding water mixed with soil sediment from earth surface (Bout et al., 2018). The slope stability can be simulated based on the infinite-slope method through the model process, but the analysis was focused on the fluid flow part to see the potential damage by flood in this study. The governing equations used for flash flood and debris flows are expressed as follow.

Infiltration is the process where water is move down from the surface to underground soil layer. The moisture content in soil pores and hydraulic conductivity is main variables drive surface water into the subsurface soil. In this study, Green & Ampt infiltration model was selected which assumes a wetting front transit downward in the soil layer by the infiltration of rainfall. The model subtract the infiltrated water to calculate the surface water amount after rainfall start following the equation below;

$$f = -Ks\left(\frac{hf - ho}{Zf}\right) = Ks(\frac{\psi}{Zf} + 1) \quad (20)$$

where f the infiltration rate ($m \cdot s^{-1}$),

hf the hydraulic head at the wetting front (m),

$h0$ the hydraulic head at the soil surface (=0) (m),

Zf the depth of the wetting front (m),

ψ the matric pressure at the wetting front ($h=\psi+Z$) (m).

The model include the hydrological process to simulate the interception before infiltration by land cover type such as vegetation, building and load. The flow of surface water in the model is computed based on the Saint-Venant equations for shallow water flow as follow the equation below (Bout & Jetten, 2018). The partial differential equation was used to simulate time-transient advection and dynamics of water flow in the suggested model. The equation consist of the two category of physics principals, which is for mass and for momentum. The equation for mass balance is required to express the continuity of surface water substance with advection. The equation set for momentum balance is similarly express the flow of momentum in tow-dimensional surface. The momentum equation is depth averaged, and friction forces is neglected.

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=R-I \tag{21}$$

$$\frac{\partial u}{\partial t}+ \quad u\frac{\partial (hu^2)}{\partial x}+\frac{\partial huv}{\partial y} \quad =S_x \tag{22}$$

$$\frac{\partial v}{\partial t}+ \quad \frac{\partial huv}{\partial x}+\frac{\partial (hv^2)}{\partial y} \quad =S_y \tag{23}$$

where h is the flow height (m),

u, v is the flow velocity ($m \cdot s^{-1}$),

$S_{x,}S_y$ is the friction terms ($m \cdot s^{-2}$).

The sediment flow to simulate the fluid dynamics interacting between floods and debris flows is expressed in a set of two-phase momentum balance equation for solid and fluid status (Pudasaini, 2012). The equation includes the factor of viscosity together with gravity, and it includes the factor for drag force by friction in solid phase. The viscosity gradient yields shearing force and it gives the stress by the plastic liquid. The solid particle generates the drag force in the suspended fluid due to velocity difference. The two-phase equation for the flood water and sediment dynamics reflecting the characteristics of rheology are expressed as below (Bout et al., 2018).

$$S_{x,s} = \alpha_s \left(g\left(\frac{\partial b}{\partial x}\right) - \frac{u_s}{|\vec{u}_s|}\tan\left(\partial P_{b_s}\right) - \varepsilon P_{b_s}\left(\frac{\partial b}{\partial x}\right) \right) - \varepsilon \alpha_s \gamma P_{b_f}\left(\frac{\partial h}{\partial x} + \frac{\partial b}{\partial x}\right) + C_{DG}\left(u_f - u_s\right)\left|\vec{u}_f - \vec{u}_s\right|^{j-1} \tag{24}$$

$$S_{y,s} = \alpha_s \left(g\left(\frac{\partial b}{\partial y}\right) - \frac{v_s}{|\vec{u}_s|}\tan\left(\partial P_{b_s}\right) - \varepsilon P_{b_s}\left(\frac{\partial b}{\partial y}\right) \right) - \varepsilon \alpha_s \gamma P_{b_f}\left(\frac{\partial h}{\partial y} + \frac{\partial b}{\partial y}\right) + C_{DG}\left(v_f - v_s\right)\left|\vec{u}_f - \vec{u}_s\right|^{j-1} \tag{25}$$

$$\begin{aligned} S_{x,f} = \alpha_f \Bigg\{ g\left(\frac{\partial b}{\partial x}\right) - \varepsilon \Bigg[& \frac{1}{h}\frac{\partial}{\partial x}\left(\frac{h^2}{2}P_{b_f}\right) + P_{b_f}\frac{\partial b}{\partial x} \\ & - \frac{1}{\alpha_f N_R}\left(2\frac{\partial^2 u_f}{\partial x^2} + \frac{\partial^2 v_f}{\partial y \partial x} + \frac{\partial^2 u_f}{\partial y^2} - \frac{\chi u_f}{\varepsilon^2 h^2}\right) \\ & + \frac{1}{\alpha_f N_R}\Bigg(2\frac{\partial}{\partial x}\left(\frac{\partial \alpha_s}{\partial x}\left(u_f - u_s\right)\right) \\ & + \frac{\partial}{\partial y}\left(\frac{\partial \alpha_s}{\partial x}\left(v_f - v_s\right) + \frac{\partial \alpha_s}{\partial y}\left(u_f - u_s\right)\right)\Bigg) - \frac{\xi \alpha_s \left(v_f - v_s\right)}{\varepsilon^2 \alpha_f N_{R_{\mathcal{A}}} h^2}\Bigg]\Bigg\} \\ & - \frac{1}{\gamma} C_{DG}\left(u_f - u_s\right)\left|\vec{u}_f - \vec{u}_s\right|^{j-1} \end{aligned} \tag{26}$$

$$\begin{aligned} S_{y,f} = \alpha_f \Bigg\{ g\left(\frac{\partial b}{\partial y}\right) - \varepsilon \Bigg[& \frac{1}{h}\frac{\partial}{\partial y}\left(\frac{h^2}{2}P_{b_f}\right) + P_{b_f}\frac{\partial b}{\partial y} \\ & - \frac{1}{\alpha_f N_R}\left(2\frac{\partial^2 v_f}{\partial y^2} + \frac{\partial^2 u_f}{\partial y \partial x} + \frac{\partial^2 v_f}{\partial y^2} - \frac{\chi v_f}{\varepsilon^2 h^2}\right) \\ & + \frac{1}{\alpha_f N_R}\Bigg(2\frac{\partial}{\partial y}\left(\frac{\partial \alpha_s}{\partial y}\left(v_f - v_s\right)\right) \\ & + \frac{\partial}{\partial y}\left(\frac{\partial \alpha_s}{\partial y}\left(u_f - u_s\right) + \frac{\partial \alpha_s}{\partial x}\left(v_f - v_s\right)\right)\Bigg) - \frac{\xi \alpha_s \left(u_f - u_s\right)}{\varepsilon^2 \alpha_f N_{R_{\mathcal{A}}} h^2}\Bigg]\Bigg\} \\ & - \frac{1}{\gamma} C_{DG}\left(u_f - u_s\right)\left|\vec{u}_f - \vec{u}_s\right|^{j-1} \end{aligned} \tag{27}$$

where α_s and α_f are the volume fraction for solid and fluid phases,
P_b is the pressure at the base surface (Kg $m^{-1}s^{-2}$),
b is the basal surface of the flow (m),
N_R is the Reynolds number,
N_{RA} is the quasi-Reynolds number,
C_{DG} is the drag coefficient,
ρ_f is the density of the fluid ($kg \cdot m^{-3}$),
ρ_s is the density of the solids ($kg \cdot m^{-3}$),
γ is the density ratio between the fluid and solid phase,
χ is the vertical shearing of fluid velocity (ms^{-1}),
ε is the aspect ratio of the model,
ξ is the vertical distribution of α_s (m^{-1}).

For the analysis of complex flooding, two different scenarios were considered, which are a case of flash flood by the intensive rainfall and a case of cascading flood effect by reservoir collapse during the intensive rainfall. Firstly, resulting hydrography were analyzed to see the deference of the outlet discharge of the catchment and the peak discharge quantity, and the distribution of maximum flood height, maximum sediment height and maximum flood velocity were examined to identify potential areas of damage in the watershed.

5.2 Result of risk evaluation and acceptance

5.2.1 QRA with physically-based landslide model

As a case study for landslide hazards, a simplified QRA was conducted in a way that could be applied for planning a pension resort. In Gangwon Province in South Korea, there is a demand for constructing pension houses for leisure purposes on hillsides in mountainous regions that are rather vulnerable to landslides. Assuming that the pension resort that originally exists in the upper left corner of Figure 24 (a) has a plan to open a branch on the other side of the mountain slope across the river, the quantitative risk was calculated, which the pension house user would be exposed to landslides. It should be noted that the QRA case study was not applied for the currently existing building in order to avoid potential implications for property values; instead, the case study was conducted for the possible selection of a new location in the planning stage.

TRIGRS model developed by US Geological Survey (USGS) was used to perform the consequence analysis, which is the model to simulate shallow landslides induced by rainfall with a presentation of timing and distribution. The study area is a northwest slope, as shown in Figure 24(b), and the total modeling area is about 1 km^2 with a pixel unit of 30 m × 30 m. For the frequency estimation, the return period was estimated by reviewing the weather data. First, the possibility of landslides occurrences were evaluated under the condition of 200 mm of rainfall for 48 hours, which is a threshold proposed by local researchers. Next, the possibility of landslides occurrences were examined in the conditions of 800 mm of daily rainfall, which is the maximum daily rainfall intensity recorded over approximately 100 years from 1904 to 2010 in South Korea (K.M.A.N.T., 2011).

As shown in Figure 24(c), when new construction was planned at location A, it was predicted that landslides would not affect the planning location, as a safety factor greater than 1 was shown with the rainfall condition of 200 mm for 48 hours. However, the continuous simulation result with the rainfall condition of 800 mm per day indicated that landslides could damage the planning area, as shown in Figure 24 (d). Therefore, the frequency of potential damage by landslides at the planning area was estimated to be 0.01 event per year. Additionally, in order to reflect real-world conditions in the risk calculation, further consideration should be given to the runout factor of debris and sediment, the occupancy factor by use time, and the vulnerability of different building types. It should be noted that variables other than rainfall conditions were arbitrarily selected for the modeling demonstration, without a field survey.

This study focused on discussing the approach and methodology for risk management and communication. The individual risk can be evaluated from the risk function below (A.G.S, 2000) :

$$R(I) = P(H) \times P(L) \times P(O) \times V(B) \qquad (28)$$

where

R(I) is the individual risk in terms of annual loss of life,

P(H) is the probability of landslide events,

P(L) is the probability of spatial impact by landslides considering the runout distance,

P(O) is the temporal probability by occupancy,

V(B) is the vulnerability of individual by building type.

Based on this formula, the annual individual risk (IR) of the case was calculated using the best available assumptions as follows:

$$IR = 0.01 \times 0.6 \times (0.3 \times 0.7) \times 0.2 = 2.5E\text{-}04\ \text{fatality}\cdot\text{yr}^{-1} \qquad (29)$$

The resulting individual risk, 2.5E-04 fatalities per year, was estimated assuming that a rainfall-induced landslide would occur once every 100 years. The probability of spatial impact was selected as 0.6, assuming the probability of the runout distance reaching 20-30m, which is a distance that can affect within a pixel unit. The annual occupancy of 0.3 was chosen considering the variation in demand between the high season and the slow season, and a daily occupancy of 0.7 was selected with the assumption that guests will go out for 8 hours a day. Finally, assuming that the building type of the pension house is a reinforced concrete structure that is relatively resistant to collapse, the associated vulnerability factor was selected as 0.2.

The resulting IR value is within the As Low As Reasonably Practicable (ALARP) zone presented on the F-N curve by UK-HSE (Dai et al., 2002), but considering additional safeguards or an alternative location may be required to achieve broad acceptance. Regarding societal risk, if more than 10 people at a time stay at the new pension location in the future, they would be exposed to intolerable societal risk, exceeding acceptable criteria. This case study only reflects an attempt to present the methodology of obtaining an useful measure of risk for planning potential construction, and does not reflect an absolute judgment (Watson, 1994).

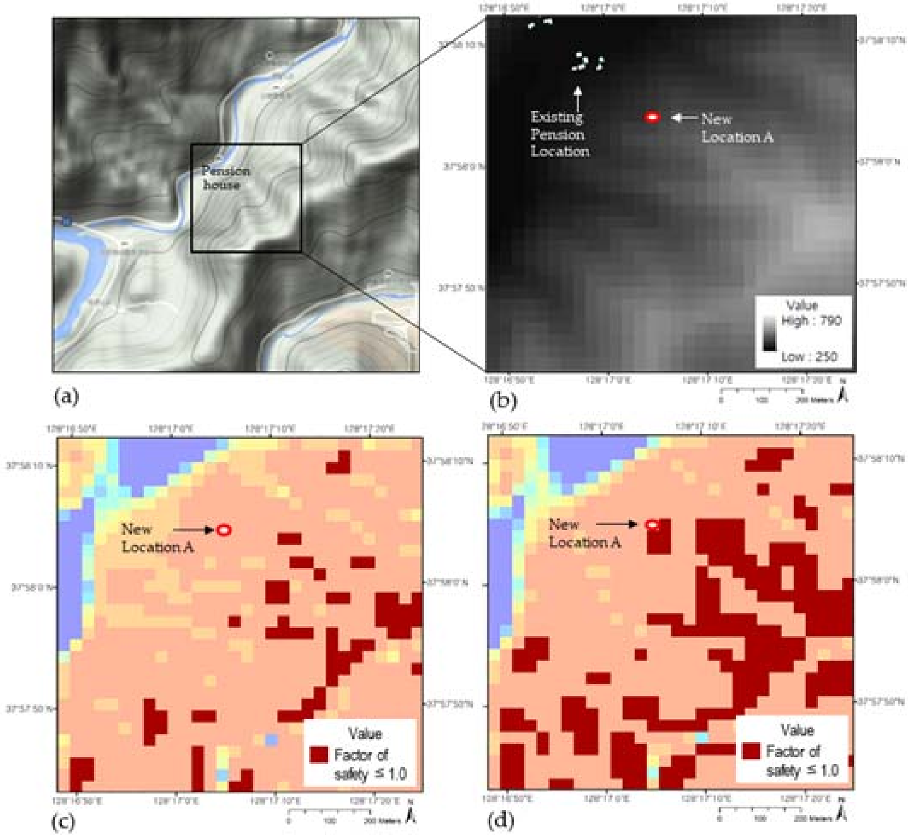


Figure 24.The case study site and the results of TRIGRS modelling, (a) The site location, (b) Topography of the site, (c) TRIGRS modelling result – 200 mm for 48 hours, (d) TRIGRS modelling result – 800 mm for 24 hour.

5.2.2 Impact assessment of post-wildfire landslides

As a case study area, about area of 8km^2 in Yongpyeong–myeon of Pyeongchang County was selected, where the risk of forest fires and landslides is high. The location of the study area and topographic feature are as shown in Figure 25. Based on the survey data of landslide occurrence, the damage and impacts of the post-wildfire landslide impact was examined. Figure 26 shows the result of TRIGRS modeling of post-wildfire landslide compound disaster impact compared to landslide single accident case under the same rainfall duration condition.

As a result of modeling, comparison of Figure 26 (a) and (c) shows that the increase of landslide susceptibility area due to the decrease of saturated saturation conductivity (Ks) of soil. The hazardous area (safety factor FS <1) by the compound disaster case of post-wildfire landslide occurred more rapidly in a wider area than the single landslide accident case in the same rainfall duration. After 4 hours of rainfall duration, variation of total hazardous area was lessen in both cases. Until the soil layer was saturated, the area of the hazardous area was broader in the post-wildfire landslide case.

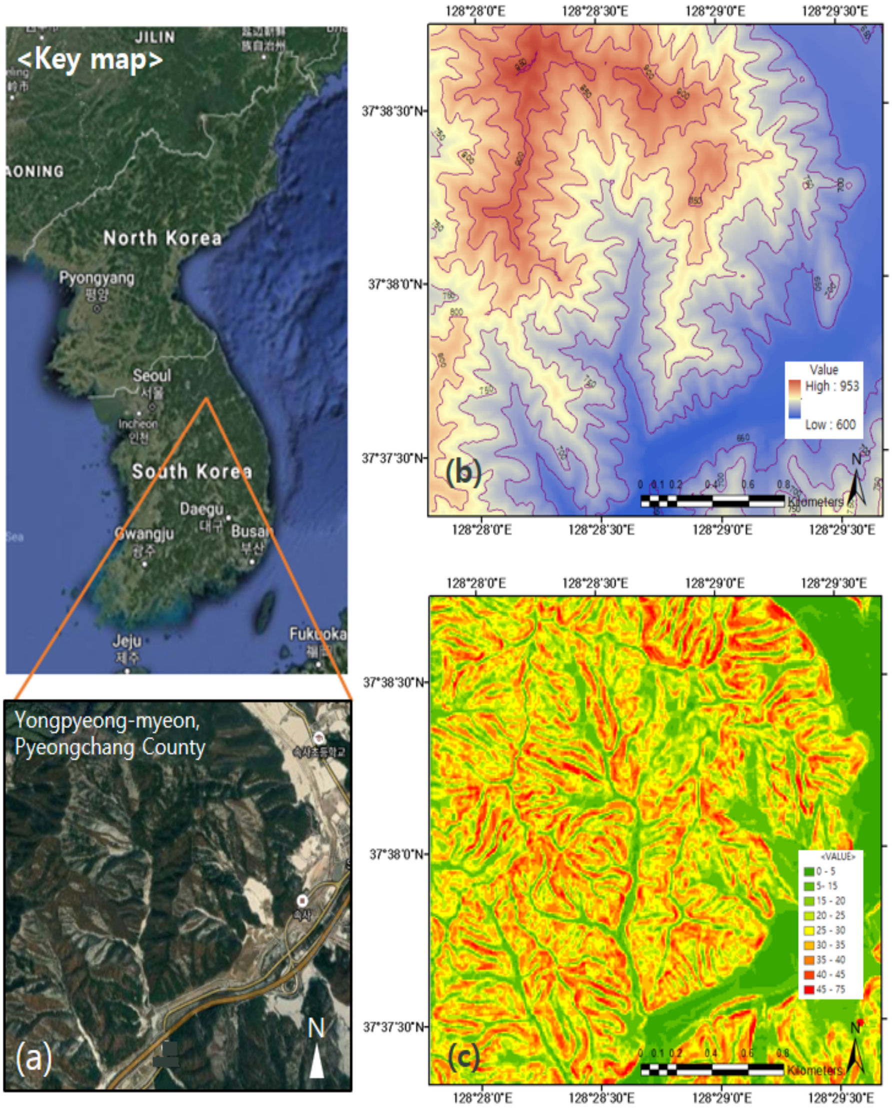
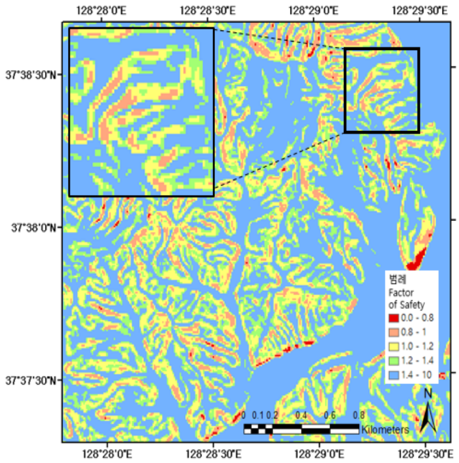
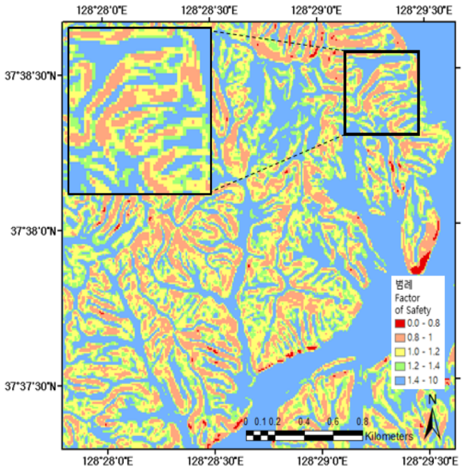


Figure 25. Location and topography of the study area, (a) Key map and satellite image (from Google map), (b) Digital elevation map (meter) (c) Slope map (degree,°)

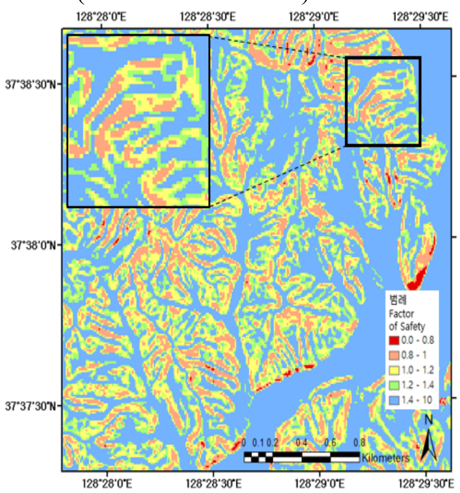
As shown in the result, post-wildfire landslide can occur even in low-rainfall intensity condition which would not trigger landslide as a single disaster scenario. Figure 27 (a) shows the change in safety factor over time. The average safety factor in the case of single landslide accidents was 2.641, while that of post-wildfire landslide was 2.579. In other words, the areas with higher landslide hazard are widely distributed in the compound disaster scenario. Figure 27 (b) shows the area change of landslide hazard area over time. In the case of a single landslide accident, the total area of the hazardous area with a safety factor of less than 1 ($FS < 1$) is 0.56 km^2, while that of the post-wildfire landslide case is 1.03 km^2. Landslide hazardous areas were increased over time in both compound and single disaster cases. However, the increasing rate of landslide hazardous areas showed a tendency to be lower as rainfall continued. Especially, landslide hazardous areas converged rapidly to the maximum value in hazardous area with scenarios of post-wildfire landslide than the case of single landslide accidents, and the same area of 1.32km^2 was maintained after 3 hours.



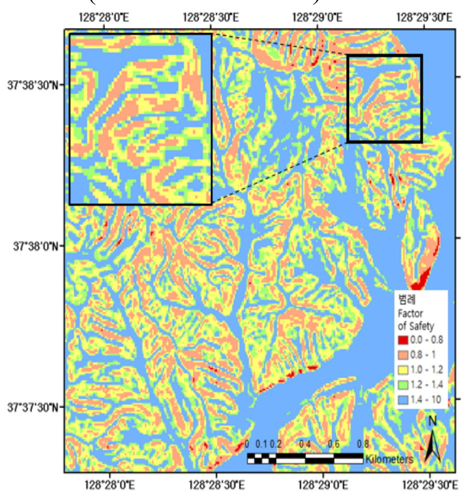
(a) Landslide single disaster case (rainfall duration–1h)



(b) Landslide single disaster case (rainfall duration–4h)



(c) Post-wildfire landslide case (rainfall duration–1h)



(d) Post-wildfire landslide case (rainfall duration–4h)

Figure 26. TRIGRS modeling result maps of post wildfire landslide compound disaster case compared to landslide single disaster case (rainfall intensity of 100mm/day), (a) Landslide single disaster case (rainfall duration of 1h), (b)Landslide single disaster case (rainfall duration of 4h), (c) Post-wildfire landslide compound disaster case (rainfall duration of 1h), (d) Post-wildfire landslide compound disaster case (rainfall duration of 4h)

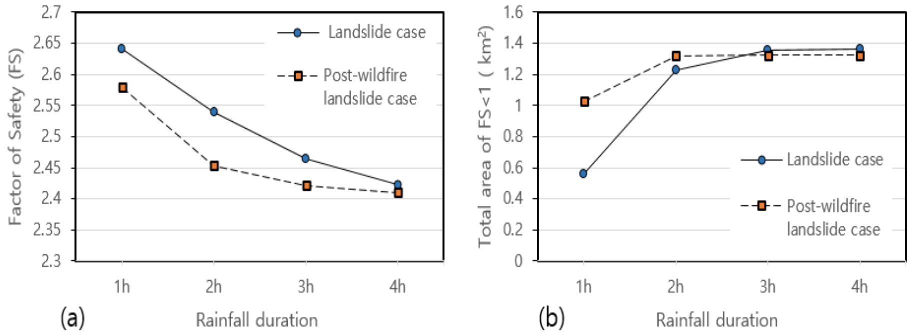


Figure 27. TRIGRS modelling result graphs of post-wildfire landslide compound disaster case compared to landslide single disaster case (rainfall intensity of 100mm/day), (a) Changes of factor of safety (FS) at different rainfall duration, (b) Changes of total area of FS less than 1 at different rainfall duration

5.2.3 Impact assessment of complex flooding

As a study area, a catchment located in Bongpyeong of South Korea selected as shown in Figure 28 below, where a reservoir dam collapsed due to heavy rainfall by typhoon in July, 2006.

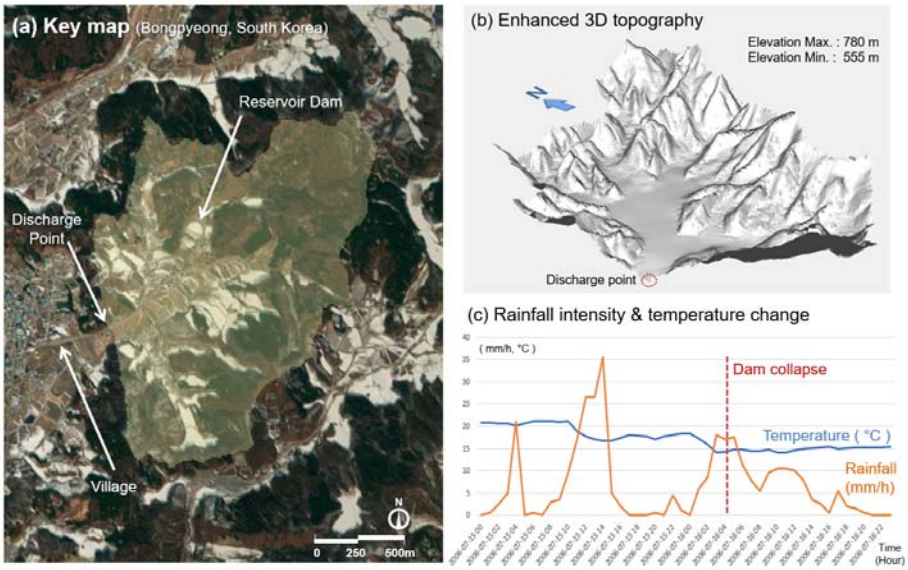


Figure 28. The study area and rainfall intensity for the flood modelling, (a) Study area in Bongpyeong of South Korea, (b) Enhanced 3D topography, (c) Rainfall intensity from 15th to 16th of July, 2006

As a result of using openLISEM Hazard model, it was possible to analyze the area where damages by flooding are estimated following time steps during heavy rainfall. Figure 29 shows the hydrographs of the analyzed two scenarios, a case of the water reservoir dam collapse during the intensive rainfall and a case of simple flash flood by heavy rainfall without dam collapse.

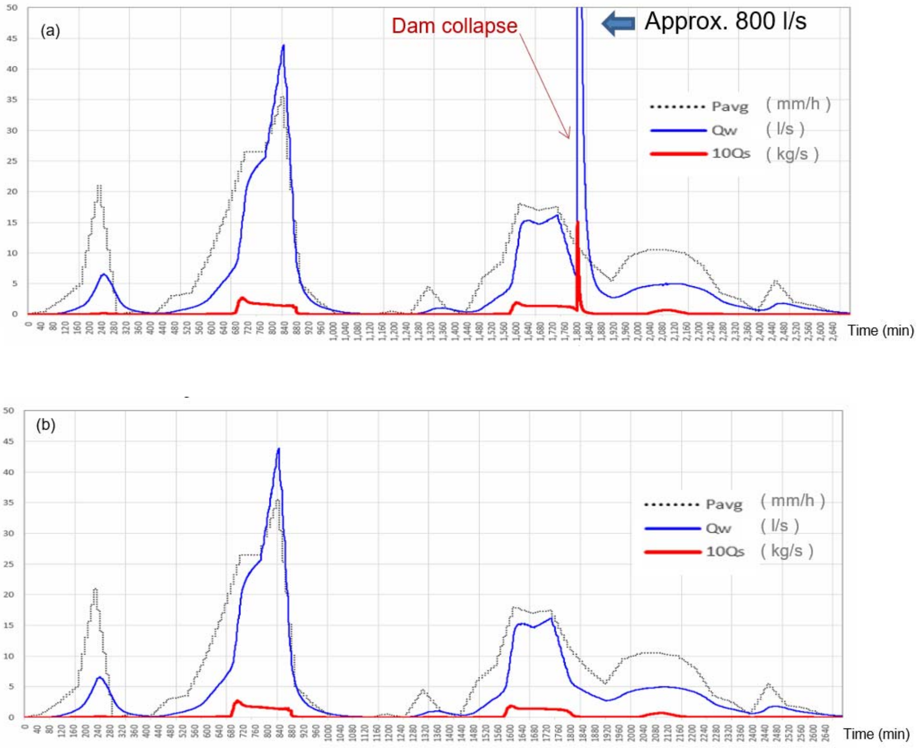


Figure 29. (a) Hydrograph of the dam collapse case during the intensive rainfall, (b) Hydrograph of the flash flood case during the intensive rainfall

Comparing the hydrographs according to the two scenarios, both results show that the total water discharge increases as rainfall intensity increases. However, it can be identified that the runoff increases rapidly at the time of dam failure occurrence in the scenario of the water reservoir dam collapse. At the pick time of water discharge, approximately 800 l/s of water was released by the collapsing event, and it takes about 100 minutes to be back on the normal water runoff profile same as with no cascading effect.

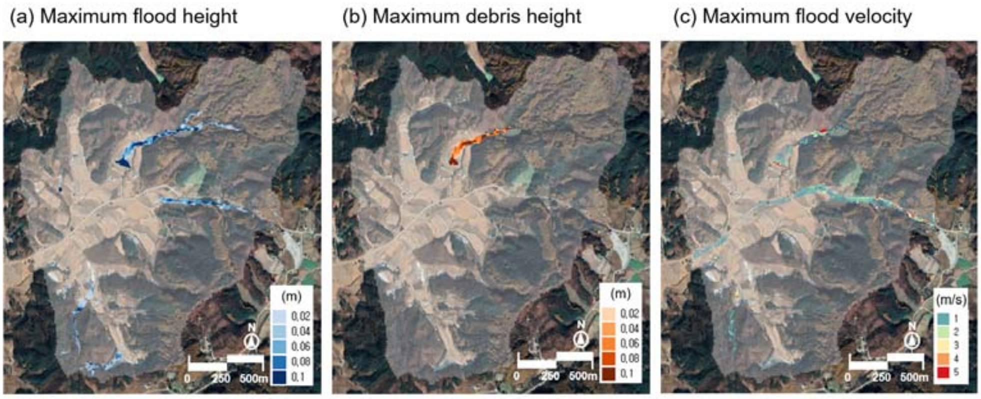


Figure 30. Estimated damages by flash flood during the intensive rainfall, (a) maximum flood height, (b) maximum debris height, (c) maximum flood velocity

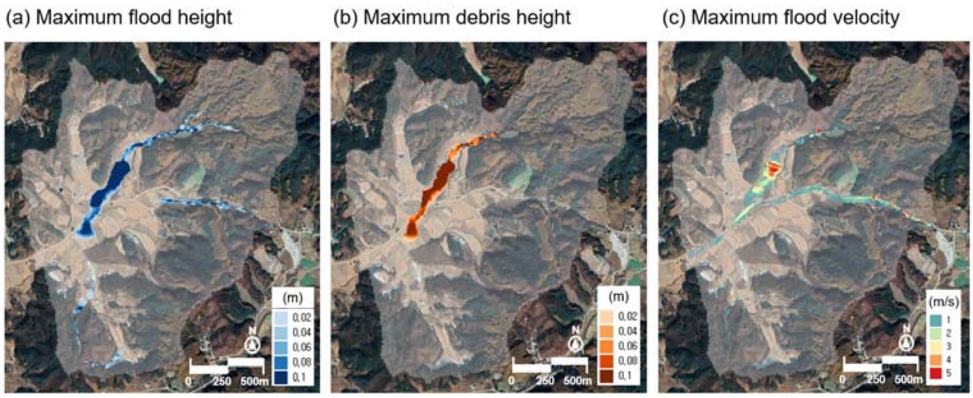


Figure 31. Estimated damages by the dam collapse during the intensive rainfall, (a) maximum flood height, (b) maximum debris height, (c) maximum flood velocity

To compare the results of flood damage according to the scenarios, Figure 30 and 31 show maximum water height, maximum debris height, and maximum flood velocity. In the scenario of the dam collapses, the maximum water height in Figure 31 (a) shows the flood damage may occur at the downstream area of water reservoir after the dam collapsed. Whereas, in the case of single disaster caused by the flash flood, the result shows that the dam of water reservoir plays a role of prevention barrier against flooding, and relatively weak flood might occur only at the upstream area of the water reservoir as shown in Figure 30 (a). The result of maximum debris height in Figure 30(b) and 31(b) is similar to that of water height, and, it is possible to predict how much damage by the muddy sediment can reach to the residential area. The resulting analysis of maximum flood velocity in Figure 31 (c) shows that potential areas of damaging due to the rapid flooding water velocity can occur in downstream area of the water reservoir in the scenario of dam collapse. Especially, it shows that houses and infrastructures damages due to high flow rate can occur not only in the downstream area near the dam but also in the vicinity area of the discharge outlet of the studied catchment. Summary of statistic results comparing between the two scenarios are shown in the Table 8 as below.

Table 8. Summary of flooding results comparison

Category	No collapse	Dam collapse	Unit
Catchment area	222.6		ha
Total rainfall	320.5		mm
Total discharge	1023.3	1706.7	m^3
Suspended sediment	128.1	2033.2	ton
Peak discharge outlet	43.9	1804.5	l/s

By using the simulation results, it is possible to analyze the location and extent of potential damaging area caused by compound disaster based on multi-hazard risk scenarios. When a man-maid infrastructure such as a dam is installed, the result of impact assessment by the physical model can be used as a reference for establishing new spatial planning or flood migration.

5.3 Discussion on risk evaluation and acceptance

QRA with physically based model

The advantages and shortcomings of QRA can be summarized as follows (Apostolakis, 2004). Most importantly, QRA can contribute to promoting a common understanding of risk issues between experts and the public. In dealing with natural disasters, informing residents who might be harmed about the exposed risk is very important in order to minimize losses, and information on the risk can reduce unnecessary arguments regarding decision-making. Next, QRA can improve the completeness of risk assessment. It is not possible to take into account all multiple-failure scenarios through qualitative risk methods; however, the complex interactions between hazardous events and safety system components can be structured by FTA and ETA. Because of these advantages, the QRA approach can examine multi-hazard risk issues from natural hazards more accurately. In addition, in the process of quantifying risk indices through informed input values, it is possible to find previously unrecognized variables, which promotes an understanding of the uncertainties of risk studies. This, in turn, raises awareness of the limitations in estimating risk for natural disasters, which has high uncertainty for prediction, and can be a basis for setting a safety margin.

However, a shortcoming of the QRA is the difficulty that it faces in incorporating human factors into the model, although it has been agreed that human errors show a pattern of probability in the operational stage (Swain, 1982). In addition, there are limitations in how the failure of digital software is reflected in QRA because the causes of failure modes may be unclear and complicated. Finally, construction or manufacturing errors at the design stage lead to significant variation in QRA results. Such design errors are rare, but can cause major hazardous events. Natural-technological (NaTec) disasters are examples of the escalation effect, which can be a serious adverse impact on human dwellings when design errors are combined with natural disasters.

The information obtained through QRA allows people to understand the actual damages that can result from natural hazards in the later stages of risk communication. By becoming familiar with location-specific risk information projected over a specific period of time, those who are at risk can reconsider their adaptation strategies. This communication feedback can play a role in significantly reducing overall risk. Nevertheless, QRA should be used as a supporting tool for cost-efficient risk management and decision making, not as a total replacement of other safety assessment methods.

Post-wild fire landslide compound disaster

Using a physically-based model such as TRIGRS, it is possible to analyze hazardous areas where show high probability of landslide occurrence. It was possible to simulate with physical parameter inputs from terrain, soil, and weather data of the actual site. The expansion of the potentially damaging areas due to landslides after a forest fire was modeled by reflecting the possibly changing physical variables that is applicable with a compound disaster scenario. This is an advantage of physically-based model that is different from statistical modeling, and it was possible to estimate the distribution of hazardous area that affected by post-fire landslides, which could be triggered by specific rainfall event over certain threshold. When the results are applied to areas damaged by wildfire in the dry season, it is possible to analyze areas where landslides can occur even in normal rainfall intensity; however, the areas were relatively safe to landslides before disturbed by wildfire. Unexpected losses by landslide in rainy season can be prevented by referring to the simulation result in advance.

Nonetheless, considering the limitations and uncertainty of the numerical model, various local experts' opinions should be included for disaster prevention, and the analysis results of the landslide hazardous area through the physical equation modeling need to be utilized as reference data. Water repellency effects from wild fires can be varied depending on exposed temperature, exposed time, type of vegetation, soil, and soil wetness. Even though a soil class is classified as a group has same texture or properties with other neighbors on the precise soil map, there might be a deviation depending on the location in detail. Modeling and impact assessment should be done based on actual sampling and experimentation, which correctly indicates the geological and geographical characteristics of the area. In addition, the results of actual post-wildfire effects were not examined because of the specific data is not available. If sufficient data on the actual post-wildfire landslide are available, the uncertainty of input variables can be reduced and the results of modelling can be verified, and it will be the subject for a further study. In the future, if on-site survey data are available, it will be possible to evaluate the accuracy of the physical model for post-wildfire landslide complex disaster using the index such as Modified Success Rate (MS) or Cohen's Kappa.

If natural disasters by climate change are recognized simply as a single-event disaster, potential impacts from multi-hazard risk could be neglected and, unpredictable damages may occur. Jordan (2016) studied the case of an increase in the impact of post-wildfire landslides from 2007 to 2009, which was not previously reported in British Columbia region of Cananda. In Korea, it is expected that not only post-wildfire landslide but also different types of compound disasters rooted from multi-hazard risk will be increased in future. Thus, researches on various types of potential multi-hazard risk and compound disaster should be continued. In order to prevent landslides after wildfire, implementation of mitigation to reduce soil loss and restoration through planting trees should be conducted as well as appropriate impacts assessment. Cawson et al. (2013) reported that more than 100 m^2 of unburned forest patches should be considered in post-wildfire landslide modeling because they play a role in preventing soil loss. If restoring an entire vegetation is difficult after a wildfire, making a vegetation patch will help to prevent landslide reducing soil erosion. In addition, the installation of contour plowing along the contour lines of the slopes can effectively reduce soil loss. Such a mitigation activity can reduce potential damage from unforeseen multi-hazard risk, when conducted as a part of emergency recovery before implement a long-term planting program.

Complex flood compound disaster

The results by complex flooding disaster shows more severe impact than the single event case. Risk assessment is required to prepare for the potential damages, and the area of impact by such a compound disaster can be estimated more exactly by using physically-based numeric model. Various input data considering actual physical condition of the study area enable us to predict potentially impacted area, and calibration process through flood plain inventory data make the modelling results valid.

The cascading effect of the flood due to the dam collapse in heavy rainfall can be explained by different conditions of soil water saturation. Porosity of soil is saturated during the heavy rainfall and water head pressure in the subsurface is increased. Subsequently, decreased infiltration of surface water yield escalation of flooding when the dam collapsed and discharge flood water to the downstream area. For simulating the increase in damage effects that is different depending on local conditions in terrain, soil and vegetation, application of physically-based model in catchment units is an appropriate approach. Characteristics of the topography, geology and land cover condition that is reflected in the model with time series rainfall intensity data make possible to estimate impact areas in time sequence as well as to extend the modeling results based on various multi-hazards risk scenarios.

In the field of impact assessment, if a water reservoir dam is to be constructed in new area, it is necessary to assess not only the positive effect of preventing flood but also the adverse impact causing the potential complex flood by extreme weather events. In addition, when analyzing potentially damaged areas by dam collapse, saturated soil condition should be included for the modeling which can cause cascading effect with flash flood, rather than merely considering dry soil condition that will show a limited impact in downstream area. Especially for a build-operate-trapper (BOT) project in developing countries, the environmental impact assessment (EIA) process should be properly conducted with public participation presenting potential adverse impact by multi-hazard risk scenarios, in that residential communities might located in a flood plain area near downstream watercourse in vulnerable housing condition.

These modeling results with multi-hazard risk scenarios can be used for a spatial planning process or establishing mitigation measures. Migration plans for people who lives in expected flooding area can be settled, or insurance can be prepared based on the simulation results adding the information about probability of occurrences. In addition to predicting flood reach time, emergency evacuation plan and warning beacon installation can be prepared on the basis of the modelling result, and a detailed disaster risk reduction activity can be planed for preventing unwanted losses. Currently, there are technical limitation, such as lack of subsurface geology data and long computation time for broad region, to use the detailed physically-based model for warning and forecasting activities; however, this study approach can be used as a part of an integrated risk management for loss prevention related to natural hazards, and the application for climate change adaption will be increased further.

6. Discussion

Enhancing risk communication for natural hazards is a complicated task due to its uncertainty, lack of context, procedural fragmentation, and involvement of diverse stakeholders (Albano et al., 2017). Nevertheless, the application of the industrial risk management tools introduced in this study and the use of information such as that presented in the case studies can help improve risk communication for natural hazards. Among the multiple purposes of risk communication (Bier, 2001), the goal of raising awareness can be achieved with distinct risk-related indicators, which can be provided by these industrial risk management practices. Such measures can support reaching agreements through active public participation and motivating action by designating parties to take action. Individual experiences of natural hazards and trust in authorities are the most significant factors in enhancing risk perception (Wachinger et al., 2013), and public participation has been recommended as an important means to strengthen those factors by increasing awareness of natural disasters and promoting self-readiness. The participation possibility of the stakeholders, including the public, in all processes from hazard identification, risk assessment, and risk treatment to risk acceptance is a major advantage of the integrated risk management practices suggested in this study.

High-magnitude risks posed by natural hazards have low probabilities, and communication about low-probability risks with people who do not have a suitable understanding of heuristics can also be challenging (Keller et al., 2006). When risk information about natural hazards is communicated through the suggested risk assessment methodologies, likelihood and consequences can be presented clearly in a quantitative manner, which can help increase risk awareness. In addition, non-structural mitigation measures, such as forecasting, early warning, and emergency response, have been recognized as crucial parts of preventing disasters from natural hazards (Sättele et al., 2015), and the application of industrial risk management practices can support building cost-efficient non-structural mitigation measures that could be prepared as a flexible response to hazardous situations. For instance, more reliable warnings about natural hazards are possible with customized hazard identification and risk assessment based on quantitative evidence, and furthermore, the results of QRA can provide risk indicators for establishing an emergency response plan that includes geo-referenced spatial information.

Importantly, risk management should be implemented as an integrated framework for effective risk communication with the public and stakeholders rather than executing each steps of risk assessment studies separately. Such an integrated approach could reduce the communication gap between experts and the end-users who are actually exposed to the excessive natural risk. As the integrated risk management framework, the application of risk identification, analysis, treatment, evaluation and acceptance can improve risk communication between experts and end-users, through cascading risk information in systematic and quantitative forms. However, the risk analysis methods shown in this study should be used as a supporting tool for decision-making because those are merely probability assessments based on the best available assumptions. Further research on regional-scale analyses using multi-events inventory data supplemented by field survey data can improve the accuracy of risk estimation. The methods and case studies presented in this study can help to improve managing natural risk and facilitate risk communication, with the goal of preventing losses from potential natural hazards.

7. Conclusion

The aim of this study was to analyze methods of studying risk that are commonly used in the process industry, and to identify how they can be converted and applied as technical tools to provide an integrated framework for risk assessment. This study has shown that the application of hazard and operability (HAZOP), safety integrated level (SIL), and quantitative risk assessment (QRA), which are key studies for risk assessment in industry, can be applied to prevent losses from natural hazards through an enhanced quantitative approach.

For risk identification, a HAZOP worksheet shows how the risk related to climate change issues can be analyzed more specifically and documented in a logical order. The case study of risk identification for climate change issues demonstrated a way to derive customized hazard identification and location-specific damage scenarios for a given entity. The results suggest that numerical estimates of the frequency of causes and the amount of losses in a risk identification session enable the acceptability of risk to be determined through a comparison with risk tolerance criteria.

For risk analysis and treatment, the frequency of landslide occurrence was analyzed and the probability of landslide occurrence was estimated. It was shown that areas with a greater landslide hazard had higher values of landslide occurrence frequency in the region that was studied, and the estimated frequency data can be used to calculate the probability of landslide occurrence based on the concept of time-dependent reliability. The results of this case study demonstrate that the estimated frequency and the resulting probability values can be used as the basis of landslide risk analysis and management. This technique can also be extended to assess various mitigation measures to handle the risk that stems from landslide hazard.

The case study of rockfall, which is also applicable for risk analysis and treatment, showed that applying the concept of functional safety could yield an appropriate methodology for classifying the rockfall occurrence rate more systematically and for estimating the risk reduction effect by applying mitigation measures quantitatively. The findings of this case study also suggest that using the time-dependent reliability equation can improve the model used to estimate the probability of rockfall occurrence. This case study demonstrates that variables related to maintenance factors, such as repair time and diagnostic coverage, could be included for estimating the rockfall probability together with the effect factor for common cause failure.

For risk evaluation and acceptance, a simplified QRA was conducted in the case study of landslide hazard in a way that could be applied for spatial planning of new buildings. The results indicate that the information obtained through QRA can provide support for decision-making on spatial planning considering the exposure to individual risk and societal risk from natural hazards. By recognizing the location-specific risk information projected over time, those who are exposed to the risk can develop and implement adaptation strategies.

For the impact assessment of multi-risk hazard scenarios, the case study of post-wildfire landslides showed that a simulation using TRIGRS, a physically-based model for landslide hazard, displayed the impact of the compound disaster, compared to the viewing the landslide as a single disaster. The results of this case study indicate that the areas potentially damaged by landslide are expanded due to changes in soil properties after a forest fire. This implies that assessments of the distribution of areas where compound disasters pose a hazard can be informed by referring to simulation results in advance.

In addition, impact assessment of the complex flooding case showed that the cascade effect from the collapse of a dam during heavy rainfall can cause more severe damage to the neighboring community than simple freshwater flooding. The flooding area was estimated in a time-step model using openLISEM Hazard, a physically-based model for flooding and sediment flow. The results of this case study suggest that flood impact assessments conducted using a physically-based model can be used as a reference for spatial planning or flood mitigation when a dam for a reservoir is newly constructed.

This study demonstrated that industrial risk management practices can be employed to develop risk management plans considering time-varying dynamic risk to implement mitigation measures against natural hazards supported by a physically-based model with a multi-risk hazard scenario. Further research needs to be performed on the regional-scale application of multi-event inventory data supplemented by field survey work to improve the accuracy of risk estimation.

Importantly, risk management should be implemented as an integrated framework for effective risk communication with the public and decision-makers, rather than executing risk assessment studies separately. The participation of stakeholders, including the public, in all processes ranging from risk identification, risk analysis, risk treatment, risk evaluation, to risk acceptance, is a major advantage of the suggested practices. The methods and the case studies presented in this study can help to establish an integrated framework for managing natural hazards and for facilitating risk communication, with the goal of preventing losses from natural disasters.

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국문초록

산사태, 홍수 및 관련 복합재해 피해 예방을 위한 통합적 리스크 관리 체계

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기후변화에 의한 자연재해는 최근 증가하는 추세이며, 폭우 등 극한 기상 현상에 의한 복합재해 피해 역시 증가하는 것으로 보고되고 있다. 그간 자연 위해 요소로부터 기인하는 리스크 관리를 개선하기 위한 노력은 있어왔으나, 통합체계 구축에 대한 논의는 부족한 편이였다. 또한 정량적 리스크 분석에 기반한 효율적 관리 체계 확립에 있어서도 리스크 평가를 위한 적정 기술 제공에 어려움이 있었다. 한편, 재해로 인한 손실 예방 및 저감을 위한 통합적 위험 관리 체계는 수십 년간 산업 부문에서 집중적으로 개발되었다. 자연재해 위험 관리를 위하여 이와 같은 체계적인 분석 방법과 검증된 운영 방식을 채택한다면, 이상 기후 노출로 인해 반복되는 인명 및 자산 손실을 줄일 수 있을 것이다. 이 연구의 목적은 석유화학 업종에서 사용되는 위험 관리 방법에 대하여 분석하고 자연재해 사례에 적용하여 통합적 위험 관리 체계를 수립하는데 있다. 특히, 리스크 관련 스터디 중 주요하게 실행되는

위험 및 작동성 평가 (The Hazard and Operability –HAZOP), 안전 통합 수준 분석 (Safety Integrated Level – SIL), 정량적 위험 평가 (Quantitative Risk Assessment – QRA) 에 대하여 자세히 알아보고, 이 방법들이 리스크의 확인, 분석, 저감, 평가, 수용으로 이어지는 자연재해 리스크 관리 전반에 어떻게 적용될 수 있는지에 대하여 분석하였다. 이 논문에서는 먼저 위에서 언급한 세가지 주요 리스크 스터디들에 대한 문헌 조사 내용을 소개하고, 다양한 분야에 적용되고 있는 현황에 대하여 알아보았다. 또한 기존의 자연재해 리스크 관리 방법들에 대하여 조사하고, 다중 위험 요소에 의한 복합재해 유형을 소개하였다. 다음으로, 이 리스크 스터디들이 실행되는 일반적 방법들에 대하여 알아보고, 자연재해 리스크 관리 분야에 적용되기 위한 방안들에 대하여 논의하였다. 첫번째 결과는 기후 관련 자연재해의 위험 요인을 식별하기 위한 HAZOP 스터디 사례이며, 워크시트 형태로 한 기관 내에 발생 할 수 있는 자연 위해 요소들을 분석하였다. 두번째 부분은 산사태와 낙석 발생의 확률을 추정하기 위하여 신뢰도 개념에 근거한 SIL 스터디를 적용한 사례 연구이며, 산정된 확률 지표를 사용하여 효율적으로 산사태 위험을 관리하기 위한 방안을 제시하였다. 셋째로, 산사태 위험을 정량적으로 분석하기위한 QRA 사례 연구를 진행하였으며, 산악 지역 펜션 리조트의 부지 선정 과정에서 노출될 수 있는 산사태 위험을 평가하고 수용하는 방법에 대하여 계획의 관점에서 알아보았다. 아울러, 이 결과 부분에서는 산불 후 산사태와 호우 시 댐 붕괴로 인한 홍수, 두가지 복합재해 사례에 대하여 알아보고 물리식 기반

모델을 사용한 영향 평가 방법에 대하여 논의 하였다. 이 논문에서 제시된 기술적 접근법인 체계적 위험성 식별, 시간에 따른 신뢰성 분석, 정량적 위험성 평가, 물리 모델에 기반한 복합재해 영향 평가는 자연재해 리스크 관리를 위한 방안들로 활용 될 수 있으며, 기술적 어려움을 해결하는데 도움이 될 수 있다. 이 논문의 연구 결과는 의사 결정자와 대중 간의 리스크 관련 의사 소통을 원활히 하고 체계적 관리 방안을 수립함으로써 자연재해 리스크 관리를 향상시키는데 유용한 통합 체계를 제공할 것이다.

■ 주요어: 리스크 커뮤니케이션; 다중 리스크; 물리식 기반 모델; 시간 의존 신뢰도; 기후변화 적응; 공간계획

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