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Dynamic response on tunnel with flexible segment

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Abstract. Dynamic behaviour of a tunnel is one of the most important issues for the safety and it is generally subjected to the seismic response of the surrounding soil. Relative displacement occurred in tunnel lining during earthquake produces severe damage. Generally, it concentrates at the connecting area when two tunnels are connected in the ground. A flexible segment is a useful device for the mitigation of seismic loads on tunnel lining. In this study, 1-g shaking table tests are performed to investigate the acceleration response for the verification of the effect of flexible segment and to determine the optimum location of the flexible segment for connected tunnels. Four different seismic waves are considered; as a result, peak acceleration is reduced to 49% in case that flexible segment is implemented adjacent to connecting area. It also exhibited that the mitigation of acceleration response is verified in all seismic waves. Additionally, 3-dimensional numerical analysis is performed to compare and verify the results. And the numerical results show good agreement to those of the experimental study.

Keywords: dynamic behavior; flexible segment; 1-g shaking table test; 3-dimensional numerical analysis

1. Introduction

A tunnel is an essential part of the infrastructure of urban areas and exhibits a wide range of application according to its purpose. During recent massive earthquakes, many tunnels were damaged significantly, which implies seismic load can be a major attack to the underground structures such as tunnels. From decades, researchers have presented hefty amounts of studies on the dynamic behavior of a tunnel. As a matter of fact, underground structures and tunnels were found less vulnerable to earthquakes compared to above ground structures (Power *et al.* 1998, Dowding and Rozen 1978). Post-earthquake observations have indicated that underground structures can experience significant deformations or even collapse under strong ground shaking (Hashash *et al.* 2001, Nakamura *et al.* 1996). Nowadays, numerical analysis is generally utilized to investigate the dynamic behavior of underground structures. Fabozzi *et al.* (2017) assess the seismic safety of a tunnel based on the case study with 2-dimensional FEM numerical analysis. The seismic increments of internal forces in the lining could be calculated through both a simplified pseudo-static analysis and a full dynamic analysis, showing a satisfying agreement. Sandoval and Bobet (2017) performed 2-dimensional numerical analysis to evaluate the seismic response of a deep tunnel considering the effect of frequency and flexibility ratio. They found that the loading in the liner decreases as the structure becomes more flexible with respect to the ground, and is smaller for a tunnel placed in a stiffer nonlinear ground than in a softer nonlinear ground, for the same flexibility ratio. Wang and Cai (2017) performed 2-dimensional numerical modelling of seismic wave propagation and ground motion in an underground mine, then areas in the mine that might have high potentials of rock burst damage could be identified based on numerical analysis. Anastasopoulos *et al*. (2007) conducted a nonlinear seismic analysis of an immersed tunnel in deep water with a beam-spring model. Argyroudis and Pitilakis (2012) suggested a methodology that implements numerical approach for the vulnerability assessment of shallow tunnels. However, the dynamic behavior of a tunnel has not well understood yet, or at least not well considered (Yan *et al.* 2016) because dynamic behavior of a tunnel exhibits complicated response according to the geometry, location, and soil conditions, etc.

Based on the literature reviews, recent researches on seismic design and analysis of tunnels are limited to theoretical and numerical approaches (Asheghabadi and Matinmanesh 2011, Pakbaz and Yareevand 2005, Liu *et al*. 2015). A model test is one of the most useful means to analyze and predict the practical behavior of civil structures such as tunnels because it is more simple, economical, and expeditious than the prototype model. Shaking table tests are always desirable to be carried out to learn the actual dynamic performance of tunnels (Yan *et al.* 2016). It can be used effectively to investigate the practical seismic response of a tunnel considering in-situ conditions. Moss and Crosariol (2013) carried on shaking table tests to investigate the horizontal racking distortion of an immersed tunnel and verified that the measured distortions were smaller than the

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numerical analysis results.

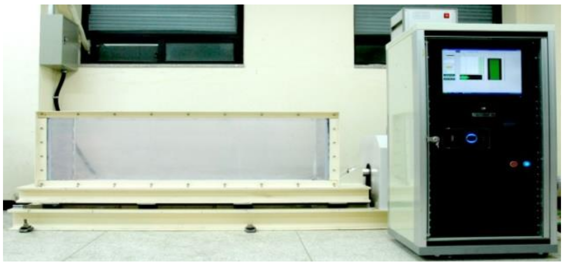
In this study, a main tunnel is considered to be connected to a ventilation shaft (another vertical tunnel). Flexible segments which are implemented to mitigate the amplification of seismic load are also considered. 1-g shaking table tests of connected tunnels with flexible segments are carried out to verify the effect, and determine the optimum location of the flexible segments. Furthermore, 3-dimensional dynamic numerical analysis is conducted to compare the results with the experimental outcome. No experimental investigation on the seismic performance of connected tunnels with flexible segments has been reported yet. Flexible segment could be a useful device to improve seismic resistance and mitigate the amplification of lining acceleration; however, practical behavior and response under a seismic load have not been studied previously. In this study, shaking table test could prove the effectiveness and applicability of flexible segments and the experimental study is also verified by numerical analysis with interface (Ouch *et al.* 2017, Samanta *et al.* 2018).

2. Shaking Table Tests

New theories and analytical solutions have been rapidly developed and modified based on destructive earthquakes. Even though the information coming out of the observation of structures which were subjected to an earthquake, the information is not systematic and adequately documented. Since the response of structures is the comprehensive result of many unknown parameters: input motion, original structural characteristics, pre-earthquake damage due to previous earthquake, foundation settlements, etc. The use of shaking tables for the assessment of the dynamic and seismic behavior of structures is effective since the sixties (Bairrao and Vaz 2000). Shaking table test is one of the most trustworthy methods that can provide reliable dynamic response of structures. Furthermore, shaking table testing can evaluate directly the performance of structures which is much influenced by the dynamic and spatial character of the earthquake action (Duarte *et al.* 1994). On the other hand, physical scales based on dimensional analysis and similitude theories should be studied and applied appropriately. Instrumentation, respecting signal acquisition and measurement, shall be also prepared with sufficient accuracy (Bairrao and Vaz 2000). In spite of a few limitations, shaking table test could be utilized to investigate the dynamic response of various civil structures. Bigger and more powerful shaking tables have been put in operation allowing for the adoption of lower scaling factors and therefore involving very important dynamic forces, according to the improvement of relevant technologies.

2.1. Test apparatus and conditions

The dynamic response characteristics of connected tunnels with flexible segments are studied with the help of the CTS-20, which is a 1-g shaking table at Hanseo University. The dimension of the shaking table is 150 cm (length)×50 cm (width)×60 cm (height), and has 2-dimensional horizontal motion along with the length and width directions. The maximum permissible acceleration is 1g, where g is the gravitational acceleration. The range of input frequency is from 1.0 to 20 Hz. Fig. 1 displays the appearance of the shaking table test apparatus.



(a) Test apparatus

(b) Shaking table box

Fig. 1 Shaking Table Test with 1-g

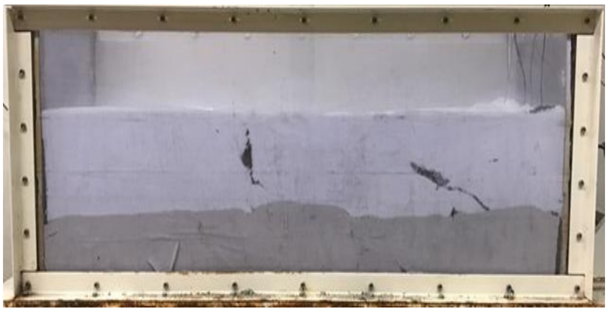


Fig. 2 Shaking Table with model soil

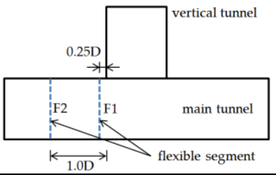
Table 1 Similitude relation used for this study (Iai 1989)

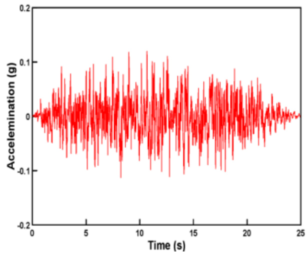
Items	Scaling factor (prototype/model)
Length	λ
Time	$\lambda^{0.75}$
Acceleration of soil/structure	1
Displacement of soil/structure	$\Lambda^{1.5}$
Total/effective stress	λ
Strain	$\lambda^{0.5}$

The model tunnel consists of a main tunnel and a vertical tunnel for ventilation, which is connected to the main tunnel. Acrylic plate is used to manufacture the shape of tunnels and rubber pad is used for flexible segments. The model soil consists of two layers: the lower layer is made of 15 to 20 cm thick sand, and the upper layer is made of 20 to 25 cm thick sand, as shown in Fig. 2. The upper layer represents weathered soil, with 60% of relative density, and the lower layer represents weathered rock, with 70% of relative density.

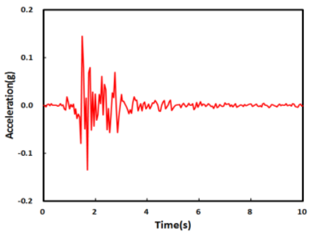
2.2 Similitude relation

Table 2 Test cases

Case	Input motions	Location of flexible segments
Case-1: 0.25D Case-2: 1.0D	Artificial	
Case-3: No flexible segments	Gyeongju	

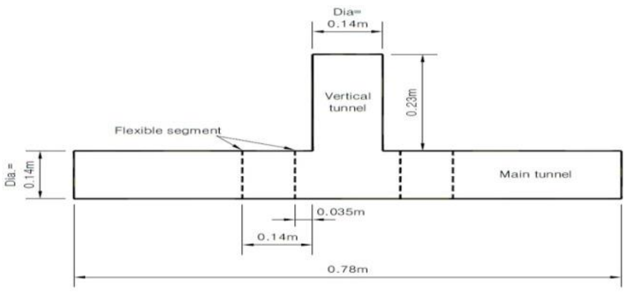


(a) Artificial wave

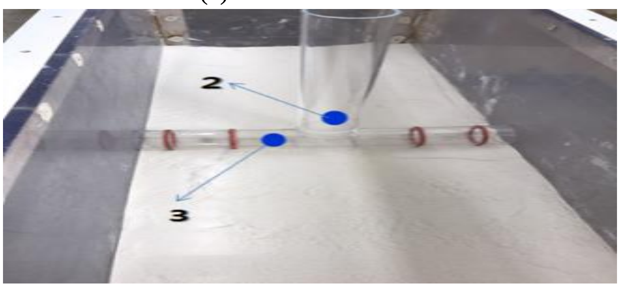


(b) Gyeogju wave

Fig. 3 Acceleration time histories of input motions



(a) Model dimension



(b) Model appearance

Fig. 4 Model tunnel and the locations of 3 accelerometers

The definition of the similitude relation between the test model and the prototype has priority over the other test procedures. Iai (1989) derived a general similitude relation for the shaking table tests on saturated soil-structure-fluid model in 1-g gravitational field, which is applied to this study. Table 1 describes the similitude relation used for this study.

2.3 Input motions and test cases

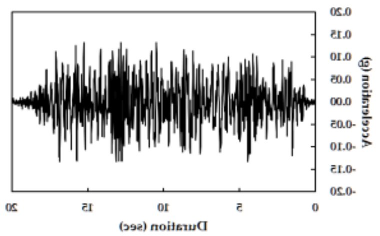
The main purpose of a series of shaking table tests is to investigate the dynamic response of tunnel; therefore, the input motions include various frequency characteristics and durations. In this study, 2 different seismic waves are utilized as shown in Fig. 3.

The artificial wave has both long and short periodic characteristics and Gyeongju wave is derived from Gyeongju earthquake occurred in 2016, which marked 5.8 in Richter magnitude and it contains short periodic characteristics. The peak accelerations of all waves are scaled to 0.154g which represents the design acceleration for 1st Grade Structures based on Korean codes.

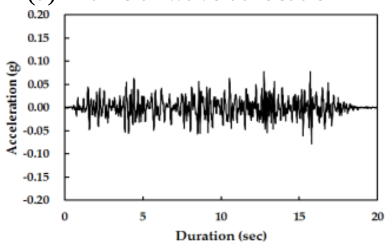
Fig. 4 demonstrates the dimension and shape of the model tunnel with 3 accelerometers implemented in the connecting area. The location of acceleration measurement points is at the soil beneath the connecting area, Location 1, spring-line of main tunnel, Location 3, and spring-line of vertical tunnel, Location 2, as shown in Fig. 4.

To determine the optimum location to mitigate the amplification of acceleration, flexible segments are installed at 0.25D and 1.0D from the vertical tunnel. The actual diameter is 14 meters, and 1:100 scaling factor is applied in this study; therefore, D is 0.14 meters. A model without flexible segments is also tested to verify the effect of flexible segments. Table 2 describes all test cases with the location of flexible segments.

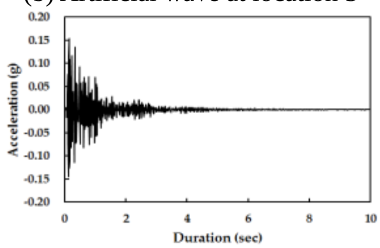
3. Test results



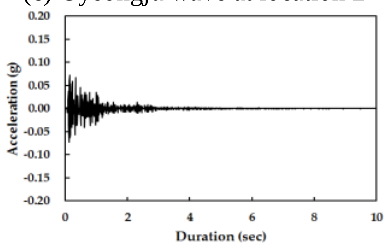
(a) Artificial wave at location 2



(b) Artificial wave at location 3



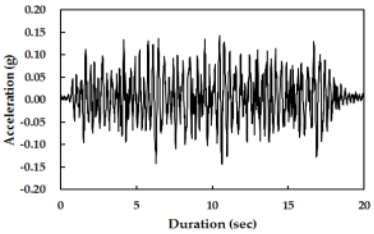
(c) Gyeongju wave at location 2



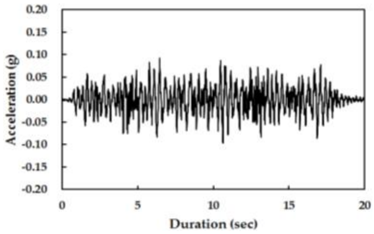
(d) Gyeongju wave at location 3

Fig. 5 Acceleration response for Case-1

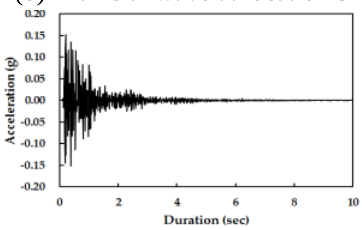
Acceleration time histories are obtained at the locations designated in Fig. 4. Acceleration responses at tunnels according to input motions and the location of flexible segments are presented in Fig. 5 to 7. Table 3 presents the peak accelerations for all locations.



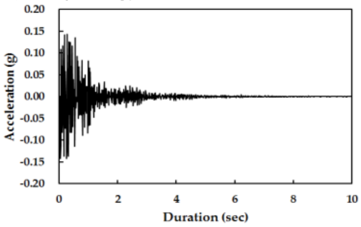
(a) Artificial wave at location 2



(b) Artificial wave at location 3

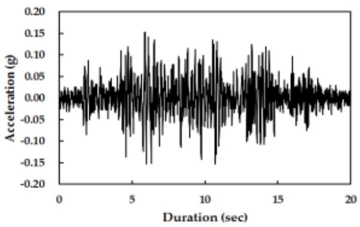


(c) Gyeongju wave at location 2

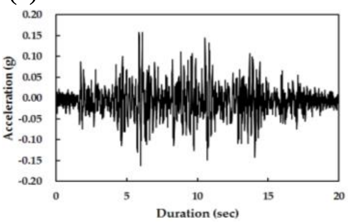


(d) Gyeongju wave at location 3

Fig. 6 Acceleration response for Case-2

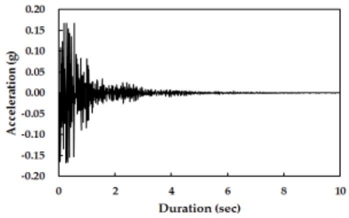


(a) Artificial wave at location 2

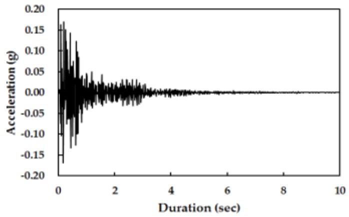


(b) Artificial wave at location 3

Fig. 7 Acceleration response for Case-3



(c) Gyeongju wave at location 2



(d) Gyeongju wave at location 3

Fig. 7 Continued

Table 3 Peak accelerations

Case	Input motion	Location	Peak Acc.(g)
1	Artificial wave	1	0.154
		2	0.132
		3	0.078
	Gyeongju wave	1	0.154
		2	0.142
		3	0.072
2	Artificial wave	1	0.154
		2	0.143
		3	0.097
	Gyeongju wave	1	0.154
		2	0.152
		3	0.142
3	Artificial wave	1	0.154
		2	0.152
		3	0.157
	Gyeongju wave	1	0.154
		2	0.167
		3	0.169

Figs. 5-7 demonstrate that peak acceleration decreases significantly in case of installing flexible segments. In general, peak accelerations exhibit lower values at Case-1 and the location 3 (spring-line of main tunnel) for both input waves. The largest reduction of peak acceleration which implies the effect of the mitigation of acceleration marks 53% and appears in case of applying Gyeongju wave, in Case-1. For Case-3, the acceleration increases 9% at the location 3, in case of applying Gyeongju wave. Therefore, it is deduced that flexible segments make an important role to reduce the amplification of acceleration. Comparing the results of Case-1 with Case-2, peak accelerations decrease 49% and 37% at Case-1 and 2, respectively when artificial wave is applied. Peak accelerations also decrease 53% and

8% at Case-1 and 2, respectively when Gyeongju wave is applied. Based on these results, it is indicated that the location of flexible segments also gives significant impact to the reduction of acceleration. In all cases, peak acceleration decreases when flexible segments located in 0.25D from the connecting area, The decrease of acceleration is more distinct in Case-1, which means flexible segments shall be installed in adjacent to the connecting area to mitigate the amplification of acceleration.

4. Numerical analysis

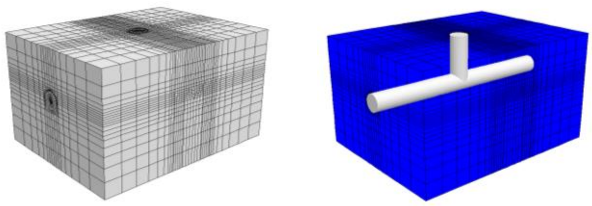
4.1 Numerical analysis conditions

3-dimensional numerical analysis by Finite Difference Method is performed to verify 1-g shaking table test results. In the numerical analysis, the trend of acceleration results considering test conditions is compared with test results. Analysis results are mostly based on the previous study (Jang *et al.*, 2017). Analysis conditions are demonstrated in Table 4 and 3-dimensional model is displayed in Fig. 8.

The locations of measuring acceleration are describing in Fig. 9 and analysis cases are same as the experimental study. The input motion is artificial wave which is the same as the experimental study as well.

Table 4 Analysis conditions (Jang *et al*. 2017)

Item	Analysis condition	Remarks
Method	Finite Difference Method (FDM)	
Commercial code	FLAC3D	
Boundary condition	Dynamic: Free-field Static-dynamic coupling	Dynamic analysis after excavation (static)
Input wave	Artificial Wave	Peak Acc. = 0.154g
Thickness of flexible segment	1,000 mm	
Structural element	Shell	



(a) 3D mesh (b) Tunnel shape

Fig. 8 Mesh generation result

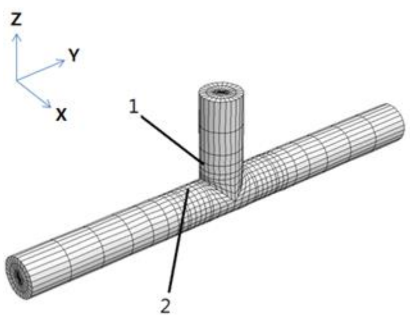
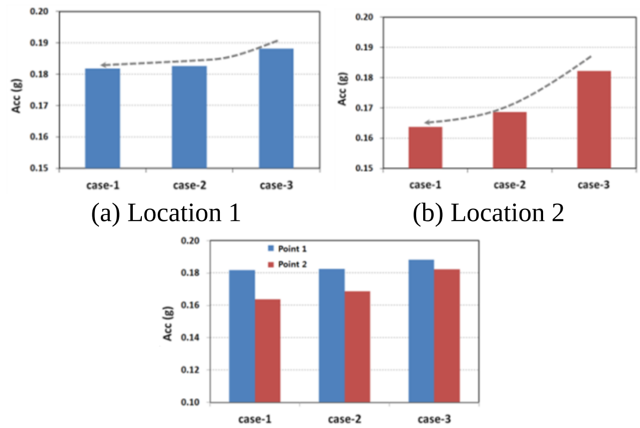


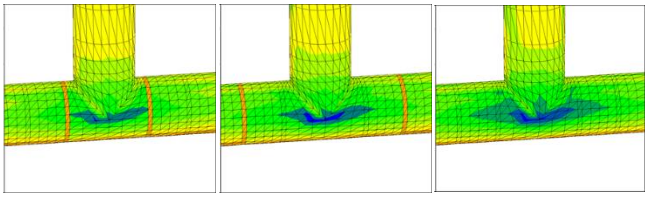
Fig. 9 Measurement locations



(a) Location 1 (b) Location 2

(c) Comparing peak accelerations

Fig. 10 Peak acceleration results



(a) Case-1 (b) Case-2 (c) Case-3

Fig. 11 Peak axial stress responses on connecting area

Table 5 Peak accelerations at location 2

Case	Input motion	Location	Peak Acc.(g)
1	Artificial wave	2	0.132
	Gyeongju wave	2	0.142
2	Artificial wave	2	0.143
	Gyeongju wave	2	0.152
3	Artificial wave	2	0.152
	Gyeongju wave	2	0.167

4.2 Numerical analysis results

Peak accelerations obtained from each measurement points are compared in Fig. 10. Without flexible segments (Case-1), peak accelerations increase at main and vertical tunnels, both. For Location 1, peak acceleration decreases 3.4% in Case-1 comparing Case-1 with 3. It also decreases 3.0% in Case-1 comparing Case-2 with 3. For Location 2, peak acceleration decreases 10.1% and 7.4% comparing Case-1, 2 with 3, respectively. Based on this result, it is deduced that the effect of the mitigation of acceleration amplification occurs more significantly in Case-1. Therefore, the optimum location of flexible segments shall be 0.25D from the connecting area.

Peak axial stress on tunnel lining is acquired and compared with the analysis case, as an additional indicator to determine the optimum location of flexible segments. The generated axial stresses exhibit identical trend with the accelerations as shown in Fig. 11. Peak axial stress surges in Case-3 and shows the minimum value in Case-1. Peak axial stress in Case-1 decreases 12.7% and 8.4% against Case-3 and 2, respectively. Therefore, the effect of flexible segment and the optimum location of flexible segment are also verified by numerical analysis.

4.3 Discussion

Peak accelerations obtained from vertical and main tunnels shows identical results in both experimental and numerical studies. As a result, the role of flexible segments to mitigate the amplification of acceleration is verified. Especially, at vertical tunnel, peak acceleration decreases from 0.167 g to 0.143 g, which indicates around 15.0%, at Case-1 under Gyeongju wave as shown in Table 5. For artificial wave, peak acceleration decreases around 13.2%, which is slightly lower than applying Gyeongju wave.

The optimum location of flexible segments shall be 0.25D from the connecting area based on both experimental and numerical studies. Peak accelerations are susceptive to the location and all cases demonstrate peak accelerations reduced in case that flexible segments are installed at 0.25D from the connecting area.

5. Conclusions

In this study, the dynamic responses of connected tunnels with flexible segments are investigated by performing 1-g shaking table tests and 3-dimensional numerical analysis. From the results of the tests and numerical analysis, the following conclusions are obtained:

(1) Remarkable effect of the mitigation of acceleration amplification by flexible segments is verified by 1-g shaking table tests. The mitigation effect is observed both in the main and vertical tunnels. The largest reduction marks 53% and appears in case of applying Gyeongju wave in Case-1. Therefore, it is induced that flexible segments make an important role to reduce the amplification of acceleration.

(2) It is indicated that the location of flexible segments gives significant impact to the reduction of acceleration. The decrease of acceleration is more distinct in Case-1, which means flexible segments shall be installed in adjacent to the connecting area to mitigate the amplification of acceleration.

(3) 3-dimensional numerical analysis demonstrates shows good agreements with the experimental study. Consequently, it is concluded that flexible segments mitigate the amplification of acceleration on tunnels and the optimum location is adjacent (0.25D) to the connecting area.

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