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Development of Resilience Index in Transport Systems

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ABSTRACT

This paper demonstrates the quantification of the resilience index (RI) in transport systems. The transport infrastructure can be managed by using the concepts of resilience. Vugrin, Warren, Ehlen, & Camphouse (2010) emphasized the enhancement of resilience in infrastructure before disasters and the establishment of efficient measures for the recovery of systems in an emergency. The concept of resilience has a significant influence on transport planning and operations for disaster preparation. Lee, Kim, & Lee (2013) investigated the concepts of resilience and examined case studies using valuable asset-management techniques in order to maintain the resilience concepts which should be introduced in transport infrastructure planning and operations. Therefore, this paper presents the RI based on Vurgrin et al. (2010) and Lee et al. (2010).

The first part of this paper focuses on the measurement of the RI using the recovery-dependent resilience (Vugrin et al., 2010) in transport infrastructures. For quantifying the RI, we have developed various variables that are used to target an achievable or a desired system performance in disaster recovery efforts. The second part of this paper focuses on the applications of the RI in case studies. The examined cases are road networks in flooded areas, heavy snowfall districts, and landslide occurrence zones. Each case is analyzed for transport costs both under normal and disaster conditions using the transport demand estimation models. Finally, we quantify the RI, which is important for establishing the provision of safety, recovery, and rehabilitation of transport infrastructures in flooding, snowfall, and landslide areas.

1. INTRODUCTION

With its indispensable role in modern living, national infrastructure (which may also be translated as “critical infrastructure”; however, this thesis is based on the term, “national infrastructure,” in accordance with the Disaster and Safety Management Fundamental Act) is often exposed to various types of hazards, including natural, man-made, and criminal. In this respect, a number of nations, including South Korea, are formally designating and protecting their national infrastructures in order to achieve sustainable national development.

Our national infrastructures are designated under the first clause of Article 25-2 of the Disaster and Safety Management Fundamental Act. The designation bases are: (1) the infrastructure’s chaining impact to other infrastructures or systems; (2) necessity of cooperative countermeasures by two or more central administrative bodies; (3) scale and range of potential damage to national security, society, and economy; and (4) possibility of disaster or restoration easiness. As of October 2011, South Korea is managing 250 designated facilities in 9 different fields which include energy, infocommunication, transportation, finance, health care, environment, and drinkable water. A thorough and consistent lookout is necessary in these fields as they pose a big threat to the national economy, life, and property once their functions are paralyzed in disasters.

Speaking of a foreign case in national infrastructure protection policy, the US left its mark in 1998 after Presidential Decision Directive 63 (PDD-63) on the matter of critical infrastructure protection (CIP). After 9/11, the US organized the Department of Homeland Security (DHS) and authorized the body for overall control of CIP. The National Infrastructure Protection Plan (NIPP) from the DHS integrates the individual efforts for infrastructure protection into a single national program in order to reinforce the protection of critical infrastructure and key resources (CIKR) and to sustain resilience (DHS, 2009). This resilience is an ability to overcome the changes in outside pressure onto a particular system and may be interpreted as recoil, recuperative power, restitution power, and also disaster prevention power. *Critical infrastructure* *resilience* (CIR) is the ability of a national infrastructure system to efficiently reduce the duration and scale of disaster damage; its concept is similar to the term “resilience” in “business resilience” (Yoo, 2009).

The DHS realized that physical protection could not guarantee the protection of national infrastructure and decided to include CIR into CIP. Organized in 2005, the national infrastructure task force under DHS designated CIR as its top priority for CIP. However, in order to utilize the concept of resilience for CIP, it requires a definition and objective-measuring method to consistently apply the concept to various infrastructures. For this matter, the Science and Technology Directorate of DHS requested Sandia National Laboratory to conduct evaluation research in order to find out the resilience-securing method for CIKR and to quantitatively evaluate resilience. Sandia National Laboratory is grouped under the Department of Energy, a federal department which develops national security policies based on science and technology and extends its research to nuclear weapons, defense industry systems, energy/climate/infrastructure security, domestic and overseas national security, and nuclear security. The research practice on CIR connects it to infrastructure security.

In order to gather important information for decision making on national security issues, Sandia National Laboratory operates the Interdependence and Consequence Effects Group. While various resilience research programs are in progress under this team, the National Infrastructure Simulation and Analysis Center (NISAC), established by the Patriot Act, is operated cooperatively with Los Alamos National Laboratory as a modeling, simulation, and analysis program under DHS. With its science technology, NISAC analyzes interdependent phenomena caused by infrastructure destruction and the economic and national security outcomes after damage to assist the nation’s decision making. To be part of this assistance, it provides federal, state, and local governments with their modeling, simulation and analysis outcome that are essential for infrastructure protection.

In order to understand the complex nature of infrastructure systems, it devises various ways of researching such as process-based systems dynamics models, mathematical network optimization models, physics-based models, agent-based simulations, etc. As seen in Table 1 that lists disasters analyzed by NISAC, it is realized that while the Federal Emergency Management Agency (FEMA) pays attention to the postdisaster countermeasures and recovery strategies, NISAC focuses on securing the predisaster resilience based on previous disaster analysis outcomes. This paper aims to quantify the resilience index (RI) in transportation systems that can be managed by utilizing concepts of resilience so damage to infrastructure can be minimized. Section 2 of this paper introduces the concepts of resilience. Section 3 deals with the study and methodology for measuring RI in the transport sector. In Section 4, we focus on applications of RI in real-world case studies involving flooding, snowfall, and landslides.

2. CONCEPT OF RI

Based on the understanding of infrastructure systems, it is necessary to figure out answers to the following questions in order to protect infrastructure systems from external hazards and to maintain its

Table 1. Selected NISAC (National Infrastructure Simulation and Analysis Center) analysis

Year	Threats	Remarks
2011	-Cascadia Subduction Zone (CSZ)	-High probability that the CSZ will produce earthquakes of magnitude 8.0 or higher in the next 50 years.
2010	-Deepwater Horizon Oil Spill -Icelandic Volcanic Ash Cloud	-Impact analyses.
2009	-H1N1 Swine Flu	-Used impact analyses to plan for 2009-2010 flu season.
2008	-New Madrid Earthquake Impacts	-Used results in developing the National Strategic Plan for a New Madrid Seismic Zone event. -provided information on infrastructure impacts for better planning efforts and design mitigation measures at local, regional and national levels
2007	-Long-term Analysis on the Impacts of Hurricane Katrina -I-35W Bridge Collapse	-Provided information for DHS event response
2006	-H5N1 Pandemic Influenza Study	-Used for the national Pandemic Influenza plan -influenced CDC1/HHS2 community containment strategy
2005	-Hurricane Katrina -Hurricane Rita	-Hurricane Pre-landfall impact analyses -Provided information for DHS pre-event planning, deployment for the events, post-event security priorities.

performance. First, which infrastructure system is more dangerous and why? Second, how does the interdependency of national infrastructure increase danger? Third, why is infrastructure vulnerable to threats? Fourth, how does infrastructure in danger affect national security? Fifth, how can such danger be minimized?

Because of the characteristics of national infrastructure, it is necessary to understand the national infrastructure system along with its physical condition in order to secure CIR. In an example of electric power supply, industrial practice may experience shortage in the power supply after a power facility is damaged. However, for a resilience-secured system, it may derive the power supply from an alternative source or reserve. Therefore, even after the destruction of a power facility, the power supply system operates normally and eventually chaining damage does not occur. Securing resilience is an infrastructure system build up that guarantees an all-time operable condition in any hazardous situations.

The dictionary defines resilience as “power or ability of a body or system to return to their original state after transformation by an external force.” MCEER researchers define resilience as “the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters” (Bruneau et al., 2003). This research paper focuses on concepts of resilience and its application in transportation planning and operations, thus, we can say that infrastructure resilience is the ability of infrastructure (roads, highways, lifelines, and other structures) to withstand natural disaster forces.

Figure 1a represents “the resilience triangle” for a damaged infrastructure system and shows its relationship with recovery (Bruneau et al., 2003). Operation disability, damage, and confusion are caused by disasters and can be recovered from over time. The system of measures undertaken for enhancing resilience in urban infrastructure improves the operation of power (vertical axis), and a full recovery will take less time (horizontal axis). Resilience-enhanced measures should aim to reduce the size of the resilience triangle through strategies that improve the infrastructure’s functionality and performance. Infrastructure resilience is influenced by these factors, and for better understanding, a conceptual framework is developed (McDaniels, Chang, Cole, Mikawoz, & Longstaff, 2008).

Figure 1b represents the effect of decision making on resilience and a system’s functionality. With the proper decision making and resourcefulness, the infrastructure’s durability and rapidity can be increased. Resilience cost (RC) is composed of the sum of system impact (SI) and total recovery effort (TRE). When the RC is bigger than the sum of the SI and TRE, a system’s resilience shall be interpreted as poor because it takes a lot effort to recover (Vugrin, Warren, Ehlen, & Camphouse 2010). Also for the same system of disaster resilience, the RC can vary depending on the total system recovery evaluation, resourcefulness, and the ability to diagnose. Thus, a relative comparison is done by using a weighing and unit conversion factor (α). Total RC then equals the sum of SI and factored TRE.

To integrate the concept of resilience with CIP, Sandia National Laboratory has recently defined resilience as a “system’s ability to hold system performance (SP) without any significant drop in

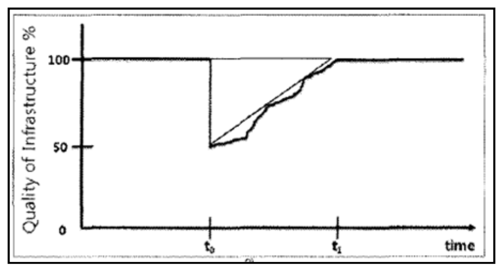


Figure 1a. Resilience triangle

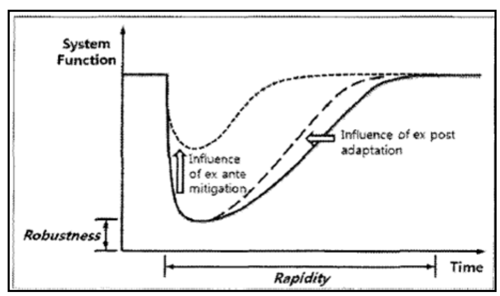


Figure 1b. Resilience triangle and effects of decision making (McDaniels et al., 2008)

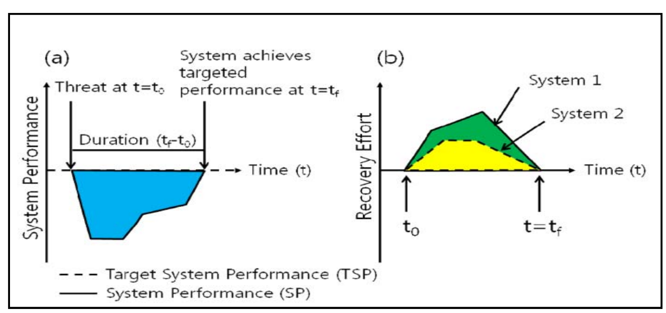


Figure 2. Two primary components of resilience: (a) System Performance (SP), (b) Total Recovery Effort (TRE). In (a) TSP is Target System Performance (Source, Aamir, 2011)

target system performance (TSP) and to shorten the time of reduced TSP condition, especially apart from typical resilience research" (Vugrin et al., 2010); this even takes TRE into consideration. Figure 2a depicts the significant drop in SP due to a disaster and its recovery to normal condition over time. Figure 2b indicates the recuperative effort spent to recover the interfered system back at its TSP, and it is shown that System 1 required a more recuperative effort that System 2. If it was to consider SP only (Figure 2a), like other research, (Vugrin et al., 2010), the resilience of both systems are identical; however, once considering the recuperative effort (Figure 2b), System 2 secures more resilience than System 1 as System 2 requires less recuperative effort.

In this formula, SI represents systemic impact while TRE and α represent total recovery effort and the coefficient for weighted value addition and unit conversion. In order to maintain basic functions after a threat, an infrastructure system displays SI and requires RE while demonstrating absorptive,

Based on this definition, RC has been devised and defined in Equation 1 in order to quantify resilience (Vugrin et al., 2010).

$$\mathrm{RC} = \mathrm{SI} + \alpha \times \mathrm{TRE} \tag{1}$$

adaptive, and restorative abilities against a threat. Therefore, in the end, the sum of SI and RE becomes the RC, as shown in Equation 1. It may be interpreted that when higher resilience cost is required, the system's resilience is poor as the TRE required is large. Also, the recovery aspect of system performance in Figure 3a may depend on the RE methods in Figure 3b so that RC may branch out into recovery-dependent resilience (RDR) cost and optimal resilience (OR) cost (Vugrin et al., 2010).

$$\mathrm{RDR(RE)} = \frac{\int_{t_0}^{t_f}|TSP(t)-SP(t)|dt+\alpha\int_{t_0}^{t_f}|RE(t)|dt}{\int_{t_0}^{t_f}|TSP(t)|dt} \tag{2}$$

$$\mathrm{OR} = min_{RE}\frac{\int_{t_0}^{t_f}|TSP(t)-SP(t)|dt+\alpha\int_{t_0}^{t_f}|RE(t)|dt}{\int_{t_0}^{t_f}|TSP(t)|dt} \tag{3}$$

Here, each t_0 and t_f indicate the point when disaster begins and the point when recovery is complete. TSP is the target value of system performance, which may not only vary before and after disaster, but also by progress of time. As SP represents the current performance, in Equations 2 and 3, TSP(t)–SP(t) shows the SI from Equation 1. Additionally, RDR of Equation 2 and/or of Equation 3 are divided by TSP of Equation 1 to enable a comparison among variously sized systems. Equations 1–3 represent a much more complex nature of resilience evaluation when considering RE. As seen in Equations 2 and 3, RC may depend upon the RE function, while recovery duration (t0, tf) and RC are dependent on RE. Also, it is possible to calculate RE that can minimize recovery duration and resilience cost.

The purpose of research on national infrastructure resilience is to build a system that can reduce SI and TRE caused by external threats so that RC may be reduced. In order for resilience research to achieve this goal, quantitative calculations of RC are required. To quantify resilience cost, it is necessary to obtain time series data of TRE consumed for normalizing SI and the system after threats. However, it is found to be difficult to quantify RC due to the lack of relevant data. Thus, it may be also considered to produce an actual event; however, cost becomes an issue. Also, SI and TRE evaluations, which are based on experts' opinions, may bring inaccurate outcomes due to their subjectivity. Therefore, modeling and simulation are utilized as alternatives. When utilizing modeling and simulation, it is possible to evaluate SI and TRE under various threats and recovery scenarios at a low cost.

3. METHODOLOGY OF QUANTIFICATION OF RI

Resilience is the system's ability to efficiently reduce both the magnitude and the duration of systemic impacts and recovery efforts, and many case studies on resilience costs show that the recovery effort should be included in resilience assessment. As mentioned in Section 2, the RI is composed of SI and TRE.

First, system impact is the damage cost that results from a disaster. For example, many travelers near a natural disaster area experience unnecessary travel time and operation costs because the road network system is paralyzed. In this study, we assume that system impact is detrimental to transportation. For calculating disadvantages, we use EMME, traffic allocating software, using the network and O-D tables from the Korea Transportation Data Base (KTDB). Specifically, disadvantages are divided into direct disadvantages and indirect disadvantages when economic analysis is progressing. For instance, a direct disadvantage, which is generated to users using transportation facilities directly, contains a discomfort benefit, additional travel time, traffic accident rate, and vehicle operating costs. Benefit of transportation, for example, discomfort, safety, and effectiveness improvements, are excluded from the procedure of assessing investment impact on transport facility because it was difficult to quantify. An indirect disadvantage is a ripple effect reaching everyone, regardless of facility use or when a road project is put into operation. We use two disadvantage categories:

additional travel time and vehicle operating costs. The disadvantage of travel time increases and operating costs is calculated on the basis of link volume and traffic speed. In a preliminary feasibility study, total travel time on the road is calculated with multiplication of link travel time and a vehicle's quantity of the volume of traffic in a direct influence area resulting from allocating traffic. The following equation is the equation for travel time increases and operating costs:

$$\mathrm{VOTS} = \mathrm{VOT}_{after} - VOT_{before} \tag{4}$$

Where VOT: $\sum_{\mathrm{l}} \sum_{\mathrm{k}=1}^{3} (\mathrm{T_{kl}} \times \mathrm{P_k} \times \mathrm{Q_{kl}} \times \mathrm{Duration(day)})$

$\mathrm{T_{kl}}$: veh-travel time by vehicle type of links l

$\mathrm{P_k}$: Value of travel time by vehicle type

$\mathrm{Q_{kl}}$: volume of links l

k: Vehicle type (1: auto, 2: bus, 3: truck)

$$\mathrm{VOCS} = \mathrm{VOC}_{after} - VOC_{before} \tag{5}$$

Where VOC: $\sum_{\mathrm{l}} \sum_{\mathrm{k}=1}^{3} (\mathrm{D_{lk}} \times \mathrm{VT_k} \times \mathrm{Duration(day)})$

$\mathrm{D_{lk}}$: veh-km by links by vehicle type

$\mathrm{VT_k}$: Operation costs/km based on travel speed of each vehicle type

k: Vehicle type (1: auto, 2: bus, 3: truck)

We quantified travel time increases and operating costs using the above equations. The specific parameters are from "The Standard Guideline of Feasibility Analysis of Road & Rail" (Korea Development Institute, 2008).

TRE is the cost of restoring an infrastructure system like road networks. We consider TRE as rehabilitation expenses. For example, recovery cost consists of time and costs to recover. Each item is measured based on "The Standard Guideline of Feasibility Analysis of Road & Rail" (Korea Development Institute, 2008).

4. EVALUATION OF RI USING A CASE STUDY

We focused on the applications of the RI in several case studies. The examined cases are road networks in flooded areas, heavy snowfall districts, and landslide occurrence zones. If the disasters take place, both operating companies and many users suffer from economic loss, so we set up situations for RI evaluation.

The urban infrastructure has a strong relationship with the transport infrastructure—both are interdependent. After the disaster, transportation logistics are disrupted and the city infrastructure is paralyzed, and the damage can last longer. But with secured resilience and proper disaster management, the transportation network can be made functional even after disaster occurs.

The impact of climate change is predicted and the probability of natural disasters, such as rainfall, snowfall, and landslides in South Korea, is measured by techniques such as the KPCC model and IPCC AR4 model (IPCC, 2007). We tried to analyze the quantification of rainfall frequency. The country's five-year frequency design rainfall for two hours is 81.4mm and marginal rainfall is 81.7mm. From 2011, the frequency of rainfall over marginal rainfall is expected to gradually increase; therefore, precautionary measures and flood disaster management plans must be enhanced.

First, disaster prevention facilities in the target area, Gulpacheon (Gulpo Creek), were investigated for concentrated rainfall. The Urban Runoff Model (XP-model) is applied to the 14,917-m long target area. Flooding damage is calculated by the multi-dimensional method and economic analysis from rainfall data, which is adjusted for expected future impacts.

Second, for calculating damage due to heavy snowfall, we selected a heavy snowfall district, Banpo-ro. As shown in Figure 4, the green links are expressed as the melting snow system installation, which reduces the delay due to increased traffic speed. In this case, the section installed for Banpo-ro and internal to Seoul improves traffic speed. After setting the target for the study area, the volume delay function (VDF) was adjusted for snow traffic analysis. To ensure the reliability of the estimated parameter values, an EMME/2 macro language was designed to estimate the parameters. For examining the spatial and temporal reduction techniques in this task, the Meteorological Administration model of KMA-RCM is applied. In the future, the frequency and probability point of the snowpack can be analyzed from data obtained from point weather stations in 57 regions. Also, using the VDF, snowfall for the recurrence period, the probability of snowfall damage phenomena criteria, and the resultant disadvantages can be calculated.

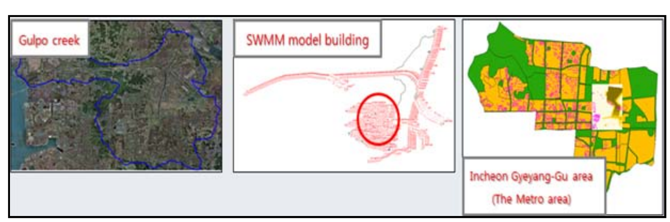
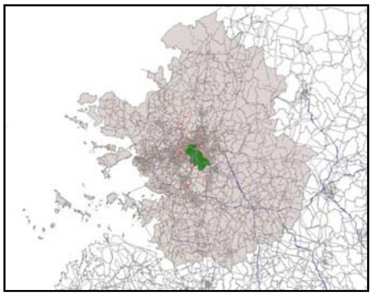
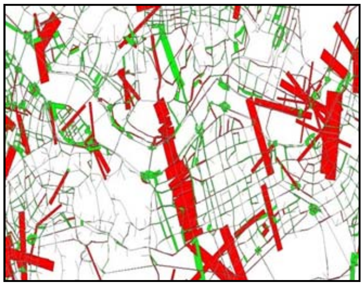


Figure 3. Review case in urban area



a. Spheres of Influence as a result set



b. Traffic Volume Rate (RV)

Figure 4. Transportation effect analysis according to snowfall

Third, the Mt. Umyeon case study was used to calculate the system impact using EMME. South Korea has many landslides caused by heavy rains during summer, and the landslides continue to cause damage in many places. These landslides occur repeatedly each year, and the frequency of landslides is expected to increase in the future due to dramatic global climate change. In Korea, 81.5% of the population is living in urban areas and about 11 million people are living in Seoul. In 2011, the landslide that occurred in Seocho-dong killed 18 people, and about 9% of Seoul's area is under the same land conditions as Seocho-dong. Even though only a small landslide would likely occur in a city, it is more likely to cause a big disaster because of the greater population density in the city. So far, an effort has been made to identify landslide vulnerability and causes, but now, a new demand has arisen for the prediction study for the areal extent of disaster areas for landslides. To calculate systemic impact, we applied the same method as the snowfall case. Then, we adapted real recovery effort data.

The results of the RI evaluation from the RC that consists of SI and TRE based on Vugrin et al. (2010) are found in Table 2.

Table 2 shows the quantification of resilience cost in three case studies (flooding, snowfall, and landslides). Systemic impact was calculated in this paper using travel time valuation theory whereas total recovery effort is the total reconstruction and rehabilitation cost for bringing back the damaged infrastructure to its original condition before disaster. Finally, the sum of systemic impact and total recovery effort demonstrates resilience cost.

5. CONCLUSION

This paper presented a framework to introduce resilience concepts in infrastructure systems, especially in the transportation sector. Basic theory related to resilience (e.g. resilience cost and quantification of disaster resilience) has been briefly discussed.

The DHS realized that physical protection could not guarantee the protection of system performance of national infrastructure and decided to integrate CIR into NIPP. In order to utilize the concept of resilience for CIP, it required discussions on its definition and measuring method, and Sandia National Laboratory was requested for an evaluation research of resilience including RE and quantified the resilience as a cost. Its resilience cost is the sum of reduced system performance and RE for system recovery. The evaluation cases of resilience explain the need to consider RE when evaluating resilience. Also, it

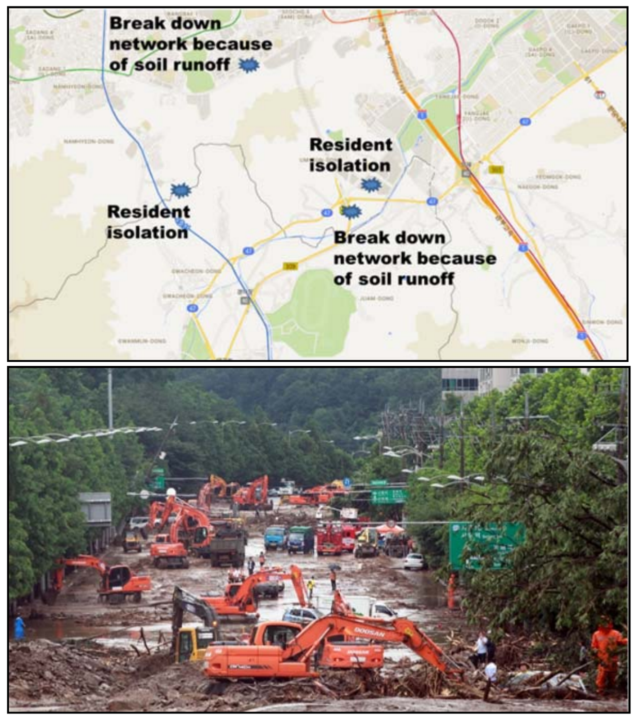


Figure 5. Mt. Umyeon landslide

Table 2. Comparison of resilience cost

Division	Days to complete recovery (Days)	Systemic Impact ($100million won)	Total Recovery Effort ($100million won)	Resilience Cost ($100million won)
Flooding	30	2,247	2,628	4,875
Heavy snowfall	24	1,047	1,199	2,246
Landslide	55	5,441	6,477	11,918

depicts that it is possible to build an infrastructure system that can enable both reduction in resilience cost and shortened recovery time.

Like American infrastructure, South Korean infrastructure also suffers great damage from disasters every year. Therefore, infrastructure resilience research is necessary for the nation's continuity. It is expected that resilience cost research introduced in this thesis may become a useful case for securing the resilience of Korean infrastructure.

ACKNOWLEDGMENTS

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