Investigations on seismic forces in two-tiered reinforced soil retaining walls

Xiao-guang Cai, Si-han Li, Xin Huang, Tong Lu & Wei-wei Liu
Disaster Prevention Engineering Department, Institute of Disaster Prevention, China

ABSTRACT: In order to study the calculation method of the horizontal seismic force, the two-tiered reinforced soil retaining walls structure model was constructed and large-scale shaking table tests was performed. The geometric similarity ratios of model was deduced by Buckingham π theorem. The 1.8m numerical model and the 18m numerical model were established by $FLAC^{3D}$ software. The acceleration amplification of the two-tiered reinforced soil retaining walls was tested. The results show that, acceleration amplification distribution along height of walls are non-linear. acceleration amplification of the top wall is larger than that of the low retaining wall. the results of shaking table test are smaller than that of the numerical model when model is under the same acceleration. Under different peak acceleration, the peak acceleration is larger, but acceleration amplification effect is more weakened. According to action of the single-tiered reinforced soil retaining wall and the two-tiered reinforced soil retaining wall under different accelerations, the acceleration amplification coefficient of two-tiered reinforced soil retaining wall suffered from horizontal seismic loading is defined. the formula for calculating horizontal seismic force of two-tiered reinforced soil retaining wall is proposed. The formula can provide theoretical support for seismic design and post-earthquake calculation of reinforced soil retaining wall.

Keywords: Two-tiered Reinforced Soil Retaining Wall, Horizontal Seismic Force, Calculation

1 INTRODUCTION

Reinforced soil retaining wall is a kind of flexible retaining structures, which reflects the good seismic performance under the previous earthquakes, such as the Chile earthquake, the Wenchuan earthquake in China and the 3.11 earthquake in Japan. The performance of reinforced soil retaining wall becomes the mainstream of academic research. some researches have been carried out on the dynamic characteristics of reinforced retaining wall[1-11]. However, the seismic force of the reinforced retaining wall is vague in earthquake. There is no recognized theory.

Using the static method to calculate the seismic force in standard[12], that is, regarded the structure and the foundation as rigid body, the horizontal seismic acceleration of each point is same as the ground without considering the self-vibration characteristic of the structure. Obviously, which does not apply to the flexible structure. In addition, getting the increase coefficient in calculation formula of seismic force along the reinforced soil retaining wall that is subjected to the horizontal seismic loading according to the gravity wall test in Railway Engineering Anti-Earthquake Design Specification. The above situation is not applicable for the flexible reinforced soil retaining wall. With the development of society, human beings pay more attention to space, which makes the height of reinforced soil retaining wall increase. When the height of single-tiered reinforced soil retaining wall is more than 12m, Specification[13] advises to use multi-tiered reinforced soil retaining wall in the form. But the seismic performance of the multi-tiered reinforced soil retaining wall is still scarcity. The situation of multi-tiered reinforced soil retaining wall subjected to seismic loading is unknown.

In this paper, the large-scale shaking table test and $FLAC^{3D}$ numerical model are used to calculate acceleration amplification of the two-tiered reinforced soil retaining wall, the seismic force of the flexible reinforced retaining wall is studied.

2 TEST MODEL

2.1 *Physical model*

2.1.1 *Test systems and equipment*

The experiment was carried out on the Bidirectional Electrohydraulic Servo Seismic Simulation Shaking Table at the Civil Engineering Test Center of the Institute of Disaster Prevention. test systems' technical parameters : the table size is 3.0m×3.0m; bidirectional horizontal seismic simulation; maximum displacement is ±100mm in X and Y direction; maximum acceleration is 1g(full load) in X and Y direction; maximum bearing is 20000kg.

The acquisition system is a domestic 16-channel acceleration acquisition system that can collect table acceleration and soil acceleration. The model box was used for the test is made of steel. The model box was built with length of 3.0m, height of 2.0m, width of 1.5m Test model was shown in Figure 1.

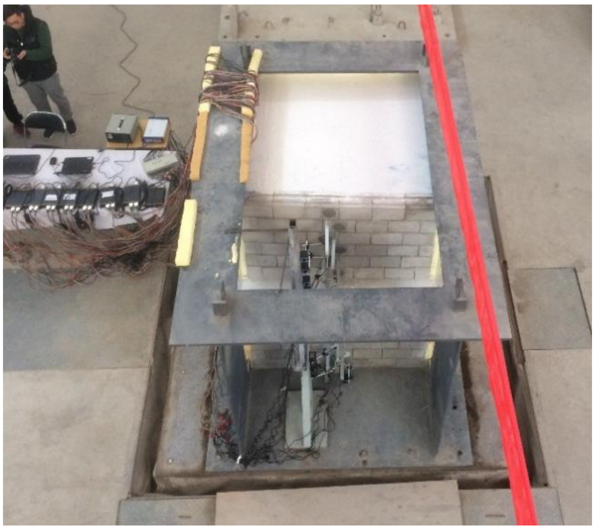


Figure 1. Model test equipment

2.1.2 *Similarity design*

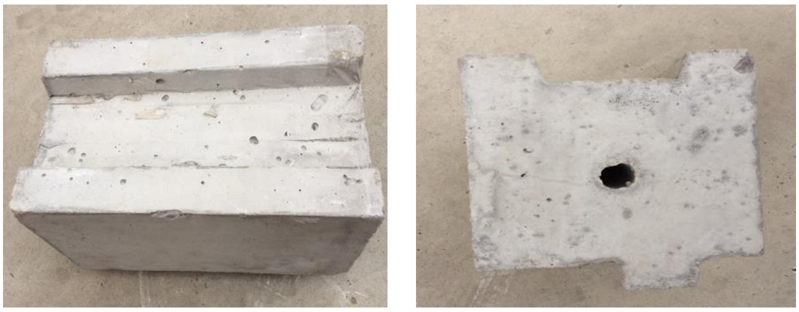
According to the bearing capacity of the shaking table and the size of the model box, the model test of 18m prototype reinforced soil retaining wall with the scale of 1:10 was introduced. Based on the geometric similarity ratios Buckingham π theorem, Regarding the model size, density, acceleration and time as the control quantities, the similarity parameters of the model are deduced. The results are shown in Table 1.

Table 1. Primary similitude coefficients of model

Physical quantities	similitude relations	Similitude coefficients
Length(L)	C_L	10
Density(ρ)	C_ρ	1
Acceleration(a)	C_a	1
Velocity(v)	$C_v= C_L^{0.5}$	3.16
Internal friction angle(ψ)	$C_\psi=1$	1
Time(t)	$C_t= C_L^{0.5}$	3.16
Frequency(ω)	$C_\omega= C_L^{-0.5}$	0.316

2.1.3 *Model material*

Test model was built with length of 1.85m, height of 1.80m, width of 1.50m. the wall is vertical. The height of the top and low walls is 0.9m. Using two kinds of self-made model brick (A, B): brick A was made with length of 25cm, height of 15cm, width of 15cm; brick B was made with length of 12.5cm,height of 15cm,width of 15cm. Model Brick is shown in Figure 2. Unidirectional geotechnical geogrid, PE50#, is produced by BOSTD Geosynthetics Qingdao Ltd in China. When the elongation of unidirectional geotechnical geogrid is 2%, the tensile strength is 17.4 kN/m by the MTS Tensile Tester. When the elongation of unidirectional geotechnical geogrid is 5%, the tensile strength is 32.7 kN/m by the MTS Tensile Tester. Horizontal isometric arrangement of reinforcement, the vertical spacing of 15cm, lay length of 90cm.Backfilling sand uses standard sand. Relative denseness is 0.7, layered pressure. The physical and mechanical properties of standard sand are shown in Table 2.



(a)Model brick front (b)Model brick side

Figure 2. Model brick

Table 2. Physical and Mechanical parameters of filling

Characteristic particle size(mm)			Nonuniform coefficient	Curvature coefficie	Maximum dry density
d_{60}	d_{30}	d_{10}	C_u	C_c	ρ_d
0.37	0.29	0.18	2.055	1.262	1.82

2.1.4 *Modeling*

The arrangement of sensors in the test model is shown in Figure 3.

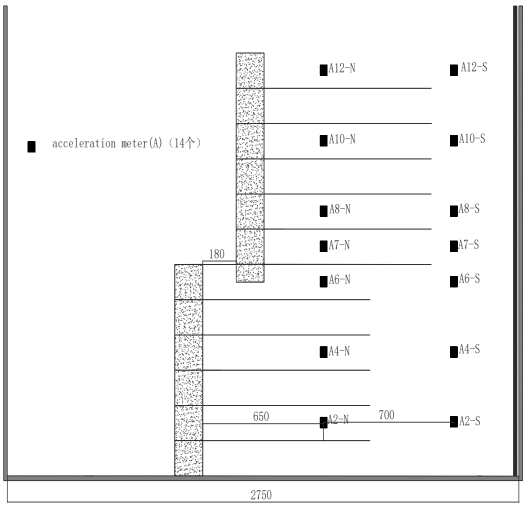
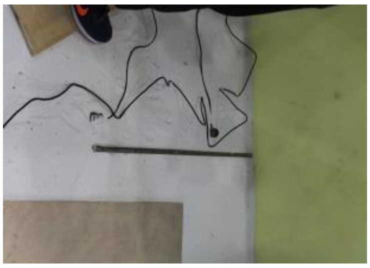


Figure 3. Shaking table test model（Unit：mm）

The arrangement of sensors: 14 accelerometers are arranged in F2, F4, F6, F7, F8, F10, F12 reinforced filling area and non-reinforced fill area and used to test the dynamic response of backfilling sand. The model is shown in Figure 4.



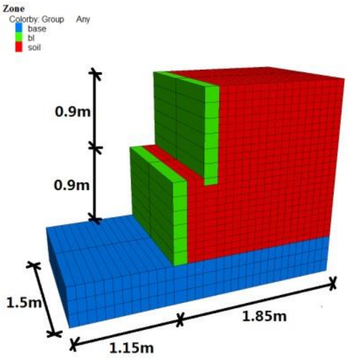
(a) Accelerometer (b) the finished model

Figure 4. Model making

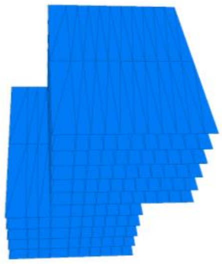
2.2 *Numerical model*

2.2.1 *Geometric model*

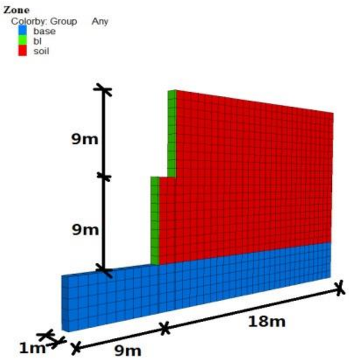
The numerical models of the two-tiered reinforced soil retaining wall are shown in Figure 5. The green part is the retaining wall, the blue part is the foundation, and the red part is the filling. 1.8m numerical model is same size with physical model. Taking 1.5m retaining wall to calculate at Y direction. After the panel, the width of the filling is 1.85m, the left margin of the foundation extends to 1.15m outside the panel, and the foundation boundary extends to 0.45m below the fill. 18m numerical model, taking 1.0m retaining wall to calculate at Y direction. After the panel, the width of the filling is 27m, the left margin of the foundation extends to 9.0 m outside the panel, and the foundation boundary extends to 5.0m below the fill.



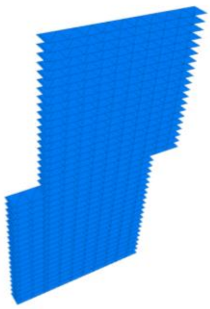
(a)1.8m Model



(b)1.8m Model geogrid



(c)18m Model



(d)18m Model geogrid

Figure 5. Numerical model of two-tiered reinforced retaining wall

The models are divided into four parts: foundation, wall panel, backfill and geogrid. In the calculation, the constitutive model of foundation and panel adopts elastic model, and the constitutive model of filling is Mohr-Coulomb model. The foundation, panel and fill are solid elements, and geogrid uses software[14] with structural unit to simulate. Panel, foundation and other calculation parameters using other scholars[15] research results, the fill parameters of the numerical calculation are the same as those of the physical model. Table 3 and Table 4 show the material calculation parameters.

Table 3. Calculation parameters of foundation and panel and filling soil

Material	Shearing modulus/kPa	Bulk modulus/kPa	Density /kg.m^{-3}	Cohesion /kPa	Internal friction angle/°
Foundation	7.70×10^{5}	1.67×10^{6}	2600	--	--
Panel	8.70×10^{6}	9.50×10^{6}	2500	--	--
Fill	1.50×10^{4}	4.04×10^{4}	1910	8.3	41

Table 4. Calculation parameters of geogrid

Elastic modulus/Pa	Poisson ratio	Friction angle of the coupling spring /(°)	Reinforcement thickness/mm	Density /(kg.m^{-3})
1.60×10^{10}	0.33	30	1	1000

2.2.2 *Boundary conditions*

The model is subjected to the initial stress calculation under static conditions before the dynamic calculation, as shown in Figure 5. The velocity of the bottom in the X, Y, Z direction remains constant. 1.8m model, the velocity in the X direction remains constant at x=-1.15m and x=1.85m surfaces, the velocity in the Y direction remains constant at y=0m and y=1.5m surfaces. 18m model, the velocity in the X direction remains constant at x=-9m and x=27m surfaces, the velocity in the Y direction remains constant at y=0m and y=1m surfaces.

Figure 6 shows the model boundary diagram. The foundation is a rock mass with large modulus, which can be regarded as a rigid foundation. Therefore, the static boundary condition can not be set at the bottom of the model, and the free field boundary is only set on both sides of the model.

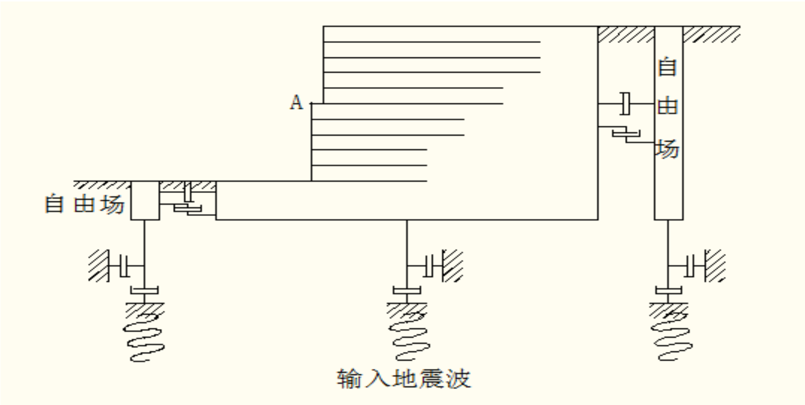


Figure 6. Schematic diagram of model boundary

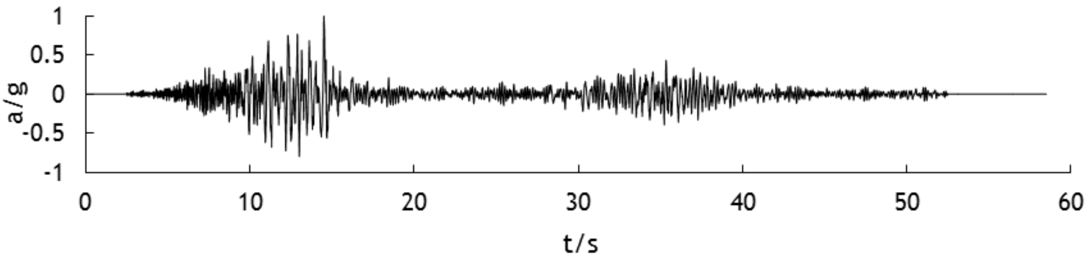
2.2.3 *Mechanical damping*

Damping mainly comes from the friction of material internal and the surface slip. FLAC^{3D} dynamic analysis module provides three forms damping, Rayleigh damping, local damping and viscous damping. In this paper, the local damping is used, and the damping coefficient is 0.157. The local damping achieves convergence by adding or subtracting the mass at the node or structural element node in the vibration cycle. Since the increased unit mass and reduced unit mass are equal, overall, the system maintains mass conservation. The local damping coefficient is: $\alpha_L=\pi \cdot D$,D is the critical damping ratio.

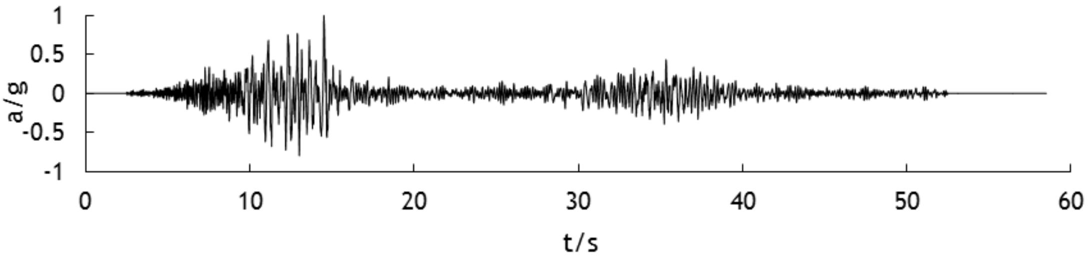
2.3 *Test conditions*

In order to understand the acceleration amplification of the stepped reinforced soil retaining wall, the peak acceleration of the test condition is gradually increased until the retaining wall is damaged. Test input unidirectional horizontal earthquake wave for the Wolong wave (code WL), EL-Centro wave (code EL). Wenchuan earthquake Wolong wave peak acceleration is 1.0g. The time interval of data point is 0.005s. EL-Centro peak acceleration is 1.0g. The time interval of data point is 0.02s. Duration time is

58.5s.Time and peak acceleration may be adjusted and compressed, seismic wave path curve as shown in Figure 7.



(a) WL wave



(b) EL wave

Figure 7. Input time history of earthquake acceleration

Each time white noise is input model to sweep before entering the seismic wave conditions, inputing conditions in Table 5.

Table 5. Loading cases for model test

Case	Earthquake wave	PGA/g	Name
1	WL	0.2	WL0.2g
2	EL	0.2	EL0.2g
3	WL	0.4	WL0.4g
4	EL	0.4	EL0.4g
5	WL	0.8	WL0.8g
6	EL	0.8	EL0.8g
7	WL	1.2	WL1.2g
8	EL	1.2	EL1.2g
9	WL	1.6	WL1.6g

3 EXPERIMENTAL RESULTS

The ratio of the counter top acceleration to the peak acceleration in the soil is defined as the PGA amplification factor. The 0~0.9m part of the 1.8m retaining wall and the 0~9m part of the 18m retaining wall are defined as the low wall, and the 0.9m~1.8m part of the 1.8m retaining wall and the 9~18m part of the 18m retaining wall are defined as the top wall. Figure 8 is the acceleration time history curve of the F2, the physical model in the time compression ratio of 3.16, the horizontal peak acceleration of 0.2g EL wave.

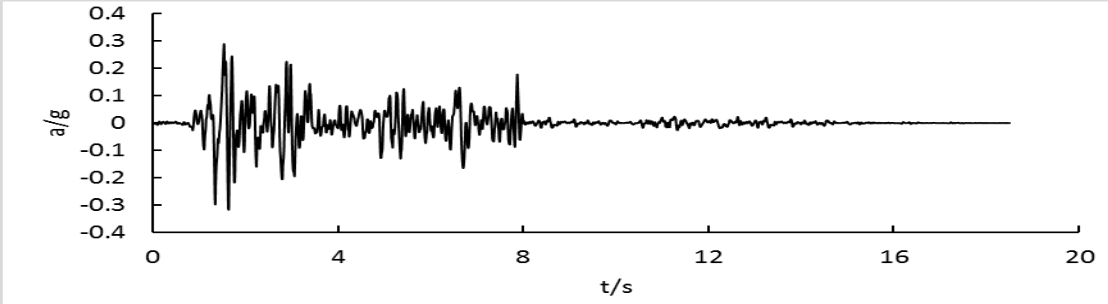
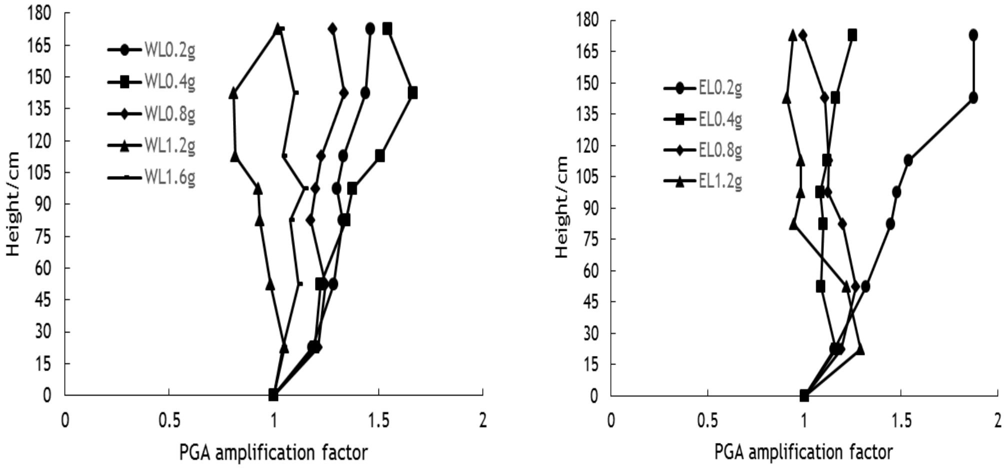


Figure 8. Time history of acceleration at F2 on EL0.2g

3.1 *Physical model calculation*

The countertop acceleration measured by the accelerometer on the table. The acceleration amplification effect is analyzed from the reinforced zone and the unreinforced zone. Figure 8 Time history of acceleration at F2 on EL0.2g.



(a) WL wave (b) EL wave

Figure 9. PGA amplification factor along the height of wall

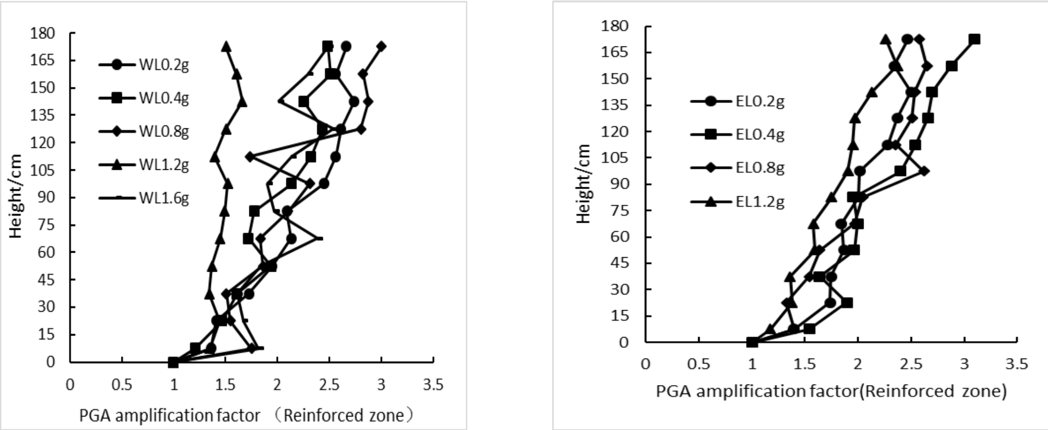
Figure 9(a) is the distribution of acceleration amplification factor along the wall height in the reinforced zone under WL wave. On the whole, there is an effect of acceleration amplification at different heights inside the retaining wall. The greater the peak acceleration is, the smaller the amplification effect is, even at WL1.2g, the amplification effect of partial position acceleration is less than 1, and the results are familiar with the results of Zhu Hong-wei. There are reasons, mainly with the increase of the peak acceleration, the wall of the retaining wall displacement, earth's settlement and the strain of the geogrid make the energy of the seismic wave dissipate along the wall greatly, which makes the amplification effect is reduced. The acceleration amplification of the low retaining wall is more concentrated, while the acceleration amplification of the upper retaining wall is more dispersed.

Figure 9(b) is the distribution of acceleration amplification factor along the wall height in the reinforced zone under EL wave. As can be seen from the figure, the acceleration amplification effect decreases with the increase of the peak acceleration, and the law is consistent with WL wave.

3.2 *Numerical calculation*

3.2.1 *1.8m model*

Figure 10 is the distribution of the acceleration amplification factor along the wall height of the 1.8m reinforced soil retaining wall. On the whole, the acceleration amplification factor increases with the height of the retaining wall. The acceleration amplification effect is the smallest under EL1.2g and WL1.2g, which is consistent with the physical model test results. Also, the acceleration amplification of the low retaining wall is more consistent, and the top retaining wall is more dispersed.

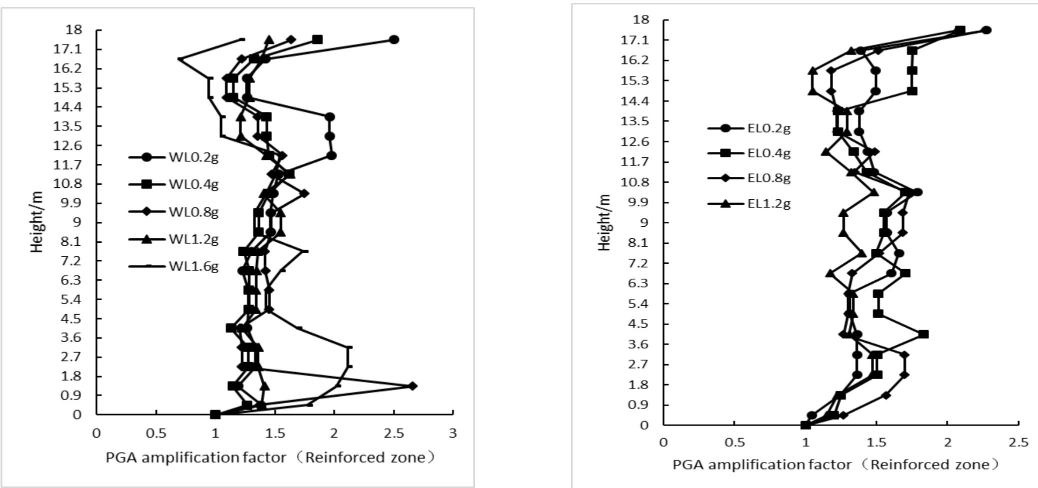


(a)1.8m WL waves (b) 1.8m EL waves

Figure 10. PGA amplification factor along the height of reinforced wall

3.2.2 *18m model*

Figure 11(a) is the distribution of the acceleration amplification factor along the wall height under WL wave in the reinforced zone of the 18m reinforced soil retaining wall. On the whole, the trend of acceleration amplification effect is same, and the acceleration amplification of the low retaining wall is gradually increasing, while the top retaining wall first decreases and then increases. Meanwhile, the acceleration amplification trend of the top retaining wall decreases with the increase of the peak acceleration, the amplification effect of partial position acceleration is less than 1, which is consistent with the physical model test.



(a) WL wave (b) EL wave

Figure 11. PGA amplification factor along the height of reinforced wall

Figure 11(b) is the distribution of acceleration amplification factor of the reinforced zone along the wall height under EL wave. From the graph, the law of acceleration amplification effect is consistent, and the amplification trend of low retaining wall first increases and then decreases, the amplification trend of the top retaining wall is reduced first and then increased, the maximum of the acceleration amplification occurs at the top of the top retaining wall.

4 ACCELERATION AMPLIFICATION FACTOR UNDER HORIZONTAL SEISMIC

In the specification[12], the horizontal seismic force at the center of the wall above the i-th section of the retaining wall is calculated according to the formula:

$$F_{ihE} = \eta \cdot A_g \cdot \eta_i \cdot m_i \quad (1)$$

where： F_{ihE}=the horizontal seismic force at the center of the wall above the i-th section(kN);

η=horizontal seismic action correction factor,the value of rock foundation is 0.20 the value of non-rock foundation is 0.25;
A_g=the peak acceleration of seismic;
η_i=along the height of wall coefficient increasing under horizontal seismic,H≤12m,η_i =1,H>12, η_i =1+h/H;
m_i=the mass of the wall above the i-th section(t).

The formula is derived from the gravity wall test, where the value of η_i is slightly conservative. It is not applicable to flexible reinforced soil retaining walls. The η_c is defined as the acceleration amplification factor under horizontal seismic forces, which is used to replace η_i. The experts[1-4] study the acceleration amplification situation of single-tiered flexible reinforced retaining wall in table 6. From the table, under different peak acceleration, the acceleration amplification situation is different; different panel form, the acceleration amplification factor is different.

Table 6. Acceleration amplification situation of single-tiered flexible reinforced retaining wall

Peak Accelera-tion(g)	Acceleration Amplification Factor				
	Strip-map	Wrap	Integral	Gabion	Soilbag
0.085	About 2.50	About 1.60	---	About 2.78	---
0.100	---	---	---	---	About 1.03
0.183	---	---	---	About 2.60	---
0.200	---	---	About 1.25	---	About 1.13
0.300	---	---	About 2.00	About 2.40	About 1.28
0.312	About 2.50	About 2.00	---	---	---
0.400	---	---	---	About 1.60	About 1.55
0.500	---	---	About 2.10	About 1.55	---
0.616	About 1.70	About 1.55	---	---	---
0.700	About 1.70	About 1.50	---	About 1.50	---
0.800	About 1.50	About 1.45	---	---	---
0.900	About 1.50	About 1.45	---	---	---
1.000	About 1.45	About 1.45	---	---	---

The retaining wall is divided to the top wall and the low wall. By the physical model test, the 1.8m and 18m numerical simulation test of the two-tiered reinforced soil retaining wall, the acceleration amplification situations of top and low wall are come out. Table 7 shows results. It can be seen from the table that the maximum acceleration amplification coefficient of the top and low wall is different under the different peak acceleration. The results of the physical model test and the numerical model are not the same under the same peak acceleration.

Table 7. Acceleration amplification situation of two-tiered reinforced retaining wall

Peak Accelera-tion(g)	Acceleration Amplification Factor Maximum Of Low Wall			Acceleration Amplification Factor Maximum Of top Wall		
	Physical Model	1.8m Numerical Model	18m Numerical Model	Physical Model	1.8m Numerical Model	18m Numerical Model
0.2	1.44	2.28	1.66	1.93	2.88	2.89
0.4	1.34	2.19	1.83	1.66	3.10	2.42
0.8	1.26	2.23	1.74	1.35	3.00	2.40
1.2	1.29	1.93	1.68	1.02	2.38	2.37
1.6	1.16	2.86	2.11	1.14	2.54	1.54

The single-tiered reinforced soil retaining wall is regarded as the top wall of the two-tiered reinforced retaining wall. Based on the results of physical model test and numerical simulation, the formula for calculating the seismic force of flexible reinforced retaining wall is following:

$$F_{ihE} = \eta \cdot A_g \cdot \eta_c \cdot m_i \quad (2)$$

Where: F_{ihE}=The horizontal seismic force at the center of the wall above the i-th section(kN);
η=Horizontal seismic action correction factor，the value of rock foundation is 0.20 the value of non-rock foundation is 0.25;
A_g=The peak acceleration of seismic;
η_c=The acceleration amplification factor under the horizontal seismic is calculated according to Table 8;
m_i=The mass of the wall above the i-th section(t).

Table 8. Acceleration amplification coefficient (η_c) under horizontal seismic

Peak Acceleration(g)	Lower Retaining Wall	Superior Retaining Wall
0~0.20	2.28	2.89
0.20~0.40	2.19	3.10
0.40~0.80	2.23	3.00
0.80~1.20	1.93	2.38
1.20~1.60	2.86	2.54

5 CONCLUSION

Through the physical model is tested by large-scale shaking table, numerical model of 1.8m and 18m retaining wall are established by FLAC^{3D}, the dynamic tests under different peak accelerations are carried out, the acceleration amplification effect of different models are analyzed. Besides, the calculation of horizontal seismic force of retaining wall is discussed, results are as follows:

(a) The acceleration amplification factor is non-linear variation, the acceleration amplification factor of the top retaining wall is larger than that of the low retaining wall.
(b) Under the same peak acceleration, the acceleration amplification effect of the physical model test is smaller than that of the numerical model.
(c) When the peak acceleration is different, the greater the peak acceleration is, the decreased the acceleration amplification effect is.
(d) According to the difference of acceleration, the acceleration amplification factor of two-tiered reinforced soil retaining wall under horizontal seismic force is defined, and the formula of horizontal seismic force of flexible reinforced retaining wall is put forward.

REFERENCES

Li Yun, Yang Guo-lin, Lin Yu-liang. Dynamic characteristics of reinforced gabion walls subjected to horizontal seismic loading[J]. Chinese Journal of Geotechnical Engineering,2009,31(12):1930-1935. (in Chinese)
Wang Li-yan，Sun Tian，Chen Su. Large scale shaking table test on seismic behaviors of geogrid reinforced retaining walls under near-fault and far-field ground motions[J].China civil engineering Journal, 2015,48（2）：103-110. (in Chinese)
Zhu Hong-wei，Yao Ling-kan, Zhang Xu-hai. Comparison of dynamic characteristics between netted and packaged reinforced soil retaining walls and recommendations for seismic design[J]. Chinese Journal of Geotechnical Engineering, 2012,34(11):2072~2030(in Chinese)
Liu Si-hong, Li Ling-jun, Zhang Yu-zhuo, Xu Xiao-dong, Xue Xiang-hua [J]. Journal of Hohai University(Natural Sciences), 2015,43（3）：236-243.
Zhu Hong-wei，Yao Ling-kan, Chen Xiao-long, Xiang Qin.Seismic Behavior and Design Recommendations of Ecological Bags Reinforced Retaining Wall[J]. Chinese Journal ofGeotechnical Engineering, 2016,34(11):2072~2030(in Chinese)
Zhu Hong-wei, Yao Ling-kan, Liu Zhao-sheng, Chen Xiao-long. Research on Seismic Deformation Characteristics of Flexible Wall[J]. Chinese Journal of Rock Mechanics and Engineering , 2013,31（S1）：2829-2838.
Wang Li-yan, Chen Guo-xing, Gao Peng, Chen Su, Iai S. Large-scale Shaking Table Tests on Seismic Deformation of Geo-grid Reinforced Soil Retaining Walls In Liquefiable Soils[J].China Journal of Highway and Transport., 2014,27（9）：25-31. (in Chinese)

Magdi M EL-Emam , Richard J Bathurst. Experimental design, instrumentation and interpretation of reinforced soil wall response using a shaking table [J].International Journal of Physical Modelling in Geotechnics，2004,4：13-32.

M EL-Emam , R J Bathurst. Facing contribution to seismic response of reduced scale reinforced soil walls [J].Geosynthetics International ，2005,5：215-238.

Magdi M EL-Emam , Richard J Bathurst. Influence of reinforcement parameters on the seismic response of reduced-scale reinforced soil retaining walls [J]. Geotextiles and Geomembranes ，2007,25：33-49.

Magdi M.EI-Emam.Modulus and damping from shaking table tests of reinforced soil walls[J].Geomechanics and Geoengineering,2014,9(4):279-293.

GB50111-2006 Code for Seismic design of railway engineering[S].Beijing: China Planning Press,2006.

JTJ015-91, Design Code of Highway Reinforcement Soil Engineering [S]. Beijing：China Building Industry Press ，1991.

Itasca Consulting Group, Inc. Fast Language Analysis of Continua in 3 Dimensions, Version 3.0, User’s Manual [K]. USA: Itasca Consulting Group, Inc, 2005.

Li Guang-xin. Behavior of structure with geosynthetics in earthquake[J]. World Earthquake Engineering, 2010,26(14):31-36.