Evaluation on Seismic Enhancement Effect of Ground Improvement for Existing Box Culvert

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概 要

The collapse of Daikai station of Kobe subway during the 1995 Hyogoken-Nanbu earthquake exhibited that underground structures are also at high risk of earthquake with shallow overburden. In this paper, in order to find an optimum ground-improvement pattern for rectangular-shaped box culvert constructed in soft ground that does not meet the present seismic requirement, numerical analysis with nonlinear 3D dynamic finite element analysis are conducted. Different patterns of the ground improvement for the rectangular-shaped box culvert constructed with cut-and-cover method are investigated and finally an optimum ground-improvement pattern is proposed by the numerical analysis. In the numerical analysis, the structural and physical quantities of the box culvert considered are taken from the Daikai station. Additionally, in the 2D/3D dynamic analyses, the ground is composed of Toyoura sand, typical clean sand, and its nonlinear mechanical behavior is described by Cyclic Mobility model. Validity of the proposed numerical method is firstly confirmed with 1g shaking table test and then the numerical analyses are conducted to find the optimum pattern for the ground improvement.

Keywords：Box Culvert, Ground improvement, Numerical analysis

1. INTRODUCTION

Underground structures consist of the major parts of the infrastructure of modern society and play an important role in its development. In the design of underground structures, it was considered that underground structures are in minimum seismic risk in comparison to the aboveground structures. The collapse of Daikai station in the Kobe subway system during the 1995 Hyogoken-Nanbu earthquake exhibited that underground structures are also at high risk of earthquake especially those are constructed in soft ground with thin overburden. Thereafter, the failure of the Bola tunnel in 1999 Turkey earthquake and failure of gas and water pipelines in 1999 Chi-Chi earthquake in Taiwan clarified that proper consideration of earthquake load in the design of underground structures is also important.

The failures of above-mentioned underground structures give rise to some problems that need to be clarified. The mechanical behavior of underground structure subjected to the earthquake loading is basically a soil-structure interaction problem. Besides, in active seismic region, some existing underground structures do not meet the requirement of present seismic design standard, which becomes a serious problem.

In this paper, numerical analyses are conducted to evaluate the effect of ground improvement as a seismic countermeasure for existing rectangular-shaped underground structure (in common called box culvert) in soft soil. Particular attention is paid to finding a most effective and economical type of ground improvement that can reduce the impact of earthquakes on the box culvert. Four cases for the analyses are considered. In the numerical analyses, 2D/3D dynamic finite element method (FEM) with the code name of DBLEAVES (Ye, 2007; Ye, 2011) is used. In order to evaluate the influence of the soil-structure interaction on the underground structures, a unified system consisted of soil and underground structure is considered. As for the mechanical behavior of soft soil, a nonlinear elastoplastic constitutive model with the name of Cyclic Mobility model (CM model) (Zhang et al., 2007&2011) is adopted. The concerned underground structure in the analysis is the Daikai station and particular attention is paid to its central columns. The failure of the central columns was the main reason of the structural collapse during the earthquake. In the analyses, the nonlinear behavior of the columns is modeled with the Axial-force Dependent model (AFD model, Zhang and Kimura, 2002).

In order to confirm the validity of the proposed numerical analyses, 1g shaking table test and corresponding 2D dynamic analysis were firstly conducted and the results of both the analysis and the test are compared in detail.

2. INVESTIGATION OF DAMAGE TO THE DAIKAI STATION

The Daikai station belongs to the Kobe Rapid Transit System was constructed by cut-and-cover method. It consisted of an RC rectangular section with uniformly spaced central columns. During the 1995 Hyogoken-Nambu earthquake the central columns and the ceiling slab were completely collapsed, followed by the settlement of overburden soil around 2.5m. Based on the works by Iida et al., 1996, the central columns failed first, and then it caused the collapse of the ceiling slab and soil cover settlement. Fig. 1 shows the longitudinal damage patterns to the Daikai station. The severe damage had occurred in the central columns of section 1. The collapse of the central columns is shown in Fig. 2. The columns were poorly reinforced horizontally, resulting in a typical shear failure (Iida et al. 1996). In addition, the design of the station in 1962 did not include seismic provisions (Hashash, Y.M.A. et al. 2001).

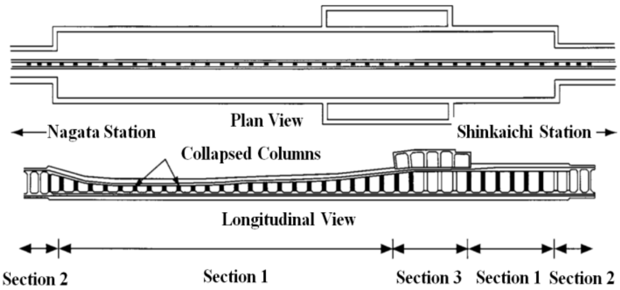


Fig. 1. Longitudinal damage patterns to the Daikai Station (adapted from Iida et al., 1996)

Fig. 2. Failure of central columns in Daikai station (Sato Industrial Inc. 1997)

3. 1G SHAKING TABLE TEST AND VALIDATION OF NUMERICAL METHOD

In this section, 1g shaking table test and 2D numerical analysis in the model scale are conducted and the results of both the analysis and test are compared in detail.

The shaking table test device used in the present study has the maximum payload, acceleration and displacement of 16kN, 9.8m/sec^2 and 0.05m respectively. In addition, the dimension of the shaking table shear box is 1.2x1.0x0.8m (length, width and height). In the model test, the Daikai station is modeled with a similarity ratio of 1/30. The model box culvert is made of iron sheet with a modulus of elasticity of 210GPa; additionally, in the model the central columns of Daikai station are assumed to be a uniform wall. Fig. 3 shows the model box culvert.

In the test, the model ground, made of dried Toyoura sand with a depth of 600mm, is prepared carefully using the air pluviation method. The model ground is prepared with two horizontally layered soils with different densities by adjusting different dropping height. The lower layer is prepared as medium dense sand with a relative density (D_r) of 70%, which is just beneath the box culvert, as shown in Fig. 4. The upper layer is prepared as loose sand with D_r=15%. The lower and upper layer has a thickness of 225mm and 375mm respectively.

Strain gauges and accelerometers are installed in different positions of the model to measure the bending strains and the accelerations. Fig. 4 shows the model box culvert and the soil layers. In the figure, the positions of the strain gauges and the accelerometers are also marked.

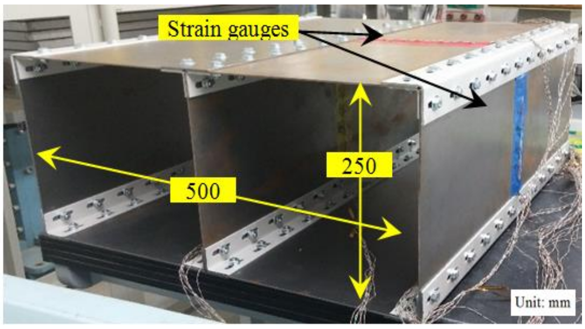


Fig. 3. Model box culvert

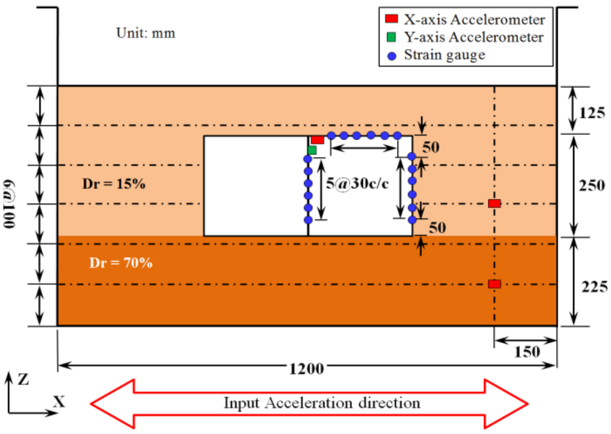


Fig. 4. Model box culvert, soil layers and measuring points

The input acceleration for the shaking table test, as shown in

Fig. 5, is in horizontal direction and lasts for 11.0 seconds with maximum amplitude of 4.0m/sec^2.

In order to validate the numerical method proposed in this paper, the model shaking table test is simulated by 2D finite element method using DBLEAVES. In the 2D analysis, the model ground and the box culvert are totally the same both in the geometry and the material properties as those used in the shaking table test. The model box culvert is model with elastic beam elements. The behavior of the soils is described by the CM model (Zhang et al., 2007&2011). The CM model is a rotating-hardening type elastoplastic constitutive model that takes into account the overconsolidation, the soil structure and the stress-induced anisotropy simultaneously. The properties of Toyoura sand as the ground material are listed in Table 1.

Table 1 Material parameters of Toyoura sand in CM model

Parameter of ground material	Symbol	Toyoura sands	Note
Compression index	λ	0.050	Same parameters as Cam Clay model
Swelling index	κ	0.0064	
Stress ratio at critical state	M	1.3	
Reference void ratio (p'=98 kPa on N.C.L)	N	0.87	
Poisson's ratio	ν	0.30	
Degradation parameter in overconsolidation	m	0.010	New parameter
Degradation parameter of structure	a	0.50	
Evolution parameter of anisotropy	b_r	1.5	
Initial structure	R_0^*	0.99	Initial values of state variables
Initial void ratio	e_0	0.65	
Initial degree of overconsolidation(2D Analysis)	OCR $(1/R_0)$	32.6 (upper) 1.4E3(lower)	
Initial degree of overconsolidation (3D Analyses)	OCR $(1/R_0)$	7.5 (upper) 30 (lower)	
Initial anisotropic	ζ_0	0.0	

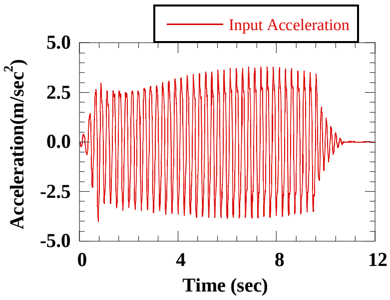


Fig. 5. Input acceleration in the shaking table test and 2D numerical analysis

In the 2D analysis, the same input acceleration as the shaking table test is applied at the base of the model ground shown in Fig. 4. The Fig. 6 shows the 2D FEM mesh, in which the model ground and the box culvert are discretized into 7749 nodes and 6212 elements. The boundary conditions of the ground are assumed to be fixed at the bottom, and the equal-displacement boundary condition is introduced in all directions at the right- and left-side boundaries.

The calculated results are compared with those from the shaking table test and the comparisons are plotted in the Figs. 7; in which the measuring points of computed and recorded data are shown in Fig. 4.

The time history of the acceleration obtained from the analysis and the shaking table test is compared in Fig. 7. Fig. 7(a) shows the vertical responding acceleration at the top of the central wall. Fig. 7(b), (c) and (d) show the horizontal responding accelerations at the top of the central wall, the levels of -300mm and -500mm respectively. From Fig. 7, it is known that the results from the numerical analysis and the shaking table test are almost the same. In addition, the Figs 7 exhibits a fact that the test results are reproduced with considerable accuracy by the numerical analysis, implying that the numerical method proposed in the present study is able to describe and predict the behavior of underground structure subjected to earthquake loading.

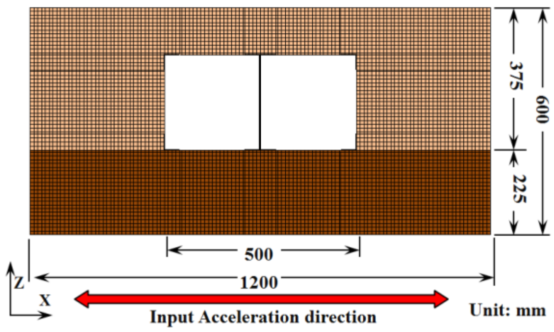
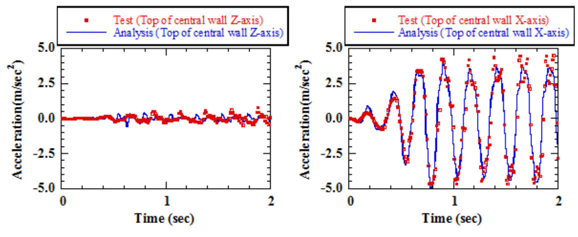
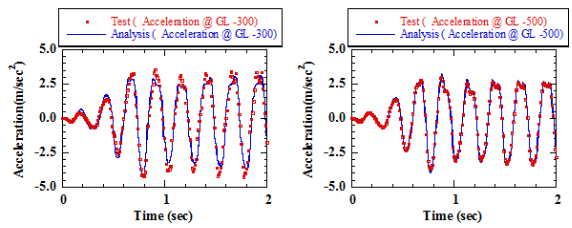


Fig. 6. 2D FEM mesh in model scale



(a) Vertical response acceleration at the top of central wall

(b) Horizontal response acceleration at the top of central wall



(c) Horizontal response acceleration at the GL= -300

(d) Horizontal response acceleration at the GL= -500

Fig. 7. Time history of acceleration from 2D analysis and shaking table test

4. NUMERICAL TESTS FOR OPTIMUM PATTERN OF GROUND IMPROVEMENT

In order to find out an optimum pattern of ground improvement that can reduce most effectively the earthquake loading on existing box culvert, the Daikai station is taken as the objective and the analyses are focused on its central column which was the main reason of the failure happened during the earthquake. Due to the periodic condition in the longitudinal direction, a span of 7m including three columns is considered for calculation. The depth and width of the surface layer ground are 18 and 60m respectively. The FEM mesh used in the analyses, with 18600 nodes and 16560 elements, is shown in Fig. 8. The boundary conditions for the ground are assumed as follow: the bottom is fixed and the equal-displacement boundary is introduced at the right and left sides.

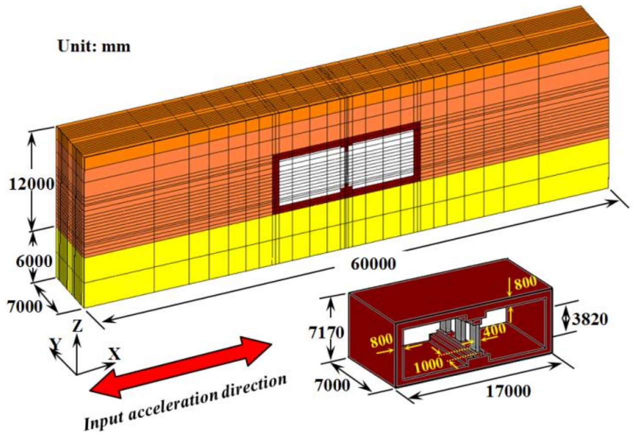


Fig. 8. 3D FEM mesh used for dynamic analysis in numerical tests

The surface ground is made of two layers, in which the layer surrounding the existed box culvert is a medium dense Toyoura sand with Dr=80%. The layer beneath the box culvert is a dense Toyoura sand with Dr=95% respectively. All the Toyoura sands with different density are described by the CM model.

The material of the box culvert, except the central column, is assumed to be elastic and its unit weight, Poisson's ratio and elastic modulus are 25kN/m^3, 0.25 and 27GPa respectively. The central column, however, is modeled with the axial-force dependent model (AFD model, Zhang and Kimura, 2002). The detailed reinforcement of the column is shown in Fig. 9. The compressive strength of the RC column is 39MPa, a value obtained from the post-earthquake survey of Daikai station. The elastic modulus of steel is E=210GP and the yield strength is 235 MPa. These values are adopted based on the research by Parra-Montesinos et al., 2006 about the central column of Daikai station.

The ground improvement in practical engineering for seismic enhancement is usually conducted by mixing cemented materials with soft soil by high-pressure jet grouting or mechanical mixing method. In the researches by Morikawa, 2013 and Kheradi et al., 2015, the ground improvement was made from adding B-type Portland blast-furnace slag cement (in short, slag cement) into the mixture of Toyoura sand and Fujimori clay. The weight ratio of the sand, the clay, the cement and the water is 80:20:3:22. The improved soil has a uniaxial compressive strength of 600 kPa (Morikawa, 2013, Kheradi et al., 2015) and the modulus of deformation of 120~300 MPa. In present study, the same improved soil with the modulus of deformation of 300MPa is used for the ground improvement.

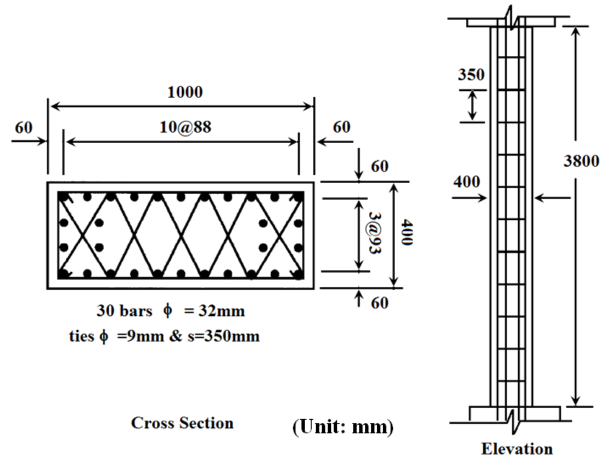


Fig. 9. Reinforcement of central column in Daikai station (Iida et al. 1996)

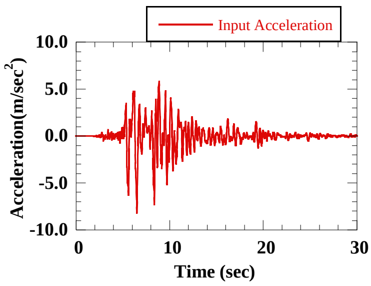


Fig. 10. Input acceleration in 3D dynamic analyses

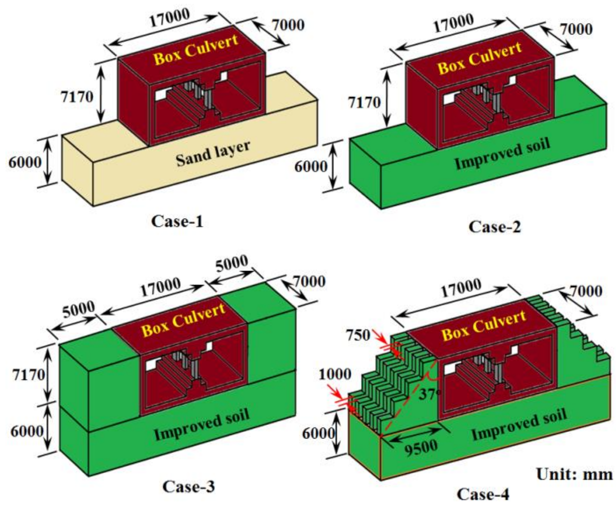


Fig. 11. Patterns ground improvement considered in 3D analyses

The input acceleration in the 3D dynamic analyses is the horizontal NS component of the 1995 Hyogoken Nanbu earthquake recorded at Kobe city with a maximum acceleration of 8.18m/sec^2. Fig. 10 shows the input acceleration. The calculation conditions for the 3D dynamic analyses are the same as those for 2D analysis in the previous section.

Four different cases are analyzed in the numerical test. These cases represent a box culvert around which the sandy ground is partially improved with different patterns, as shown in Fig. 11.

Case-1 is the base case without any ground improvement and its soil profile is just shown in Fig. 8. In Case-2, the sandy layer beneath the box culvert is improved with the cemented soil. The property of cemented soil as ground improvement material was discussed before. In Case-3 and Case-4, in addition to layer beneath the box culvert the soil around the side-walls of the box culvert is improved as well.

In Case-3 the ground improvement around the side-walls of box culvert has the shape of a rectangular prism. Alternatively, in Case-4, the quantity of ground improvement around the side-walls is reduced from full to partially ground improvement. In Case-4, the ground improvement around the side-walls of box culvert has a shape like a downstairs with an inclined angle of 37°, as shown in Fig. 11. The quantity of ground improvement around the side-walls of box culvert in Case-4 is 35% smaller than Case-3. Indeed, the Case-4 is the most cost-effective pattern of ground improvement for the box culvert. The standard for choosing the optimum pattern of the ground improvement is based on the condition that the horizontal displacement of the central column should be the minimum. It is known from the previous section that the central column is the critical member in considering the safety of a box culvert.

In order to identify the influence of the soil layer beneath the box culvert, the results from Case-1 and Case-2 are compared. The time history of horizontal displacement at the top of central column in Case-1 and Case-2 is shown in Fig. 12. The horizontal displacement in Case-1 is much larger than that of Case-2. In both cases, however, the horizontal displacements at the top of central column are large enough to cause the failure. The existence of sand layer beneath the box culvert may largely contribute to the increase of the horizontal displacement of the box culvert.

In Case-3 and Case-4, in addition to the soil beneath the box culvert, the soil around the side-walls is improved as well. However, the shape and amount of improved soil around the side-walls are different in each case, as shown in Fig. 11.

The time history of horizontal displacement at the top of the central column in Case-1, Case-3 and Case-4 is shown in Fig. 14. The figure shows that the wrecking horizontal displacement at the top of the central column of Case-1 is reduced significantly in Case-3 and Case-4. In addition, the horizontal displacement in Case-4 is the smallest among these three cases.

The comparison of the distribution of maximum horizontal displacement along the height of the central column in Case-1 and Case-2 is shown in Fig. 14(a). The horizontal displacement at the top of the column in Case-1 is larger than Case-2 as well as the bottom of the column. The relative displacement of top of column with respect to the bottom of the column, however, is nearly the same in both cases; implying that the seismic reinforcement effect is very limited.

The comparison of the distribution of the maximum horizontal displacement along the height of the column in Case-1, Case-3 and Case-4 is shown in Fig. 14(b). The reduction of the wrecking horizontal displacement at the top of the central column in Case-3 and Case-4 is significant, 72% in Case-3 and 76% in Case-4, if compared with Case-1.

Based on above-discussion, it is reasonable to say that Case-4 is the optimum pattern of ground improvement for the existing box culvert constructed in soft ground.

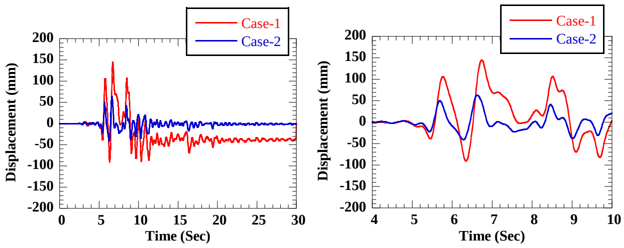


Fig. 12. Time history of horizontal displacement at top of central column in Case-1&2

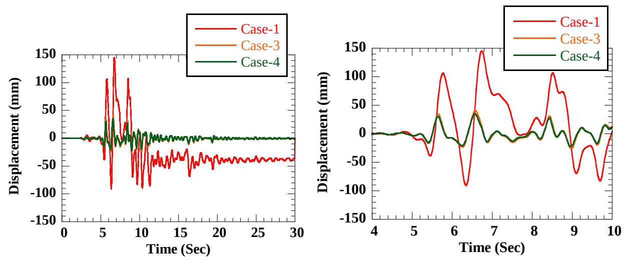
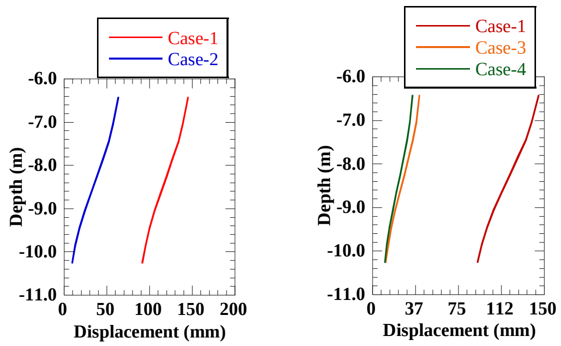


Fig. 13. Time history of horizontal displacement at top of central column in Case-1, 3 and 4



(a) Case 1 & 2 (b) Case 1 & 3,4

Fig. 14. Distribution of maximum horizontal displacement along height of column in Case-1, 2, 3 and 4

5. CONCLUSIONS

In this paper, 1g shaking table test and corresponding numerical analysis were conducted to investigate the effect of ground improvement as a seismic countermeasure for existing box culvert constructed in soft ground. Meanwhile, particular attention was paid to find an optimum pattern of ground improvement to reduce the earthquake loading.

In the numerical analysis, 2D and 3D nonlinear dynamic finite element method with the program named DBLEAVES was used. The structure of Daikai station that failed in 1995

Hyogoken-Nanbu earthquake was selected as the objective box culvert. The Toyoura sand was assumed as the ground material and its mechanical behavior was described by the CM model.

At first, in order to verify the numerical method, the 1g shaking table test is simulated with 2D analysis in model scale. After then, in order to find an optimum pattern of ground improvement, 3D numerical analyses were conducted. In the 3D numerical analysis, the central column of Daikai station, that was the critical member during earthquake, was described by the AFD model. Four different cases were numerically investigated and the following conclusions can be given.

(i) The comparison between the 2D analysis and the shaking table test shows that the test results were well reproduced by the numerical analysis. Therefore, the numerical method proposed in the present study is able to predict reasonably the behavior of box culvert during an earthquake.

(ii) The assessment of Case-1 (basic case, without improvement) and Case-2, in which only the soil layer beneath the box culvert is improved, shows that the absolute displacement is reduced significantly due to the ground improvement but the relative displacement between the top and the bottom of the central column remains unchanged; implying that the seismic reinforcement effect is very limited.

(iii) Improvement of the soils around the side walls, proved to be very effective. The optimum pattern of the ground improvement is found to be Case-4, in which a partial ground improvement with a shape of downstairs at an inclined angle of 37° around the side-walls was used. In Case-4 the soil beneath the box culvert was also improved as well. It is found from the analysis that the relative horizontal displacement was reduced significantly; therefore, the column is in safe domain. In addition, the volume of the ground improvement around the side-walls in Case-4 is 35% smaller than Case-3, implying that Case-4 is the most cost-effective pattern.

In the future, the predicted results for the optimum patterns of the ground improvement for existing box culvert should be confirmed by the shaking table tests.

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