

Article

Assessing the Risk of Natural Disaster-Induced Losses to Tunnel-Construction Projects Using Empirical Financial-Loss Data from South Korea

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Abstract: Tunnel construction, a common byproduct of rapid economic growth and transportation-system development, carries inherent risks to life and various kinds of property that operations and management professionals must take into account. Due to various and complicated geological conditions, tunnel construction projects can produce unexpected collapses, landslides, avalanches, and water-related hazards. Moreover, damage from such events can be intensified by other factors, including geological hazards caused by natural disasters, such as heavy rainfall and earthquakes, resulting in huge social, economic, and environmental losses. Therefore, the present research conducted multiple linear regression analyses on financial-loss data arising from tunnel construction in Korea to develop a novel tunnel-focused method of natural-hazard risk assessment. More specifically, the total insured value and actual value of damage to 277 tunnel-construction projects were utilized to identify significant natural-disaster indicators linked to unexpected construction-budget overruns and construction-scheduling delays. Damage ratios (i.e., actual losses over total insured project value) were used as objective, quantitative indices of the extent of damage that can be usefully applied irrespective of project size. Natural-hazard impact data—specifically wind speed, rainfall, and flood occurrences—were applied as the independent variables in the regression model. In the regression model, maximum wind speed was found to be correlated with tunnel projects' financial losses across all three of the natural-hazard indicators. the present research results can serve as important baseline references for natural disaster-related risk assessments of tunnel-construction projects, and thus serve the wider purpose of balanced and sustainable development.

Keywords: risk assessment; construction financial loss; natural disasters; tunnel construction; geological hazard

1. Introduction

1.1. Research Background and Objective

Tunnels are vital to the transportation of people and goods, and are proliferating worldwide as a consequence of rapid industrialization and urbanization, and the associated growth of road and rail networks. At the same time, the intensity and frequency of floods in urban areas has increased, driven by climate change and by the geographic expansion of cities [1–3]. Tunnels' construction techniques

and the geological characteristics of their immediate surroundings inevitably render them especially vulnerable to heavy rains and flooding in certain regions [4–7].

Economic growth in South Korea is underpinned by railways and highway systems, which pass through many tunnels due to the complicated geomorphological and geological settings. Far from mitigating their inherent disadvantages, including but not limited to vulnerability to collapse, landslides, and flooding during construction [8–10], increased demand for tunnels has merely proliferated risk and uncertainty [11]. Insurance Statistics Information Services [12] revealed that insured losses during tunnel construction in South Korea over the period 2005–2016 totaled US\$8.77 million.

E. Vaughan and M. Vaughan [13] reported that natural disaster-related damage during tunnels' construction and operations-and-management phases is much more costly than other types of accidents. As well as heavy rain and other directly water-related hazards, tunnel construction is very easily affected by earthquakes. However, it is difficult to measure or predict the risk indicators for such hazards due to their inherent uncertainty. Although the South Korean government has sought methods for reducing natural disasters' negative impacts on the construction projects, these have tended to be broad and general, emphasizing systems for safety management [14], and have relied too heavily on past experience and individuals' judgements [15,16]. More specific risk-management tools, rooted in quantitative methodologies, are therefore still required to address these limitations and more effectively mitigate the risks and losses related to natural hazards.

According to Ahn et al. [17], because the focus of construction risk management is on reducing the risk factors that can have negative effects during both the construction and operations-and-management stages, it should consider the external as well as the internal causes of risk. Natural hazards and third-party damage [17,18] both fall into the external category, and therefore should both be the subject of accurate risk-prediction and loss-estimation methodologies. Nevertheless, most previous studies of construction risk management have focused on the internal category: chiefly, physical injury to workers, structures, and foundations during construction activities.

The owners of large infrastructural elements such as dams, bridges, roads, and tunnels are encouraged to take out third-party liability insurance, which covers damage caused by construction activities to third parties' properties. This category of damage can give rise to unexpected costs, taking the form of not only compensation, but also scheduling delays and other project-level issues. Moreover, external risk factors can magnify one another, such as when natural hazards cause third-party damage. Accordingly, more comprehensive risk-management frameworks for sustainable construction would seem to be long overdue.

In the present study, insurance information—including both direct damage to, and third-party damage arising from, tunnel projects in South Korea—is used to identify the most significant external risk factors during tunnel construction. the damage ratios, i.e., the ratios of actual losses to total insured project values, are calculated for both the direct and third-party damage caused by natural disasters in and around tunnel projects in progress. the collected claim-payout data are analyzed statistically to establish the relationships between natural-hazard indicators and actual losses, with the wider aim of developing a novel framework for tunnel construction risk management that takes due account of both third-party damage and natural-disaster indicators.

Because quantitative data can produce more reliable and objective results in risk management [19], the present study performs multiple linear regression analysis with the immediate objective of identifying the relationship between damage that actually occurred during tunnel construction and damage risk factors, and the wider one of building a better risk-management framework for construction management. the damage ratio explained above is used as the dependent variable, which is tested for normality. an approach based on damage ratios is very useful, in that it can be utilized to evaluate the extent of damage regardless of a construction project's size.

1.2. Literature Review

Tunnels are an obvious and economically efficient alternative to highway and railway systems having to traverse mountains and rivers on the surface [20]. In recent decades, demand for them has been increasing all over the world, driven by the increasing scale of infrastructure projects in general [21]. Yet, despite tunnels' clear benefits to transportation efficiency and economic growth, their construction is not always possible or desirable. According to Wang [22] and Noferini et al. [23], the excavation of tunnels can cause stress redistribution when they are opened, which in turn deforms the surrounding ground, potentially causing landslides or rendering them more severe when they do occur. Even in cases where the risks inherent in tunnel-building are judged to be of an acceptable level, various built-environment and geological characteristics at the job site can lead to frequent accidents, resulting in threats to life, scheduling delays, and increased operation costs [24]. In Prague, Czech Republic, the collapse of a tunnel under construction resulted in the ground above sinking by 15 m [25]. Similar incidents have occurred in Poland, where water leakage caused serious damage to tunnel structures. Furthermore, in 2008, a tunnel in China collapsed one year after its construction was completed, resulting in 12 fatalities, mainly due to inrush of water during heavy rain [26].

The overall number of tunnel-construction accidents has also been increasing over time. According to Yoo and Lee [27], the main reason for such accidents is ground deformation, which may be linked with ground-surface movements. Such movements affect the foundation systems of the nearby roads and buildings, and thus can indirectly bring about unexpected significant damage to society. Qian and Lin [26] noted that, although the causes of accidents in tunnel construction vary considerably alongside different projects' distinctive characteristics, the majority can be classified as civil-engineering accidents. The same study divided liability losses from tunnel construction into objective and subjective causes. Examples of subjective causes include poorly chosen construction techniques, project mismanagement, and poor construction performance. Objective ones, on the other hand, include natural hazard-induced losses during construction, such as from heavy rainfall and ground deformation. Qian and Lin [26] further calculated that 30% of tunnel-construction losses by value were due to subjective causes only; 10%, to objective causes only; and the remaining 60%, to a combination of both.

Risk-management activities aimed at enhancing construction safety have long been studied intensively in the United States and Europe [28]. In 2004, the International Tunneling Association promulgated a set of guidelines for tunnel-construction risk management [29], and two years later, the International Tunneling Insurance Group published a code of tunnel-construction practice aimed at mitigating risks and accidents [30]. Mainland China's government has also issued detailed policies for enhancing the risk management of underground construction projects, including but not limited to tunnels, across their design, construction, and operations-and-management stages [26].

Academic risk-analysis and risk-management research that focuses on the mitigation of construction accidents and related damage has adopted both qualitative and quantitative approaches [31]. Its qualitative methods prominently include fault-stress analysis and comprehensive fuzzy evaluation. Its quantitative ones, on the other hand, have included neural networks, support vector machines, and statistical analysis, among others. Studies of tunnel construction per se have sometimes adopted novel technological approaches, such as structural-health monitoring: a technique widely recognized as able to capture the risk to tunnels' structural systems after they have been completed [32]. The primary advantage of structural-health monitoring, which was invented specifically to predict the structural and environmental risks of tunnel construction, is that it automatically monitors the status of tunnels' structural systems in real time [32–34]. Risk-monitoring methodologies have also been enhanced by the accuracy of tunnel-data tracking technologies, notably including radio frequency identification devices, the global positioning system, wireless local area networks, and ZigBee [35–37]. As well as reducing the error levels that are inevitably associated with manual monitoring [38], these information technologies enable monitoring of a wider range of structural elements than humans could ever physically access [39]. Forecasting and prevention of environmental risks to tunnels, such as water inrush, have also been made possible by the emergence of advanced geological-analysis techniques,

including micro-seismic monitoring, as demonstrated by theoretical analysis as well as by laboratory and field tests [40]. According to Shi et al. [40], these systems can be utilized for risk detection and mitigation for entire construction stages.

In addition to simply reducing the incidence of construction accidents and the severity of the damage they cause, construction companies have long sought alternative methods of risk mitigation and allocation. Construction insurance is one approach to covering the costs of accidental and other damage across both the construction and operations-and-management stages, including damage and losses to construction materials and to third-party property in and around the job site [41]. In the absence of appropriate insurance coverage, compensation paid in relation to such damage to third-party property can cause unexpected, sometimes large increases in construction budgets; and this has led some governments, including South Korea's, to mandate the buying of construction insurance by companies that perform certain types of work [17].

In addition to construction-industry and governmental efforts to mitigate the number and severity of construction accidents, the insurance industry itself has developed risk-assessment models for potential construction project-related losses [11]. However, those in-house models are limited in their usefulness, since they are typically derived from narrow ranges of projects and/or particular regions. For example, even though Risk Management Solutions and Applied Insurance Research have developed elaborate loss-estimation models and used them widely for their own business purposes, the applicability of such models to a wider range of construction projects and regions is limited, due not only to the variety of environmental characteristics around construction sites, but also to aleatory uncertainty regarding the intensity and frequency of natural hazards, such as typhoons, earthquakes, and heavy rain in different locations [41,42]. Any inaccurate information or errors in construction-project risk assessment—notably, regarding the vulnerabilities of the built environment—can also increase unexpected construction-budget overruns and delays in construction schedules, in addition to the third-party damages [17].

Various approaches to identifying natural-hazard risk factors have been used, including literature reviews and questionnaire surveys (e.g., Kuo and Lu [43]), rankings based on expert opinions (e.g., Chan et al. [44]), prior natural-hazard data, construction data, and site surveys (e.g., Kim [45]). However, these efforts have not yet produced any consensus about which risk factors are most important even at the site-specific level, let alone the regional level. It is therefore hoped that the present study's adoption of loss data including third-party damages and total construction amounts will help break this impasse and allow for more comprehensive, quantitative tunnel-construction risk management.

2. Research Methods

2.1. Case-Study Approach

Data on 277 cases of damage that occurred during tunnel construction in South Korea between 2004 and 2019 were utilized in the development of this study's quantitative risk-assessment methodology. The analyses used for this purpose included direct and third-party damage, both material damage and accidents involving workers, derived from data provided by an insurance company. For each of the 277 cases, these data included the total amount insured, the actual loss, the construction company's size rank, the total duration of construction, and a natural-hazard indicator score on the Munich Re index. Five of the most common natural hazards—i.e., heavy rain, floods, storm surges, high winds, and earthquakes—were initially adopted as the basis of our determination of the relationship between damage and natural hazards. However, because no surges or earthquakes occurred in the vicinity of the focal construction projects during the 16-year period covered by the loss data, those two variables were eliminated from further consideration.

The insurance-company loss data were used as the dependent variable in our statistical analysis. Specifically, in the hope of obtaining more meaningful findings that were not sensitive to project size, the ratio between the total insured value of the project and actual losses was used in place of actual

losses alone. To establish the relationships between the dependent and independent variables, multiple linear regression analysis was conducted. In the following two subsections, each of those variables and the relevant statistical procedures are described in more detail.

2.2. Data Collection and Management

Table 1 presents all the variables utilized in the present study. High winds, floods, and precipitation were measured on the indexed ordinal scale (zones 1–5) of the Natural Hazard Assessment Network system, according to their incidence/quantity during the construction period at each tunnel-construction site.

Table 1. Data types and sources.

Variable	Description	Unit	Data source
Dependent variable			
Natural log-transformed damage ratio	Actual amount of loss dividend by total insured value of tunnel project	Ratio	Insurance company
Independent variables			
High winds	Maximum sustained wind speed (10 m/s)	Ordinal scale	Natural Hazards Assessment Network
	1: 21–40		
	2: 41–50		
	3: 51–60		
	4: 61–70		
Flooding	Occurrence per year (number of times)	Ordinal scale	Natural Hazards Assessment Network
	1: 0–1		
	2: 2		
	3: 3		
	4: 4		
Rainfall	Amount of precipitation (10 mm/h)	Ordinal scale	Natural Hazards Assessment Network
	1: below 30		
	2: 30–70		
	3: 71–100		
	4: 101–110		
	5: 111–180		

To accurately evaluate and visually express the characteristics of the many types of natural disasters that occur around the world (earthquakes, hurricanes, floods, lightning storms, etc.), various insurance companies have created and used natural-disaster mapping systems. Notable examples include Munich Re's NATHAN, Swiss Re's CatNET[®], and Samsung Fire & Marine Insurance's Global Risk Map. Underwriters can use disaster maps to, for example, recognize the risk of natural disasters to a particular property at a glance, and thus make an accurate risk assessment for it more quickly; while a cumulative-risk manager can not only check the distribution of their company's insured properties through such maps, but also learn about the amounts and types of danger that are associated with particular places in such a distribution. For these reasons, each company strives to make its natural-disaster risk map as accurate as possible. Therefore, in this study, the risk of natural disaster was quantified by borrowing NATHAN from Munich Re, one of the world's major reinsurers. Specifically, data on flood frequency in number of events per year, on wind speed in meters per second, and on rainfall in millimeters per hour at the precise locations of each of the sampled 277 tunnel-construction

projects were collected from NATHAN, because it was the natural-disaster mapping system regularly used by the insurer that cooperated with the researchers.

All three independent variables' raw values were converted into positions on a five-point scale. Specifically, high winds were defined as a score of 3 or above (i.e., at least 51 m/s) on a five-point scale of maximum sustained wind speed at each point. Flooding ranged from 1 = zero or one floods to 5 = five floods or more per year; and rainfall ranged from 1 = 30 mm/h or less, to 5 = 111 mm/h or more.

2.3. Dependent Variable

According to the insurance company that provided the data for the present study, the total insured amount is regarded as the total construction cost of a tunneling project. Initially, damage ratios were expressed as:

$$\text{Damage ratio} = \frac{\text{Actual loss amount}}{\text{Total insured amount}}. \quad (1)$$

As such, the value of a damage ratio approached 0 when the actual loss amount was relatively small compared to total insured amount.

However, the Shapiro-Wilk test, which can verify whether a dependent variable is normally distributed or not, yielded a significance level of 0.00 which, being smaller than 0.05 (Table 1), indicated a non-normal distribution in the initial model. The histogram and Q-Q plot shown in Figure 1 further confirmed this. Therefore, the researchers transformed the damage ratio via natural logarithm (LN) to resolve these issues, as shown in Equation (2):

$$\text{Transformed damage ratio} = \text{LN} \left(\frac{\text{Actual loss amount}}{\text{Total insured amount}} \right). \quad (2)$$

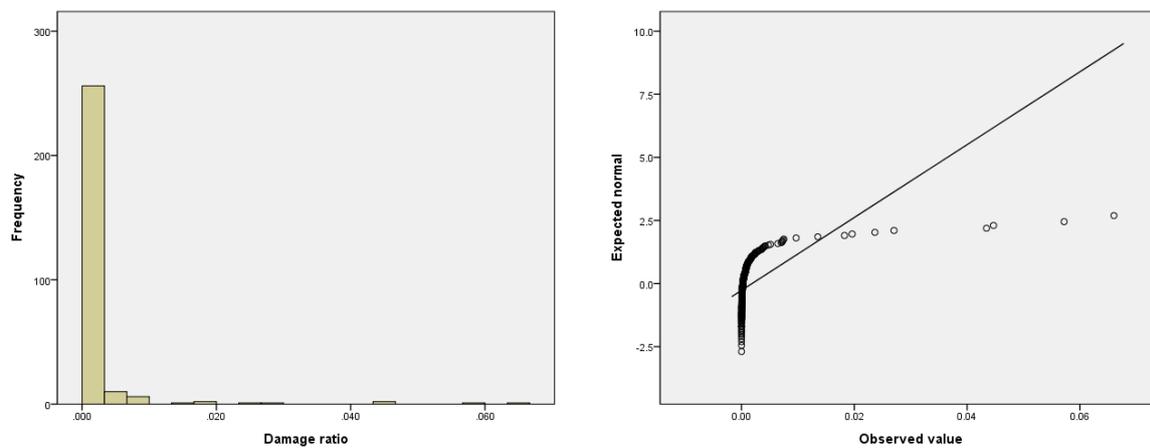


Figure 1. Histogram and Q-Q plot, normality test of initial damage ratio.

As a result of the LN transformation, the range of the damage ratios changed, as can be seen in Figures 1 and 2. That is, the non-transformed ratios are depicted on the x-axis of the former figure, and the LN-transformed ones on the x-axis of the latter one.

As can be seen in Figure 1, the normality of the initial dependent variable appeared to be excessively left-leaning. After LN transformation, the dependent variable's Shapiro-Wilk significance value was 0.256, i.e., larger than 0.05, showing that the transformed damage ratio followed a normal distribution (Table 2). This result was also then confirmed via the histogram and Q-Q plot illustrated in Figure 2.

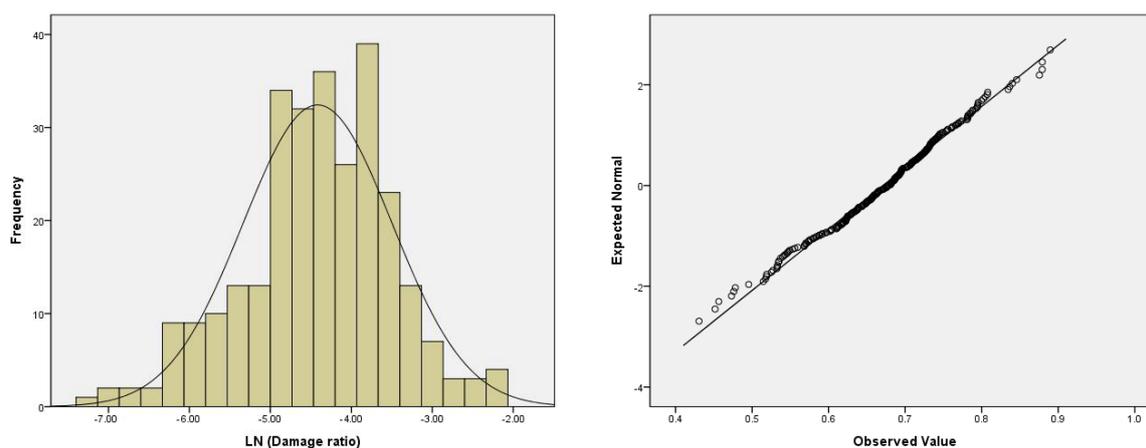


Figure 2. Histogram and Q-Q plot, normality test of natural log-transformed damage ratio.

Table 2. Shapiro-Wilk normality tests of damage ratios.

	Statistic	df	Significance
Initial Damage Ratio	0.259	281	0.000
Natural Log-transformed Damage Ratio	0.989	241	0.256

2.4. Independent Variables

In a period without any major earthquakes, typhoons are likely to be the cause of the most serious damage to construction projects and infrastructure systems in East Asia [11]. The intensity of typhoons can be measured by a variety of characteristics, including but not limited to their wind speed, radius, motion speed, and angle of approach to the coastline. Among these, maximum sustained wind speed is usually used as the key factor for measuring typhoons' intensity [46–48].

Our statistical analyses' independent variables, and their site- and time-specific values, were adopted from the records of an insurance company that used Munich Re's 2019 NATHAN risk map to rank construction sites' risk exposures. Each of the focal sites' risk was therefore represented as a rank, from 1 = very low to 5 = very high. As noted above, precipitation, floods, high winds, earthquakes, and storm surges were initially adopted as the independent variables/natural hazard indicators, though in the event, only the first three of them were actually utilized. The critical importance of these three remaining risk factors to construction activities has been emphasized by numerous studies, including those that adopted a lifecycle-costs perspective [49–51].

NATHAN depicts natural-disaster trends based on recorded data from all over the world, and offers a quick and user-friendly means of assessing the risk of events such as typhoons, storm surges, and earthquakes at any desired location.

3. Results

3.1. Descriptive Statistics

Descriptive statistics of the dependent and independent variables are presented in Table 3.

3.2. Multiple Regression Analysis

Multiple regression analysis helps researchers to understand the tendencies of their collected variables. The results of the present study's multiple linear regression analysis are presented in Tables 4 and 5. Analysis of variance (ANOVA) showed that the present research's regression model was

statistically significant, as its significance level of 0.007 was smaller than 0.05. Also, as can be seen in the *P-P* and scatter plots in Figure 3, the multiple linear regression model was normally distributed. Additionally, the scatter plot of the residuals shows a variance that is constant and normally distributed, indicating that the linear regression model is homoscedastic.

Table 3. Descriptive statistics for all variables.

Category	N	Mean	SD
Dependent Variable			
Damage ratio	277	0.002	0.007
Independent Variables			
High winds	277	4.769	0.549
Flooding	277	1.487	0.501
Rainfall	277	1.935	1.092

Note. SD = standard deviation.

Table 4. Summary, analysis of variance and multiple regression modeling results.

	Sum of Squares	df	Mean Square	F	Sig.	Adjusted R ²
Regression	364.69	4	92.673	31.366	0.007	0.317
Residual	790.63	272	2.907			
Total	1150.32	276				

Note. Df = degree of freedom.

Table 5. Coefficients of multiple regression analysis.

Variable	Non-Standardized Coefficient	Standardized Coefficient	Significance Probability (<i>p</i> -Value)	Collinearity (VIF)
High winds	0.649	0.163	0.007 *	1.017
Rainfall	0.180	0.505	0.309	1.010
Flooding	0.094	0.051	0.292	1.011

Note. VIF = variance of inflation factor; * $p < 0.05$.

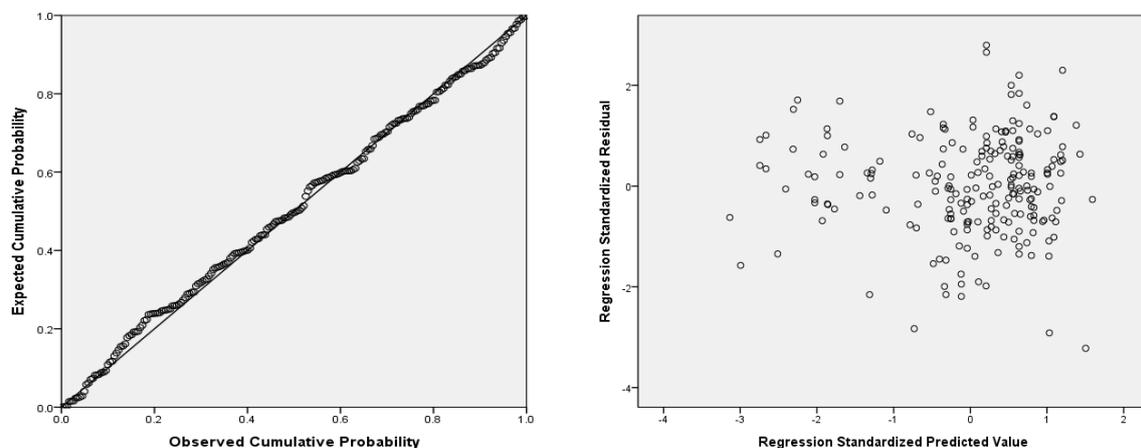


Figure 3. *P-P* and scatter plots of standardized residuals from regression analysis.

R^2 coefficients of determination are used to measure variance and correlations among the independent variables used in linear regression. Specifically, they allow us to determine how well the model describes the collected actual data. the closer the value of R^2 approaches to 1, the better the predictive power of the model. Our model's adjusted R^2 was 0.317, with $F = 31.366$, meaning that 31.7% of the damage ratios could be explained by the linear regression model's three natural-disaster indicators.

Next, variance of inflation factor (VIF) was utilized to determine whether there was multi-collinearity among the independent variables. the larger its VIF is, the more likely an independent variable is to be largely dependent on one of the others: i.e., not meaningfully independent. In this study, the VIFs were 1.010 for rainfall, 1.011 for flooding, and 1.017 for high winds: all well below 10, the threshold above which they should be excluded from analysis as collinear.

The regression model in Equation (3) presents the natural-hazard predictors as the straight prediction trend-line of the analyzed data. In the present study, the line from the equation can be used to estimate the relationship between the dependent variable and the independent variables, and the LN-transformed damage ratio can be established from the non-standardized regression coefficients of each independent variable.

$$\text{LN (Damage ratio)} = \alpha + \beta_1 * X_1 + \beta_2 * X_2 + \beta_3 * X_3, \quad (3)$$

- α : Constant;
- β_1 : Slope of high wind speed;
- β_2 : Slope of flooding;
- β_3 : Slope of rainfall.

The non-standardized coefficients in Table 5 can be utilized to predict the extent of damage ratios according to the variance in the natural hazard indicators. the researchers interpreted the non-standardized coefficients of the independent variables in their regression model as follows. First, high wind speed's non-standardized coefficient was 0.649, which implied that when the ordinal scale for wind increased by 1, the LN-transformed damage ratio increased by 64.9%. Second, the non-standardized coefficient for rainfall was 0.180, implying that the LN-transformed damage ratio would increase by 18% if the ordinal scale for rainfall increased by 1. Lastly, flooding's non-standardized coefficient, 0.094, meant that when this variable's ordinal scale increased by 1, the LN-transformed damage ratio increased by 9.4%.

The significance probabilities (p -values) indicated that, among the independent variables, only high winds had a significant effect on damage ratios at a confidence interval of 95%. However, absolute standardized coefficients, utilized to determine which factor had the most influence on the dependent variable, indicated that rainfall (0.505) had the largest such effect, followed distantly by high winds (0.163) and flooding (0.051). From this, it can be concluded that, of these two meteorological factors and one natural-hazard impact, rainfall affected the 277 sampled South Korean tunnel-construction projects most severely.

4. Discussion

Natural disasters are well known to have a range of negative impacts on economies, societies, and the environment at both national and local levels [52–55]. However, previous studies that have calculated the magnitudes and costs of damage arising from natural disasters have not thoroughly explored the correlations among actual financial losses and the multiple specific causes of damage within a 'single' disaster [56–58], e.g., wind, rain, and floods within a typhoon.

The current study's multiple linear regression modeling, which used insurance-company payout data pertaining to direct and third-party damage in the contexts of 277 South Korean tunnel-construction projects, yielded an adjusted R^2 value of 0.317, indicating that 31.7% of the variance in LN-transformed

damage ratios could be ascribed to two meteorological impacts and one natural-disaster impact. the other 68.3% of such variance could not be explained by these three independent variables.

Previous research has indicated that natural hazards have significant negative effects on the construction projects [43,59]. Shin et al. [60] reported that the movement speed and direction of typhoons were the main reasons for the damage they caused to properties on the Korean Peninsula. Kim et al. [61] indicated that typhoon-induced wind storms caused serious damage to commercial buildings, and Kim et al. [11] reported that distance from the shoreline and wind speed were both closely related to the damage suffered by residential buildings during typhoons. In addition to directly wind-induced damage, Ryu et al. [62] pointed out that flooding was a main reason for damage-related losses in bridge construction, and Ahn et al.'s [17] results supported this. According to Choi [63], the Korean Peninsula's geomorphological characteristics expose it to ongoing risk of damage from typhoon-induced high winds and rainstorms. Kim et al. [64] conducted vulnerability-functions analysis of various types of buildings in South Korea and found, based on wind information from historical typhoons that had struck the country, that windstorms were the most serious cause of financial losses to properties there. In short, previous studies have broadly concurred that, in the South Korean case, typhoons—and in particular, typhoon winds—are the most significant damage factor for both existing buildings and for construction sites.

In the current study, insurance-claim payout data and total insured amount data were both utilized to determine the relationship between South Korean tunnel constructors' financial losses and three natural-disaster indicators. Its findings concretize the previous findings discussed above, by providing correlations between financial loss, on the one hand, and on the other, high wind speed and rainfall. Its finding that maximum wind speed was significantly correlated with financial losses lends support to prior studies that reported wind speed as the main reason for natural disaster-induced losses to infrastructure systems [52,53]. Therefore, it can be concluded that wind speed is a useful variable in the prediction of financial losses during tunnel construction in South Korea. However, the fact that rainfall was found to have the largest impact on LN-transformed damage ratios also tends to confirm previous findings by Shi et al. [40] regarding the importance of this factor in tunnel-construction scenarios.

Identifying the factors related to natural disasters that most strongly influence financial losses in tunnel construction should be a priority for those seeking to mitigate unexpected losses. the present paper's findings thus constitute an important contribution to the ability of construction projects of this type to prepare for and cope with natural extreme events. These findings also provide an opportunity to enhance the operations-and-management stage of current lifecycle-cost assessment of building and infrastructure systems, which is the costliest stage when their entire lifecycles are taken into consideration [65]. Looking beyond construction projects, it will also be worth considering the opportunity cost of preparation for potential natural disasters in extremely disaster-prone areas.

Various stakeholders, including the insurance industry, the construction industry, and governments, could also benefit from referring to the present study's findings. Specifically, construction companies can utilize the results of this study to help them estimate potential losses from natural disasters and thereby reduce unexpected construction costs and scheduling delays. a clearer understanding of the natural-hazard risk factors in tunnel-construction projects can also help inform their structural designs, emergency/rescue plans, and recovery plans. Additionally, monitoring facilities or construction projects that are vulnerable to known risk factors can help with effective construction management. Together, all these efforts can ultimately reduce the losses, including those from indirect damage, that may occur during construction.

Insurance companies can benefit from this study, in particular by utilizing the results to reflect risk indicators in their business models for reducing financial losses, maximizing their profits, estimating the maximum losses from natural hazards, and setting appropriate premiums. This contribution to premium-setting is perhaps especially important, given that premiums are usually estimated based on catastrophe-risk modeling. In short, business continuity planning reflecting the risk variables

identified in this paper should help insurance companies' clients mitigate their losses from unexpected risk exposures at construction sites.

Last but not least, governments can utilize the results of this research in their efforts to strengthen their regulations and laws about structural-design standards, with the wider aim of mitigating the potential risks to large construction projects from natural disasters in windstorm-prone areas. Also, they can enhance their current restoration and resilience plans based on the identified risk factors. Such plans, in turn, can reduce the levels of business disruption to construction companies and other stakeholders caused by the natural disasters, and thus could ultimately result higher tax revenues. Advanced risk management reflecting natural-hazard indicators should be conducted regularly by governments in response to climate change and intensified natural disasters, as it will allow more effective risk-mitigation planning that enhances the safety of whole communities.

The statistical-analysis approach developed in the present paper could be applied in any high wind-prone area around the world, provided that a reasonable quantity of reliable wind and damage data are available. Also, its use of actual losses and total insured amounts could reasonably be extended beyond tunnel construction, to improve the validity of the data and analyses in catastrophe-risk management for other types of construction projects.

5. Conclusions

Tunnels, which are critically important to the enhancement of existing transportation networks and the creation of effective new ones, require advanced and sustainable risk assessment and management, especially given the increasing frequency and unprecedented magnitude of natural disasters in recent times. The present study's analysis of the relationship between financial losses by 277 South Korean tunnel-construction projects and three types of natural hazards between 2004 and 2019 concluded that high winds during typhoons represented a significant loss factor. In addition to this and other specific findings, the present study fills a methodological gap in the existing research, lying between the known causes of damage during construction and theoretical damage estimation, using a novel quantitative approach and empirical financial-loss data. Even though this research only focused on tunnel construction in South Korea, its findings support those of previous studies conducted in other contexts, that typhoon-induced maximum wind speed is the key factor in damage to buildings and infrastructure systems [46–48]. In future research, the set of three natural-hazard indicators used in the present study could usefully be expanded, as part of a search for detailed causal relationships between types and levels of damage sustained during tunnel construction, on the one hand, and particular aspects of natural disasters, on the other. As noted above, the present research's methodology is also likely to be generalizable to insurance-industry and construction-industry risk management for infrastructure systems other than tunnels, and could be useful to governments during the creation of transportation-network and disaster-resilience plans.

Future research of this kind should include additional tunnel-construction project information, such as the type of structural system and materials used, and the features of the surrounding built environment, to enhance the accuracy of its prediction models. Additionally, damage data from multiple insurance and construction companies should render the results of such research more fruitful, by enabling deeper understanding of natural-hazard risks to construction projects of a wide range of types and scales.

Natural hazard-induced damage in tunnel construction may cause direct damage such as collapses, as well as indirect costs such as business interruption and construction delays. Even though the present research included third-party damage as a component of indirect damage, it is also important to consider indirect losses borne by tunnel-construction stakeholders themselves, if a comprehensive picture of losses related to natural extreme events is to be arrived at.

The present paper's methodology could also be usefully extended to the development of rapid post-disaster restoration plans, to reduce indirect damage to tunnel construction projects and make tunnels more sustainable. For instance, heightened awareness of natural-hazard risk indicators can

serve to usefully mitigate risk in hurricane-prone areas where tunnel construction is planned. Over the long term, identifying more key risk variables for tunnel construction should be able to inform advanced risk assessments that are capable of coping with the effects of climate change.

The achievement of sustainable tunnel construction, however, will also require comprehensive consideration of the social, environmental, and economic impacts of natural hazards, and should include whole-lifecycle assessment. Even though the present research did not consider tunneling-site-specific geographical, environmental, or economic factors, future researchers should consider incorporating those factors into their risk assessments and loss predictions. Likewise, weighting factors for various geological characteristics should be taken into consideration. To enhance the accuracy of future statistical results, both meteorological and built-environment characteristics of regions—e.g., distance of buildings from waterways, and hurricane movement direction—should also be taken into consideration, as a means of expanding the present methodology's fields of application.

Fragility or vulnerability functions could also be incorporated alongside natural-disaster indicators when estimating financial losses. Such statistical analysis could increase the accuracy of such estimation by making it more sensitive to the intensity of the natural disaster. Lastly, advanced statistical-analysis techniques such as Monte Carlo simulation and deep learning should be applied to the estimation of long-term trends in certain natural hazards such as typhoons and earthquakes, as a key element of sustainable risk management. In sum, although the data utilized in the present research were limited, the three selected natural-disaster factors were shown to be capable of illuminating variation in tunnel-construction financial losses, and the developed methodology shows considerable promise.

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