Dynamic Geo-Centrifuge Test on Twin Tunnel

Changwon Kwak, Dongin Jang, Innjoon Park

ABSTRACT--- ***Tunnel is one of the most efficient ways to connect each spot with considerable reduction of the length of road or railway by underground excavation. Therefore, the whole construction cost can be also reduced, however, the seismic safety issues emerges and becomes more important since the hefty earthquakes occurred all over the world, recently. The dynamic behaviour of the underground structures such as tunnel is different to that of superstructures mainly because of the in-situ stress conditions. In this study, dynamic geo-centrifuge test is performed to consider the in-situ stress condition of the surrounding soil against a twin tunnel. Long-term period wave is applied as an input motion and flexible segment is simulated to investigate the effect of acceleration mitigation. As a result, the deviation of peak acceleration increases according to the growth of base acceleration and 17.8 % of acceleration reduction is verified due to the flexible segment.***

Keyword - tunnel, dynamic behaviour, dynamic geo-centrifuge test, flexible segment

I. INTRODUCTION

Physically reduced model test comparing with the prototype is very useful in civil engineering field because it is simple and economical. However, in the geotechnical regime, underground structures such as tunnel are always under the effect of in-situ stress, therefore the static and dynamic behaviours show different response to that of superstructures. Dynamic geo-centrifuge test was invented to simulate the in-situ stress condition in the ground by applying centrifugal acceleration to the model. It also may reduce the test cost dramatically without giving up the reliability for the test. Recent developments in robotics, control, electronics and miniaturisation seem to be occurring so rapidly that any description of instrumentation or of techniques for modelling geotechnical processes at small scale must rapidly go out of date (D. M Wood, 2004).

The difference of stiffness and density between structures and soil causes soil-structure interaction around the structures (Chen and Shen, 2014). Soil-structure interaction can play an important role in tunnels (G. Madabhushi, 2015). Cilingir & Madabhushi (2011) investigated the seismic behaviour of circular and square tunnels with different wall thicknesses to change the flexibility of the tunnel using dynamic centrifuge modelling. Test results clearly showed that flexible-walled tunnels interacted more with the soil around it and changed the stress wave propagation in the soil. Seismic behaviour of tunnel depends on the permanent deformation such as seismic wave transmission, shear failure of soil, lateral spread, etc. and very complicated (Pitilakis et al., 2014).

In this study, flexible segment is employed to restrain the amplification of acceleration at twin tunnel and modelled for dynamic geo-centrifuge test. Flexible segment is a discontinuous unit to allow excess displacement and modelled by silicon material. The peak accelerations at the tunnel crown and springline are analysed and compared with each other.

II. DYNAMIC GEO-CENTRIFUGE TEST

A wide range of geotechnical problems including tunnels can be investigated using geo-centrifuge physical modelling techniques (Corte, 1988). Geo-centrifuge test provides a tool for geotechnical modelling in which prototype structures can be studied as scaled-down models while preserving the stress states (Avgherinos and Schofield, 1969). The acceleration of the model is raised until the stress state reaches the level of prototype in order to simulate in-situ condition, then static or dynamic load applies to the model.

Geo-centrifuge test also has limitations that it is often complicated to convert test results into actual behaviours by scaling law. Geo-centrifuge test does not reproduce exactly the in-situ condition of the soil surrounding geotechnical structures since soil is not homogeneous and isotropic practically. In spite of those limitations, there is no considerable liability to obtain overall trend of the model and verification of modelling. Additionally, mechanical limitation of test apparatus can be a major restraint to perform more accurate and practical test, however, this sort of limitations is getting vanished because of the rapid improvement and development of relevant technologies.

Various geo-centrifuge tests to investigate the dynamic response of tunnel have been performed (Cilingir & Madabhushi, 2009; Lanzano, 2009). However, the previous studies just verified the analytical solutions, or assess the effect of seismic behaviour of tunnel without discontinuous segment.

A. Test Apparatus

The dynamic geo-centrifuge test apparatus with electro-hydraulic servo type shaking table at Korea Construction Engineering Development (KOCED) in Korea Advanced Institute of Science and Technology Constitution. The

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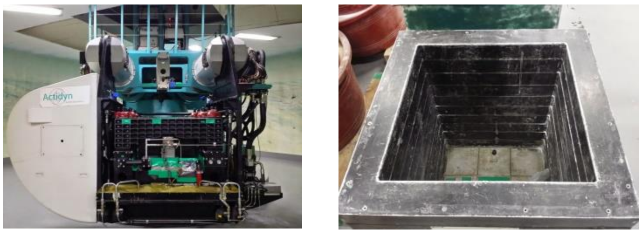
maximum centrifugal acceleration of 20g is applied. Table 1 shows the detail of the apparatus.

TABLE 1 Specifications of dynamic geo-centrifuge test apparatus

Category	Specifications
Maker	ACTIDYN SYSTEMES SA (France)
Platform radius	5.0 m
Max. capacity	240g-tons
Max. payload	2,400kg up to 100g
Payload dimensions	1.2m(L)×1.2m(W)×1.2m(H)
Max. acceleration	130g @ 1,300kg payload
Allowable frequency	20 up to 300 Hz

Shaking table is operated by electric control system. A counter weight which is same as the model weight is attached to the shaking table to avoid overturning moment; therefore, the dynamic balancing system is established to minimize the unnecessary movement. Dynamic loading applied to the shaking table may cause the residual high-frequency wave at the stiff wall of the shaking table, and if the reflected wave is in the range of the response wave may occur an error in the test result. Therefore, an equivalent shear beam (ESB) is employed to simulate the free-field boundary condition in the shaking table box. The ESB is composed of a few layers of aluminium frame and ball bearing and rubber connector are installed to link the frames. This type of shaking table box is appropriate to consider the earthquake response and amplification analysis, soil-structure interaction, and seismic performance of geotechnical structures. Fig. 1 displays the apparatus.



(a) Appearances of dynamic geo-centrifuge test apparatus

(b) ESB of Shaking table

Fig. 1. Dynamic geo-centrifuge test apparatus

B. Test Conditions

The shape of twin tunnel was modelled with the scale of 1/100. The material to model tunnel is acrylic plate and flexible segment is modelled by silicon. The input base motion is Hachinohe wave, which shows long period characteristics and displayed in Fig. 2. The peak amplitude of input motion is scaled to 0.154g and 0.22g, which represent the design acceleration of Korean seismic design guideline (KBC2016). Acceleration is applied to the base of the shaking table gradually to avoid abrupt failure of the model and interference of the seismic wave. Duration of the wave is 15 seconds.

The diameter of each tunnel is 7 cm, which represents the 7 m in the prototype. The distance between tunnel centre points is 14 cm, and the inner dimension of ESB is 49 cm (wdith) Χ 49 cm (length) Χ 60 cm (length). Ground around tunnel model is granular soil with unit weight of 15.5 kN/m^3 and relative density is 80 %. The input acceleration is applied to the base of the shaking table with 10 stages. Table 2 demonstrates the summary of the test conditions. Test schedule is divided into 2 cases according to the application of flexible segment

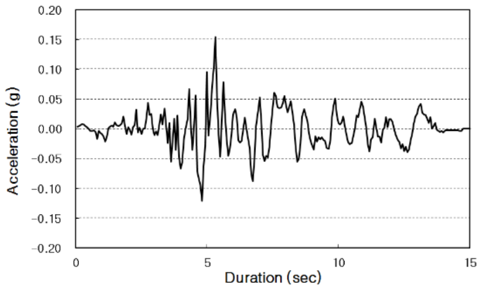


Fig. 2. Acceleration time history of Hachinohe wave (peak acceleration = 0.154g)

TABLE 2 Test conditions

Case	Description	Monitoring location	Input motion	Scaling factor
case-1	without flexible segment	crown / springline	Hachinohe	1:100
case-2	with flexible segment (thickness = 8.0 mm)	crown / springline	Hachinohe	1:100

One of the most important factors is the scaling law because the principle of centrifuge test is based on the requirement of similarity between the model and the prototype (Zornberg et al., 1997). Geo-centrifuge test is a model test, therefore, the scaling law should be considered to analyse and interpret the test results. If a model is constructed with dimensions reduced by a factor of 1/N, then an acceleration field of N times of the gravity, g, should be applied to generate the identical stress condition in the model. Table 3 displays the main scaling factors. Additional scaling law can be obtained dimensional calculation or solving governing differential equations, if required.

TABLE 3 Scaling law for geo-centrifuge test

Variables	Scaling factor	Dimensions	Values
Length	1/N	L	1/100
Strain	1	$ML^{-1}T^{-2}$	1
Stress	1	1	1
Duration	1/N	T	1/100
Frequency	N	LT^{-2}	100
Acceleration	N	1/T	100

The plan, section of the model and acceleration monitoring points are designated as shown in Fig. 3.

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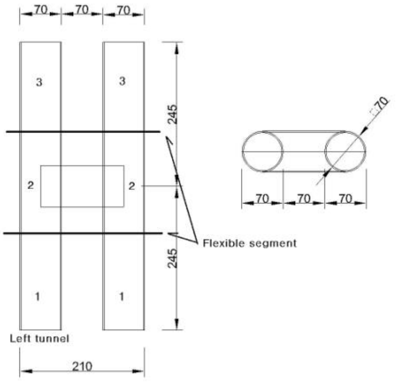
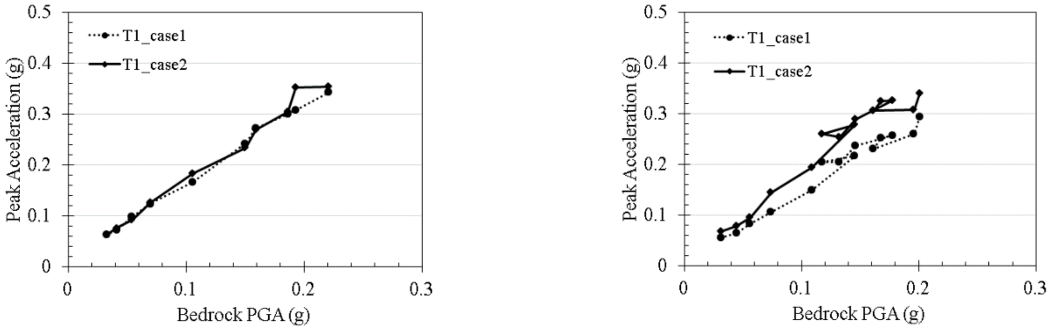


Fig. 3. The locations of acceleration monitoring points

III. TEST RESULT

Peak accelerations at tunnel crown and springline are obtained and analysed. T1 represents left tunnel and T2 means the right. S1 ~ S3 designates the longitudinal location of tunnel as shown in Fig. 3.

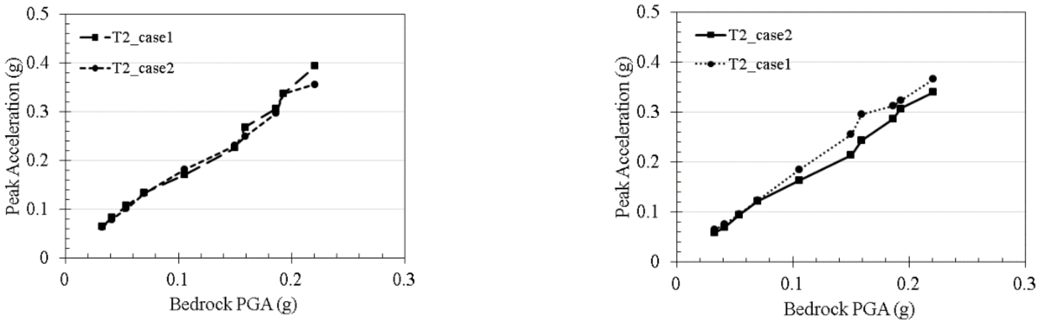
Peak acceleration at the left tunnel is shown in Fig. 4. Generally, the deviation of peak acceleration at each point with increases of input acceleration. The maximum deviation of peak acceleration is 12.7 % at crown (point 2) at left tunnel, and 17.6% at springline (point 2) of left tunnel, as shown in Fig. 4. The deviation of peak acceleration displays about 17.6 % at springline (point 2) at left tunnel. The acceleration mitigation effect is more obvious at the connection point between two tunnels, i.e. point 2.



(a) Crown (point 1) at left tunnel (T1)

(b) Crown (point 2) at right tunnel (T2)

Fig. 4. Test result for springline



(a) Springline (point 2) at left tunnel (T1)

(b) Springline (point 2) at right tunnel (T2)

Fig. 4. Test result for springline

Table 4 displays peak accelerations at crown and springline. In general, peak acceleration at crown and spring decreases in case of tunnel with flexible segment. Maximum decrease shows 17.6% at springline of left tunnel (T1). Peak acceleration reduction occurs at crown with almost same ratio, 12.7% and 12.6% at left (T1) and right (T2) tunnel, respectively. However, the maximum variation at springline, which is 17.6% and 9.4% at left (T1) and right (T2) tunnel, respectively, exhibits large discrepancy.

TABLE 4 Variation of peak accelerations

Location	Case	Crown		Springline	
		Peak acc(g)	Max. Variation	Peak acc(g)	Max. Variation
T1	1	0.352		0.295	
	2	0.308	-12.7%	0.243	-17.6%
T2	1	0.330		0.393	
	2	0.289	-12.6%	0.356	-9.4%

IV. CONCLUSION

The effect of flexible segment of twin tunnel is verified by dynamic geo-centrifuge test. Test result indicates a few conclusions below.

(1) The maximum deviation of peak acceleration is 12.7 % at crown (point 2) of left tunnel, and 17.6% at springline (point 2) of left tunnel, therefore, the effect of applying flexible segment is verified successfully.
(2) The deviation of peak acceleration at each point with increases of the amplitude of input acceleration, which means severe earthquake causes more different dynamic displacement and member forces along the longitudinal direction.
(3) The peak acceleration exhibits solid trend of mitigation at crown and shows some discrepancy at springline. Therefore, it can be deduced that springline is more vulnerable to seismic load.
(4) Consequently, the effectiveness of seismic acceleration mitigation of flexible segment has been verified based on the laboratory test and it exhibits better performance according to the increase of the amplitude of input acceleration.

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