Development of seismic fragility functions for korean railway box structures based on finite element numerical analysis

Y. Lee
Gachon University, Seongnam, Republic of Korea, dldbtjd0704@gachon.ac.kr

M. Yoo
Gachon University, Seongnam, Republic of Korea, mintaekyoo@gachon.ac.kr

J. Han
Korea Institute of Civil Engineering and Building Technology (KICT), Goyang, Republic of Korea, jimmyhan@kict.re.kr

J. Kim
Korea Institute of Civil Engineering and Building Technology (KICT), Goyang, Republic of Korea, jongkwan@kict.re.kr

H. Song
Gachon University, Seongnam, Republic of Korea, thdgusals12@gachon.ac.kr

J. Jeon
Gachon University, Seongnam, Republic of Korea, jiyunjeon@gachon.ac.kr

ABSTRACT: In this study, a two-dimensional finite element model was developed using OpenSees to assess the seismic performance of an underground railway box structure considering ground conditions representative of those in Korea. The geometry and dimensions of the underground box structure were defined based on the design plans of a cut-and-cover concourse commonly used in Korea, and, using the developed model, seismic fragility function were proposed through analysis of the structure's dynamic behavior across Korean soil classifications. As a result, the dynamic response characteristics of the structure varied under different conditions, and it was found that the structure became more vulnerable to earthquakes as the depth from the ground surface to the bedrock increased and the soil stiffness decreased.

1 INTRODUCTION

In recent years, Korea has experienced the 2016 Gyeongju earthquake (M 5.8) and the 2017 Pohang earthquake (M 5.4), while large-scale earthquakes such as the 2023 Türkiye earthquake (M 7.8) and the 2025 Philippines earthquake (M 6.9) have also occurred worldwide. The occurrence of such earthquakes has heightened public awareness of seismic hazards across all sectors of society, leading to a rapid increase in interest and research demand for earthquake prevention and mitigation technologies. Owing to their location within the ground, underground structures have generally been regarded as relatively safe against earthquakes compared to surface structures (Kim et al., 2023). However, several case studies have reported that underground structures suffered significant damage during real earthquakes, depending on factors such as ground conditions, embedment depth, and soil–structure interaction (SSI) (Hashash et al., 2001). In particular, the seismic response of underground structures is more strongly influenced by the dynamic properties of the surrounding soil than by the characteristics of the structures themselves, making the soil conditions a dominant factor governing structural behavior (Park et al., 2024).

Accordingly, extensive research has been actively conducted to enhance the seismic performance of underground structures. Tian et al. (2020) analyzed the dynamic behavior of tunnels with embedment depths ranging from 2.0 m to 4.0 m in 0.5 m intervals to investigate the effect of structural depth on tunnel performance. Kechidi et al. (2021) pointed out that many conventional seismic design approaches neglect soil–structure interaction (SSI) and site amplification effects, which can lead to an overestimation of the actual seismic response of structures. To address this, they developed a model capable of implementing SSI based on realistic soil properties. Asheghabadi et al. (2019) analyzed the influence of underground structures on seismic wave amplification and attenuation by comparing the analytical results between a free-field model and a model including underground structures. Argyroudis et al. (2012) numerically derived seismic fragility curves to quantitatively assess the probability of damage for underground structures that are essential to urban transportation networks. Although numerous studies have actively investigated the dynamic behavior of underground structures and their complex interactions with surrounding soils, numerical models that sufficiently reflect Korean ground conditions—with relatively shallow bedrock depths compared to those in other countries—are still limited. Such limitations can act as factors that increase uncertainty in the seismic design and safety evaluation of underground structures in Korea.

Accordingly, in this study, a two-dimensional numerical model suitable for Korean ground conditions was developed using the finite element analysis program OpenSees(McKenna et al., 2011), and seismic fragility functions were derived based on the model considering different Korean soil classifications.

2 NUMERICAL MODELING AND ANALYSIS CONDITIONS

2.1 Soil Modeling

The numerical modeling in this study was conducted using two-dimensional finite element analysis (FEM). To improve computational efficiency while considering the soil nonlinearity and to minimize the influence of reflected waves, the two lateral boundaries of the model were connected using equal degrees of freedom (EDOF). The soil domain was modeled with a width of 80 m and a height of 40 m, and was discretized using four-node quadrilateral (Quad) elements with two degrees of freedom per node. The element size was set to 1 × 1 m to avoid unrealistic responses, based on the method proposed by Kuhlemeyer and Lysmer (1973), as expressed in Equation (1). Here, ΔL is the element length, Vs is the shear wave velocity, and f is the maximum effective frequency of the input seismic wave.

$$\Delta L \leq \frac{\lambda}{8{\sim}10}, \lambda = \frac{V_s}{f} \quad (1)$$

The soil material was modeled using the PressureDependMultiYield (PDMY) constitutive model (Yang et al., 2016), which exhibits elastoplastic characteristics to simulate the nonlinear behavior of soils. The shear wave velocities of the soil layers were set to 360 m/s for weathered soil and 150 m/s for reclaimed soil (Kwon et al., 2024), and the corresponding detailed input properties are summarized in Table 1. The rock layer was also modeled using the same quadrilateral (Quad) elements as the soil, and was assigned an ElasticIsotropic(Mazzoni et al., 2007) material representing weak rock with a shear wave velocity of 800 m/s, as summarized in Table 2.

Table 1. Input Parameters for PDMY Model

Parameters	Vs=360m/s	Vs=150m/s
Soil density, ton/m^3	2.0	1.7
refShearModul, Kpa	259,200	38,250
refBulkModul, Kpa	432,000	146,625
FrictionAng, degree	37	29
PeakShearStra	0.1	0.1
refPress, Kpa	312.44	255.32
PressDependCoe	0.5	0.5
PTAng, degree	27	29
contrac	0.03	0.21
diliat1	0.8	0
diliat2	5	0
liquefac1	0.0	10
liquefac2	0.0	0.02
liquefac3	0.0	1.0

Table 2. Input Parameters for Rock

Vs(m/s)	Unit Weight (KN/m^3)	Poisson's ratio	Elastic Modulus (KN/m^2)
800	23	0.2	3,600,000

2.2 Modeling of the Underground Box Structure

The underground box structure was modeled based on the actual cut-and-cover concourse commonly used in Korea, as illustrated in Fig. 1. The structure was defined with a width of 14 m, a height of 8 m, and a wall thickness of 1 m, and was modeled as a reinforced concrete box section. The structural components were modeled using DispBeamColumn(Mazzoni et al., 2007) elements, which can account for the nonlinear material behavior as well as axial and flexural responses of the section. The material properties assigned to each element are summarized in Table 3. In addition, ZeroLengthContactASDimplex(Oliver et al., 2008) elements were applied along the interface between the structure and the surrounding soil to realistically simulate the frictional behavior at the contact surface.

Table 3. Input Parameters for Each Structure Element

Element type	Beam
Elastic modulus of concrete (Mpa)	26,950
Unit weight (KN/m^3)	25
Element Area (m^2)	1
Moment of Interia (m^4)	0.083

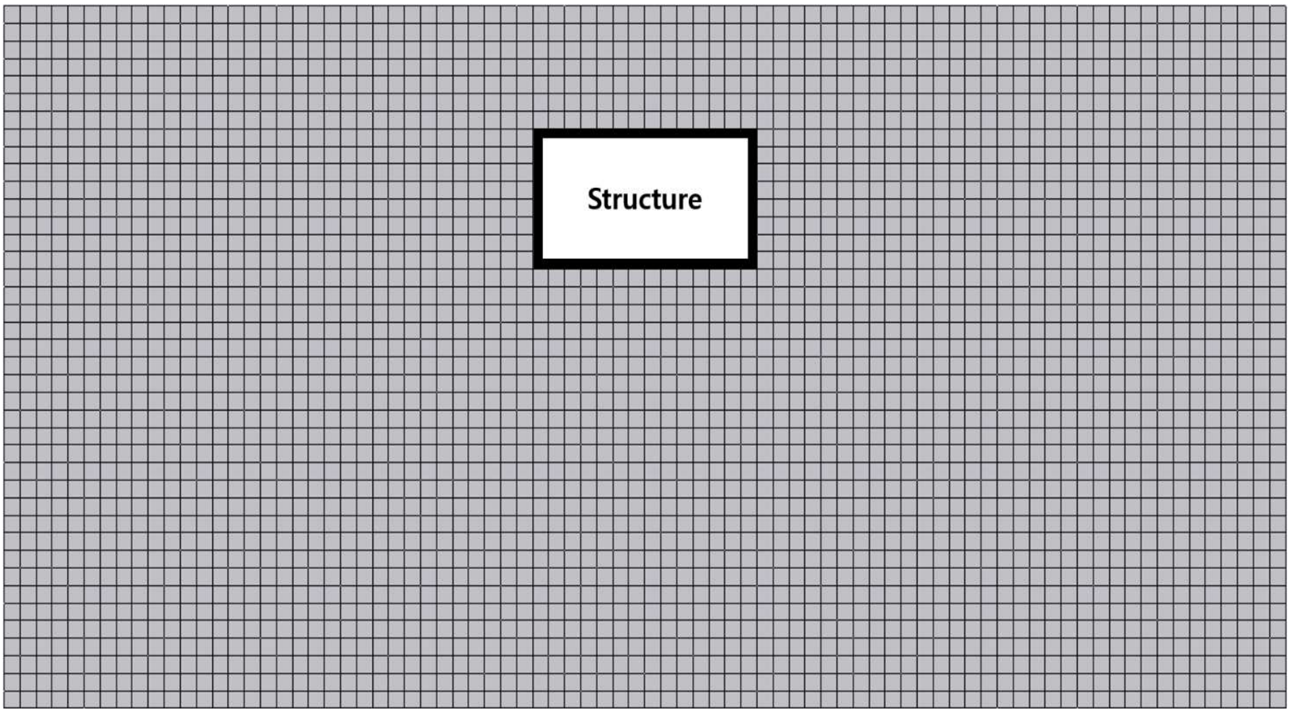

Figure 1. Cross-Section of Soil-Structure Modeling

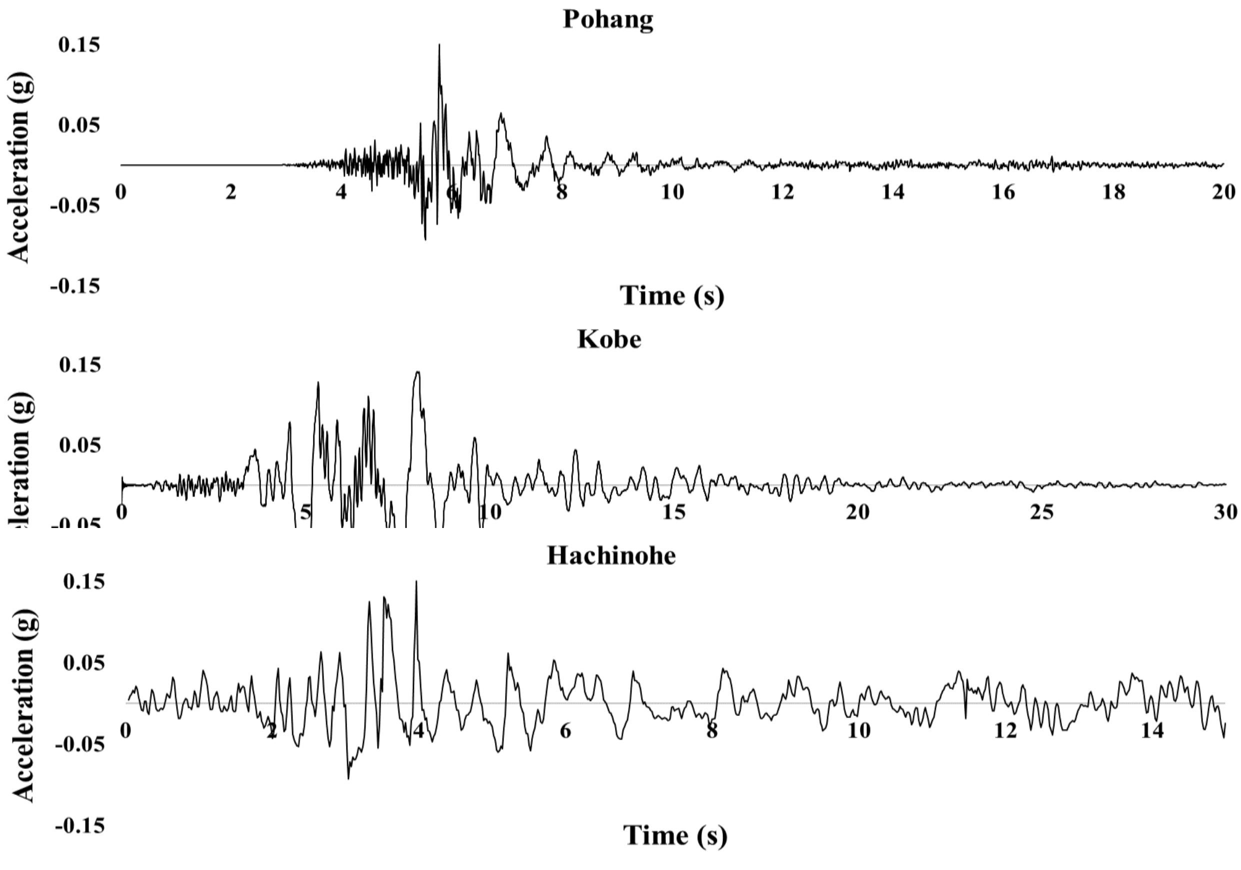

Figure 2. Input ground motions corresponding to a 1,000-year return period

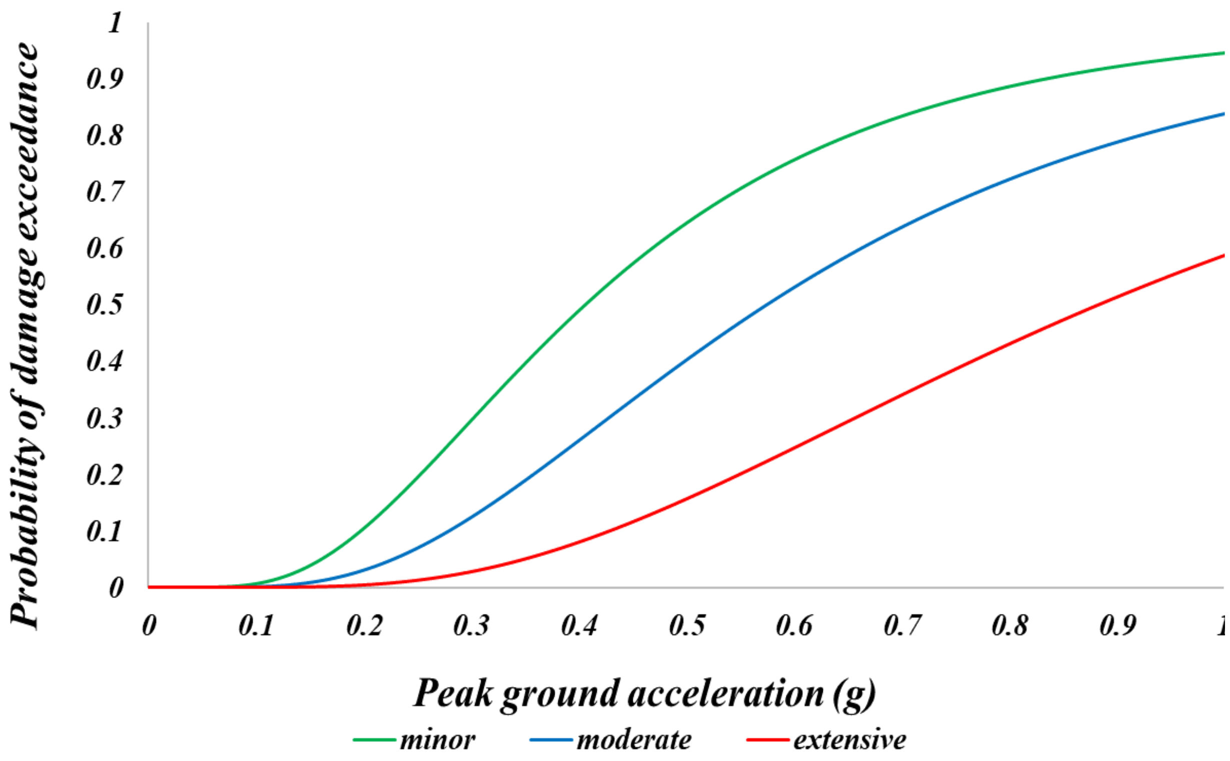

Figure 3. Seismic fragility functions for case 1

2.3 Analytical Cross-Section

For the analytical cross-section, the Korean seismic design code (KDS 17 10 00) was referenced to propose a model representative of domestic ground conditions. For the analysis of dynamic characteristics according to Korean ground conditions, the embedment depth of the structure was uniformly set to 7m. The effects of soil stiffness and the depth to bedrock are analyzed by reflecting the ground conditions from S2 to S5, as shown in Table 4.

Table 4. Analysis Cases under Different Conditions

Case No.	Vs(m/s)	Depth to Bedrock (m)
Case 1	360(S2)	15
Case 2	150(S3)	15
Case 3	360(S4)	30
Case 4	150(S5)	30

2.4 Input Ground Motions

Since the model was constructed to represent Korean ground conditions, the 2017 Pohang earthquake recorded in Korea was adopted as the input ground motion. In addition, the Kobe and Hachinohe earthquake records were also employed to reflect a wider range of frequency and amplitude characteristics of ground motions. The time–acceleration histories of each earthquake corresponding to a 1,000-year return period are shown in Fig. 2. Using the three selected ground motions, scaling was performed from 0.05 g to 0.8 g, and a total of 48 scaled records were applied at the base of the model to conduct dynamic analyses.

3 DEVELOPMENT OF SEISMIC FRAGILITY FUNCTIONS

3.1 Methodology for the development of seismic fragility functions

This section describes the procedure used to derive seismic fragility functions from the results of the dynamic numerical analyses. For underground box structures, the damage index has been defined as the ratio between the maximum moment applied to the structure and the yield moment of the structure (Argyroudis and Pitilakis, 2012; Kwon et al., 2024). Furthermore, this study adopts the existing fragility assessment methodology for box structures to analyze the seismic fragility trends based on Korean ground conditions. Accordingly, in this study, to represent the damage states for each case, bending moments were derived at the vulnerable corner points of the underground box structure. The maximum bending moment among these values was used as the reference to calculate the four-level damage index (DI) using the method in Equation (2) as described by Park et al. (2016). Here, M represents the maximum measured moment, and M_y denotes the yield moment of the structure. The damage states were classified into three levels, ranging from minor to extensive damage, as summarized in Table. 5.

Table 5. Input Parameters for Each Structure Element

Damage state	Damage index
None	$DI < 1.0$
Minor/Slight	$1.0 \leq DI < 1.4$
Moderate	$1.4 \leq DI < 2.3$
Extensive	$2.3 \leq DI$

$$DI(Damage\ index) = M/M_y \qquad (2)$$

$$P_f(ds \geq ds_i|S) = \Phi(\frac{ln(IM/IM_{mi}}{\beta_{tot}}) \qquad (3)$$

$$ln(DI) = a \cdot ln(PGA) + b \qquad (4)$$

The seismic fragility was developed based on the damage indices derived for each case. PGA is the most commonly used intensity measure for developing seismic fragility curves of underground structures (Nguyen et al., 2019). Therefore, in this study, PGA was used as the seismic intensity measure for the seismic fragility assessment of underground structures, based on previous research. The seismic fragility function used defines the cumulative analysis results according to the input acceleration, following the linear regression methodology of (Argyroudis and Pitilakis, 2012), with the maximum peak ground acceleration - exceedance probability being defined as a lognormal distribution function with respect to the maximum peak ground acceleration, as shown in Equation (3) below. The linear regression equation represents the relationship between PGA and DI as a linear function, defined as shown in Equation (4). Here, a is the slope of the regression line, and b is the intercept. Using this method, the damage probability can be predicted based on PGA. Notably, even in the absence of observed damage, the extrapolation of the linear regression equation allows for the derivation of the seismic fragility function. In other words, even when no damage occurs, the calculation of exceedance probability enables the evaluation of seismic fragility for underground structures.

In the above equation, P_f represents the probability of exceeding a specific damage state (ds) for a given ground motion intensity, and the peak ground acceleration (PGA) was used as the intensity measure in this study. Φ denotes the standard normal cumulative distribution function, and IM_{mi} represents the median value of the intensity measure (IM) that causes the i-th damage state. The total lognormal standard deviation, β_{tot}, was derived as shown in Equation (5). β_D represents the uncertainty associated with ground motion. The value of β_{ds} was set to 0.4 according to the HAZUS guidelines for buildings, while β_c was assigned a value of 0.3 based on engineering judgment (Argyroudis and Pitilakis, 2012). The definition of β_tot serves as an example from previous studies that derived fragility functions for underground structures. Using the same method, this study aims to derive seismic fragility functions and examine the variation trends of the fragility functions under the shallow bedrock conditions of Korean ground.

$$\beta_{tot} = \sqrt{\beta_D^2 + \beta_{ds}^2 + \beta_c^2} \qquad (5)$$

3.2 Suggested seismic fragility functions

The seismic fragility function for Case 1 is shown in Fig. 3, and the median peak ground acceleration μ corresponding to a 50% probability of damage, as well as the standard deviation β, for each case is presented in Table. 6. First, when comparing Cases 1 and 2, as well as Cases 3 and 4, it was found that even with the

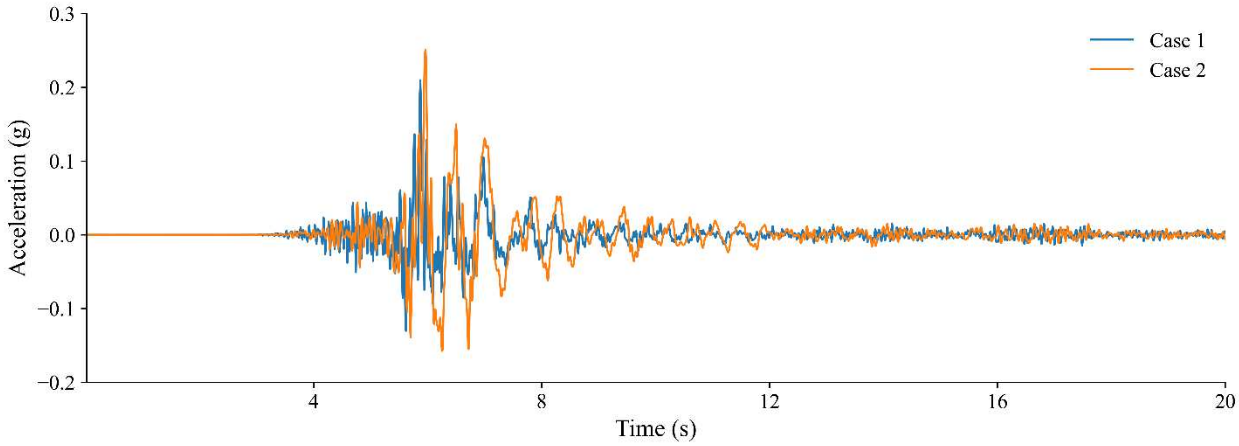

Figure 4. Comparison of site response results for Case 1 and Case 2 under the Pohang earthquake (0.15 g)

Table 6. Seismic fragility parameters for each case

Case	μ (g)			β
	Minor	**Moderate**	**Extensive**	
Case 1	0.406	0.575	0.885	0.563
Case 2	0.315	0.446	0.685	0.557
Case 3	0.372	0.547	0.879	0.518
Case 4	0.287	0.400	0.603	0.514

same depth to bedrock, the structure became more vulnerable as the soil stiffness decreased. The higher fragility of structures on soft ground is attributed to the amplification of surface acceleration during seismic excitation and the shift of dominant response frequencies toward lower frequency ranges compared to those on stiffer soils. Fig. 4 presents the site response analysis results for the Pohang earthquake (0.15 g) for Case 1 and Case 2. In Case 2, where the ground stiffness is reduced, clear amplification of the seismic motion and a shift of the response toward lower-frequency components are observed. Since the seismic behavior of underground structures is predominantly governed by the surrounding ground response, such phenomena are considered to have a more detrimental effect on structural performance. In other words, even under earthquakes of identical intensity, the ground response varies depending on ground stiffness, which in turn leads to significant differences in the dynamic response of underground structures. On the other hand, when comparing Cases 1 and 3 as well as Cases 2 and 4, it was observed that the structure tended to become more vulnerable as the depth to bedrock increased. This is because, as the thickness of the soil layer increases, the travel time of the seismic waves becomes longer, resulting in larger amplitudes and greater relative deformations. Overall, the results indicated that the S2 ground, which is shallower and stiffer, exhibited the highest seismic stability, whereas the S5 ground, which is deeper and softer, was the most vulnerable to earthquakes. To verify the reliability of the numerical analysis results obtained in this study, a comparative analysis was conducted with the results of a previous study (Kwon et al., 2024). In the previous study, a rectangular cut-and-cover underground structure with a width of 22 m and a height of 10 m, representative of Korean conditions, was modeled, and the same Hachinohe earthquake record used in this study was applied. Accordingly, the dynamic responses of the section with an embedment depth of 6 m in the previous study, which is structurally most comparable, were compared with those of Case 1 and Case 2 in this study under the Hachinohe earthquake scaled to 0.4 g. The previous study reported that Minor damage occurred under shallow and stiff ground conditions, whereas Moderate damage occurred under shallow and soft ground conditions. In this study, the damage index of Case 1 was calculated as 1.07, corresponding to Minor damage, while Case 2 exhibited a damage index of 1.87, indicating Moderate damage. Although there are differences in the detailed structural dimensions and numerical modeling approaches between the two studies, the damage levels obtained show overall similar trends. This comparison confirms that the proposed numerical model in this study reasonably captures the seismic response characteristics of cut-and-cover box-type underground structures.

4 CONCLUSIONS

In this study, a two-dimensional finite element model was developed to evaluate the seismic performance of an underground box structure representative of Korean ground conditions characterized by shallow bedrock depth.

The soil was modeled using the PDMY material to simulate nonlinear behavior, and detailed physical properties were assigned according to the soil stiffness. The underground box structure was modeled using two-dimensional beam elements. In addition, ZeroLengthContactASDimplex elements were used to simulate realistic frictional behavior between the structure and the surrounding soil. Furthermore, based on the developed model, the dynamic behavior—specifically the bending moment—of the box structure was analyzed under 48 input ground motions for each case, and seismic fragility functions were proposed accordingly.

To analyze the trends according to the ground conditions, the embedment depth of the structure was uniformly set to 7 m, and the analysis results are presented as follows. First, the S2 ground, which is shallower and stiffer, was found to be the most stable under seismic loading. This can be interpreted as being due to the relatively high soil stiffness and the smaller thickness of the soil layer, which resulted in a reduced amplification of seismic waves. In contrast, the S5 ground, which is deeper and softer, was found to be the most vulnerable to seismic loading. This was interpreted as being due to the lower soil stiffness and greater thickness of the soil layer, which increased the travel time of seismic waves and caused stronger amplification. In addition, the shift toward lower-frequency components of the seismic waves resulted in more critical effects on the structure.

This study derived seismic fragility using PGA by inputting earthquake waves of various magnitudes and frequencies through a 2D finite element model of box structures reflecting the ground conditions in South Korea. However, the study analyzed a model with a uniform embedment depth of 7m for the structures, which has the limitation of not reflecting the characteristics of the actual heterogeneous ground. In the future, the validity of fragility curves using various seismic intensity measures such as PGV and PGV/Vs30 should be examined, and a more refined numerical analysis model should be developed by incorporating more specific ground conditions and variables such as different structure embedment depths.

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