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Dynamic Analysis of Subsea Tunnel based on the Dynamic Geo-centrifuge Test

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Abstract

The importance of cost-wise effective engineering and construction is getting increase due to the surge of traffic volume in the metropolitan cities. Accordingly, the necessity of the tunnel has large section becomes more critical. Subsea tunnel can be one of the most appropriate solutions to that kind of necessity. The dynamic stability of subsea tunnel is essential against seismic load since it has large section and connection between perimeter lining and interim slab. In this study, dynamic geo-centrifuge test was also performed to analyze the seismic behavior of subsea tunnel. Additionally, 3-dimensional dynamic numerical analysis was conducted based on the Finite Difference Method to compare the seismic behavior of subsea tunnel. Seismic joint for dynamic stability and the mitigation of seismic impact on the lining was considered in the modeling and analysis. Consequently, seismic behavior of subsea tunnel showed similar behavior and the mitigation of acceleration, lining displacement and stress were verified successfully.

Keywords: subsea tunnel; dynamic geo-centrifuge Test; seismic joint

1. Introduction

The importance of cost-wise effective engineering and construction is getting increase due to the surge of traffic volume and complexities in the metropolitan cities. Therefore, the necessity of the tunnel has large section becomes more critical and related technology has been developed. Subsea tunnel can be one of the most appropriate solutions to that kind of necessity. Especially, the dynamic stability of subsea tunnel is essential against seismic load since it has large section and the dynamic behavior of the interface between perimeter lining and ground. A few studies are reported on the seismic characteristics of subsea tunnels. Nilsen and Palmström (2001) studied key factors determining stability and water leakage in hard rock subsea tunnel based on the case study of subsea tunnels in Norway. Geng et al. (2007) suggested a seismic design concept for an underwater shield tunnel which has a large cross section. Gao et al. (2012) researched the dynamic characteristics and failure mechanism of a river-crossing tunnel using 3D dynamic finite difference method. Cheng et al. (2014) investigated the seismic response of the fluid-structure interaction of an undersea tunnel in a broken fault zone during a bidirectional earthquake. Based on the numerical analysis, the vertical displacement of the lining structure is greater than its horizontal displacement under El Centro wave. Though these recent researches, studies on the seismic characteristics of subsea tunnels lags behind. In this study, dynamic geo-centrifuge test was performed to analyze the seismic behavior of subsea tunnel. Additionally, 3-dimensional dynamic numerical analysis was conducted based on the finite difference method to compare the seismic behavior of subsea tunnel and analysis result. Seismic joint for dynamic stability and the mitigation of seismic load on the lining was considered both in the modeling and analysis.

2. Dynamic geo-centrifuge test

Dynamic geo-centrifuge test is one of the state of the art laboratory test methods in civil engineering field. Dynamic geo-centrifuge test can simulate the in-situ stresses and conditions under dynamic loading, then, the behavior of test model can represent the behavior of physical model effectively and accurately. In this study, twin tunnel with seismic joint was modeled and examined.

C72-2 Geo-centrifuge apparatus in KAIST (Korea Advanced Institute of Science and Technology) was employed to perform the tests. The shape of the apparatus is shown in Fig. 1. Based on scaling law, 3 cases were considered as Table 1 below. The size of tunnel was reduced by 1/100. Tunnel was modeled by acrylic plate and seismic joint was implemented by rubber. The input motion is Ofunato wave, which has relative short period characteristics. Dimensions are described in Fig. 2. Diameter of each tunnel is 7 cm, which means 7 m in physical model considering scaling factor, and the distance between tunnels, i.e. center to center is 14 cm. The length of tunnel is 49 cm and depth of tunnel crown is 21 cm. The size of the platform is 49 cm (width), 49 cm (length), and 60 cm (height). The input seismic motion is Ofunato wave, which can be classified as short-term period wave.

Table 1 – Test conditions

Case	Description	Monitoring location	Input motion	Scaling factor
case-1	without seismic joint	crown	Ofunato	1:100
case-2	with thin seismic joint (2mm)	crown	Ofunato	1:100
case-3	with thick seismic joint (10mm)	crown	Ofunato	1:100

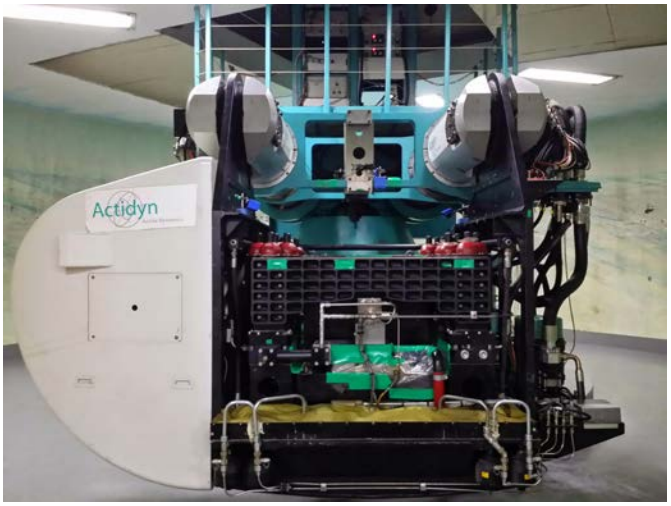


Fig. 1 – Shape of Dynamic geo-centrifuge apparatus (C72-2)

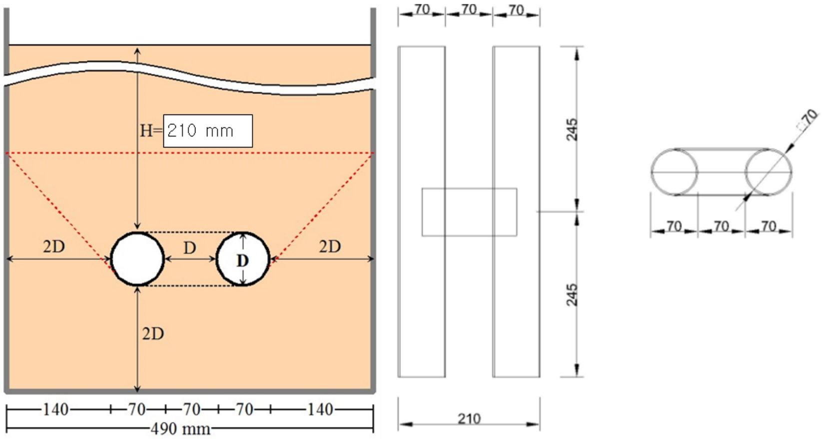


Fig. 2 – Size of model

3. Numerical analysis

3D numerical analysis based on finite difference method is performed to verify test results. Table 2 describes the analysis conditions.

Table 2 – Analysis conditions

Items	Conditions	Remarks
Analysis method	Finite Difference Method (FDM)	
Analysis code	FLAC 3D Ver. 3.00	
Boundary condition	Static : fixed Dynamic : free-field	
Analysis sequence	Static-dynamic coupling	Dynamic analysis after excavation(static)
Input seismic wave	Ofunato	

Ground was modelled as solid element and tunnel lining and seismic joint were modelled as shell element. 3D mesh dimension is identical with test conditions and acceleration histories are monitored at the crown. Whole ground material is considered as rock and simulated by Mohr-Coulomb elasto-plastic model. Table 3 shows material properties and Fig. 3 displays 3D mesh and grouping result.

Table 3 – Material properties

Young's modulus	**Poisson's ratio**	**Friction angle**	**Cohesion**	**Unit weight**
300 MPa	0.30	30 deg	30 kPa	21,000 kN/m^3

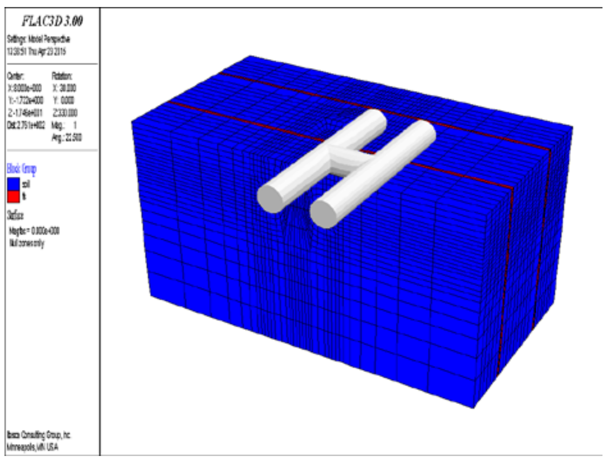


Fig. 3 – 3D mesh and grouping

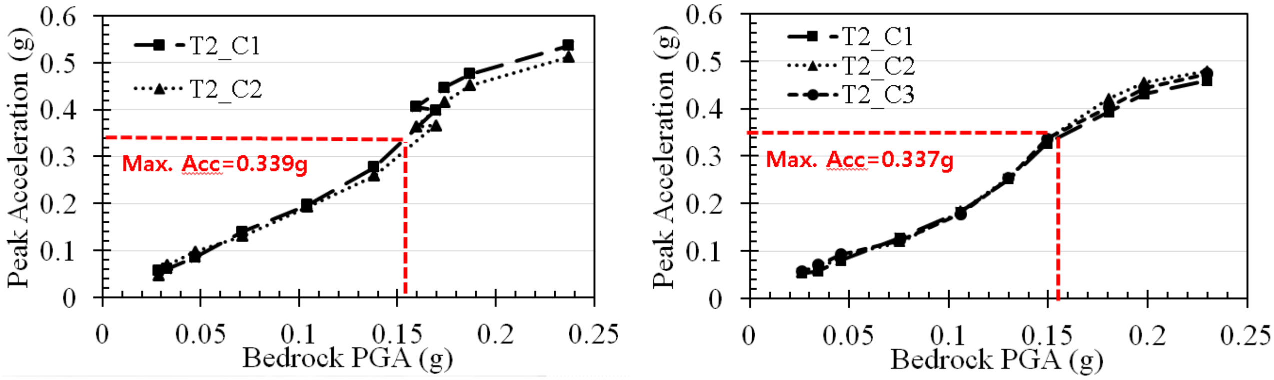
In-situ static equilibrium is reached by static analysis, then, all deformation and velocities are initialized. After the initializing, free-field boundaries are applied on side boundaries, then seismic loading is applied at the bottom of the mesh.

4. Results

4.1 Test results

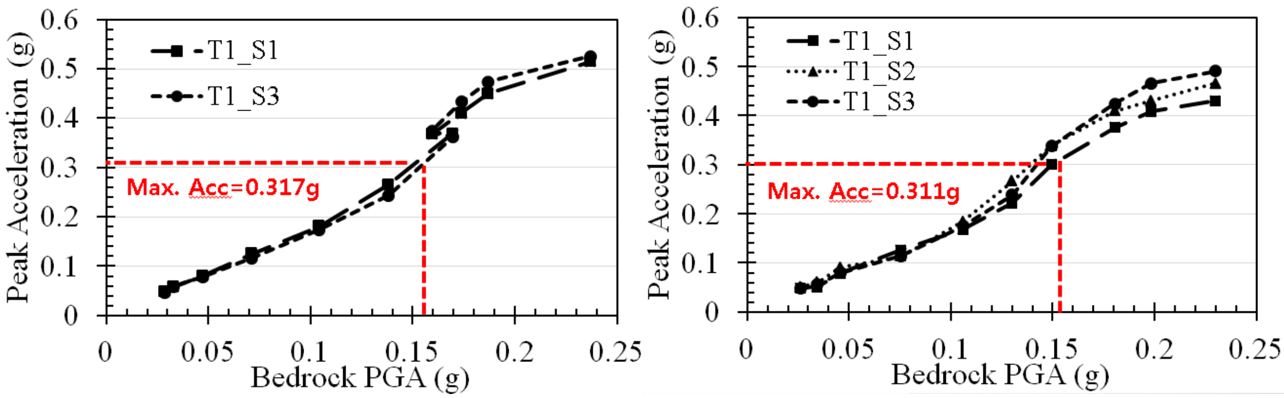
Dynamic geo-centrifuge test was conducted based on the test conditions in Table 1. Acceleration histories at the tunnel crown were monitored and analyzed. Fig. 4 displays the comparison of acceleration histories of right tunnel (T2) crown at front (C1), middle (C2), and end (C3) according to longitudinal direction in case of without seismic joint (case-1) and with thin seismic joint (case-2). Fig. 4 shows the deviation of acceleration values increases with the magnitude of bedrock acceleration. The acceleration increases as 16.9 % in case-1 at C1 position. Fig. 5 demonstrates the comparison of acceleration histories of left tunnel (T1) spring-line at front (S1), middle (S2), and end (S3) according to longitudinal direction in case-1 and 2. Fig. 5 shows the deviation of acceleration values increases with the magnitude of bedrock acceleration, which is identical trend as Fig. 4. The acceleration increases as 19.7 % in case-1 at S1 position. Fig. 6 displays the comparison of acceleration histories of left tunnel (T1) crown in case of thin seismic joint (case-2) and thick seismic joint (case-3). Fig. 6 shows the deviation of acceleration values increases with the magnitude of bedrock acceleration as well. The acceleration decreases from 0.353 g in case-2 to 0.278 g in case-3 (21.2 %) at C1 position.

Based on the test results, the acceleration reduction due to the seismic joint was verified and thick seismic joint shows greater acceleration reduction.



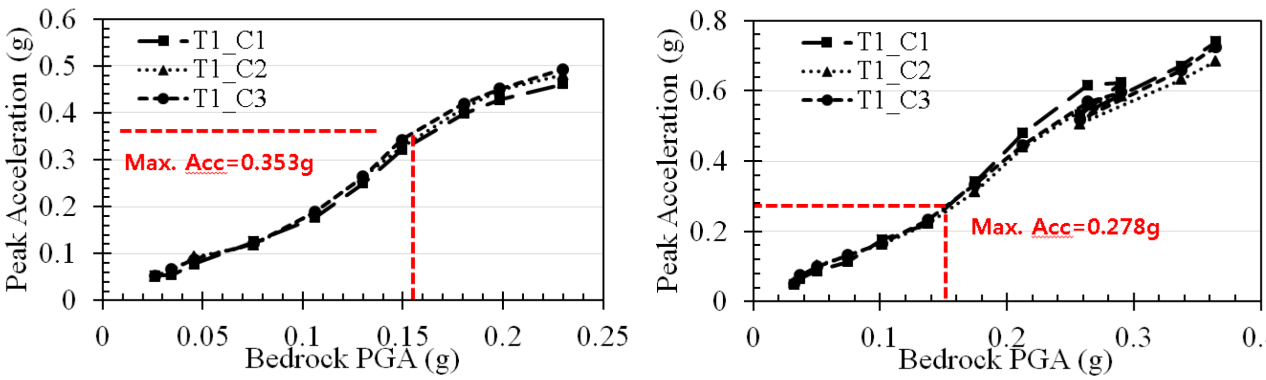
(a) case-1 (b) case-2

Fig. 4 – Acceleration histories at the right tunnel crown



(a) case-1 (b) case-2

Fig. 5 – Acceleration histories at the left tunnel spring-line

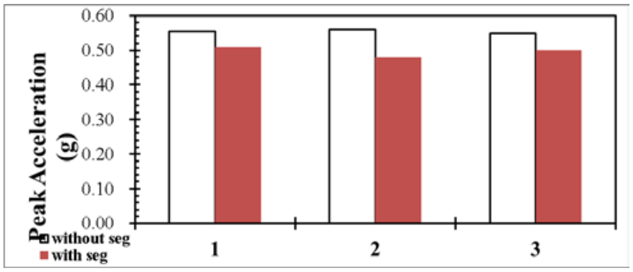


(a) case-2 (b) case-3

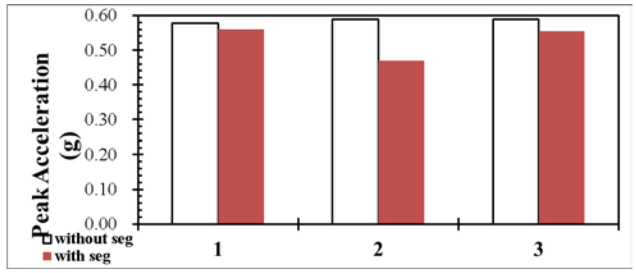
Fig. 6 – Acceleration reduction according to the thickness of seismic joint at the left tunnel crown

4.2 Analysis results

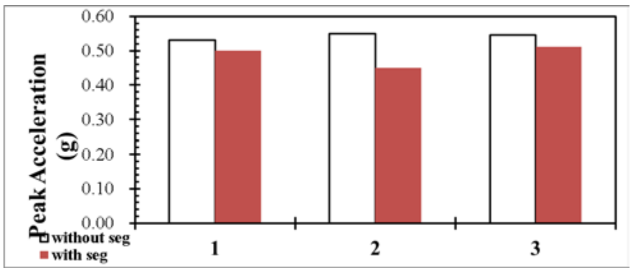
3D numerical analysis was performed to simulate dynamic behavior of subsea tunnel. Seismic joint was considered to verify the effect of acceleration reduction based on the dynamic geo-centrifuge test results. Fig. 7 shows peak accelerations at crown and spring-line.



(a) at crown of right tunnel



(b) at spring-line of left tunnel



(c) at crown of left tunnel

Fig. 7 – Peak acceleration results by numerical analysis

Based on Fig. 7, peak accelerations reduced at all locations in case of applying seismic joint, which is shown as "with seg" column in the charts. At crown of right and left tunnel, peak acceleration decreases 7.78 and 18.1 %, respectively. At spring-line of left tunnel, peak acceleration decreases 20.2 %. Figure 8 displays the acceleration reduction according to longitudinal locations. Table 4 shows the comparison of the acceleration reduction in case of applying seismic joint in the test and numerical analysis results. These results shows identical trend, therefore, the acceleration reduction effect of the seismic joint was verified successfully.

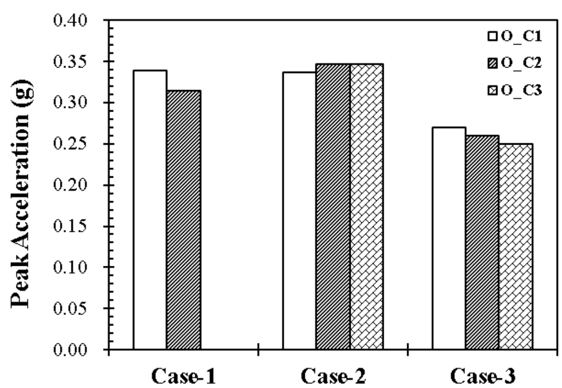


Fig. 8 – Comparison of peak acceleration at crown of right tunnel

Table 4 – Acceleration reduction result

Location	Acceleration reduction in case of applying seismic joint		
	Crown of right tunnel	Spring-line of left tunnel	Crown of left tunnel
Test	14.5 %	16.5 %	11.4 %
Numerical analysis	7.8 %	18.1 %	20.2 %

5. Conclusions

(1) Dynamic geo-centrifuge test was conducted to investigate the dynamic behavior of subsea tunnel with, or without seismic joint.

(2) Acceleration reduction due to the seismic joint was verified and thick seismic joint shows greater acceleration reduction based on dynamic geo-centrifuge test results.

(3) 3D numerical analysis was performed to simulate dynamic behavior of subsea tunnel and the analysis results showed good agreement of test results, therefore, the acceleration reduction effect of the seismic joint was verified successfully.

6. Acknowledgement

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