Dynamic behaviour of reinforced soil retaining wall under horizontal seismic loading

Sihan Li¹, Xiaoguang Cai²³⁴, Honglu Xu²³, Liping Jing¹², Xin Huang¹²³ and Chen Zhu²³

¹Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration. Harbin Heilongjiang 150080, China;
²College of Geological Engineering, Institute of Disaster Prevention, Sanhe Hebei 065201, China;
³CEA Key Lab for Building Collapse Mechanism and Disaster Prevention, Sanhe Hebei 065201, China

Email: caixiaoguang123@163.com

Abstract. Based on the status that the reinforced soil retaining wall (RSRW) is difficult to popularize in highway in high earthquake intensity region of China. The dynamic behavior of modular-block RSRW was investigated by large-scale shaking table tests. The standard soil was taken as the backfill. The concrete blocks were selected as panel. The geogrid was reinforcement. The failure mode of the wall was observed, and dynamic response and the displacements were measured. The results showed that, the middle of retaining wall panel was slightly bulged under the inputted earthquake motion, the mortar on the surface of wall was breaking down. When the input motion was WL2.0g (model scale: 1/2), the blocks at the top fell down, then the retaining wall was destroyed. The settlements of the soil and lateral displacement of the wall increased with the increase of the acceleration motion. The acceleration amplification factor is decreased with the increase of input acceleration. When the input acceleration was larger than 0.8g, the acceleration amplification factor of upper wall gradually is decreased less than 1. When model scale and inputting earthquake motion is different, the range of acceleration amplification factor is different. Shaking table tests results of RSRW with different panel forms and reinforced materials are summarized. The results show that seismic behaviour of RSRW is excellent. It is advise to revise some items of “Chinese Specification of Seismic Design for Highway Engineering” in order to promote the application of RSRW in highway.

1. Introduction
Geo-textile technique was proposed by French engineer Henri Vidal in the 1960s. Because of it have many advantages such as short construction period, it has been widely applied in many fields such as transportation system, hydraulic engineering, port engineering and construction structure. Many reinforced soil structures built in high-risk areas of earthquakes are tested by earthquake and show good seismic behavior. Guangxin Li [1] and Kyle Rollins et al. [2] introduced the post-earthquake investigation of reinforced earth structures in Japan, the United States, Turkey, Central America, Chile, Taiwan and Sichuan in China. The results showed that the reinforced soil structures had excellent performance in earthquake without overall instability. Andrew. C. Sander et al. [3] conducted the
shaking table test by full-scale model of 6.55 m (high) × 9.10 m (length). After the seismic wave of 0.55g was input, the model was not damaged.

At the same time, many scholars have analyzed the damage cases of RSRWs. Robert M. Koerner et al. [4] investigated the failed cases of 320 RSRWs in North America, the results show that reinforced packing (73%), backfill soil compaction (76%), improper design or construction (99%), and internal or external water problems (63%) are the causes. Guangqing Yang [5] analyzed damage cases, pointed out that the damage may be caused by the insufficient connection strength between the reinforcement and the panel, the imperfect waterproof and drainage system, the insufficient use of poor packing and compactness, and the external factors of rainwater infiltration and overloading of the wall top. It can be seen from the analysis that the failure of reinforced soil structure is mainly caused by construction and has nothing to do with the structure itself.

In the Specification of Seismic Design for Highway Engineering [6], it is pointed out that "RSRW should not be adopted in areas where the designed peak acceleration of ground motion is greater than or equal to 0.20g", which seriously restricts the application of reinforced soil technology in the field of highway transportation in China. Based on modular-block RSRW as the research object, the large-scale shaking table tests (model scale: 1/4 and 1/2) were carried out. The damage phenomenon and acceleration amplification effect under seismic load were studied. The results can provide theoretical support for the RSRW application in the field of highway transportation.

2. Test system and equipment

The experiments were performed on the Bidirectional Electrohydraulic Servo Seismic Simulation Shaking Table at the Civil Engineering Test Center of the Institute of Disaster Prevention. The main technical parameters of the shaking table are as follows: the table size is 3.0 m × 3.0 m; the bidirectional lateral seismic simulation is used; the maximum displacement is ± 100 mm in the X direction and ± 100 mm in the Y direction; the maximum acceleration is 2 g (full load) in the X direction and 2 g (full load) in the Y direction; and the maximum bearing is 20 t.

The acquisition system is mainly of two types: one is a domestic 128-channel dynamic acquisition system that can collect reinforcement strain data; the other is a domestic 16-channel acceleration acquisition system that can collect table acceleration data and soil acceleration data. The model box used for the test is fabricated using steel. The internal size of the model box: 3.0 m (length) × 2.0 m (height) × 1.5 m (width). The test model was presented in Figure 1.

![Figure 1. Model test equipment.](image1)

![Figure 2. Model block.](image2)

3. Test model

3.1. Scaling factors

According to the load capacity of the shaking table and the size of the model box, the 1.8 m high wall model was made. The model scale is 1:4 and 1:2. Taking model size, density, acceleration and time as...
the control quantity, the main similar parameters of the model were deduced according to rules by Iai [7], as shown in Table 1.

| Variable                        | Scaling factor (Prototype/model) | Scaling constants |
|---------------------------------|----------------------------------|-------------------|
| L ( length (m) )                | $C_L$                            | 4 2               |
| $\rho$ ( density (g/cm$^3$) )   | $C_\rho$                         | 1 1               |
| $a$ ( acceleration (m/s$^2$) )  | $C_a$                            | 1 1               |
| $v$ ( velocity (m/s) )          | $C_v$                            | $C_L^{0.5}$ 2 1.414|
| $\varphi$ ( internal friction angle (°) ) | $C_\varphi$ | 1 1               |
| $t$ ( time (s) )                | $C_t$                            | $C_L^{0.5}$ 2 1.414|
| $\omega$ ( frequency ( Hz ) )   | $C_\omega$                       | $C_L^{-0.5}$ 0.5 0.707|

### 3.2. Model Materials

The test model is 2.0 m (length) $\times$ 1.5 m (width) $\times$ 1.8 m (height). Two types of self-made block are adopted with size of 0.25 m (length) $\times$ 0.15 m (width) $\times$ 0.15 m (height) and 0.125 m (length) $\times$ 0.15 m (width) $\times$ 0.15 m (height), respectively. Figure 2 is the blocks model. The geogrid material is PE50, the tensile unit is 22.5 cm, rib spacing is 2.22 cm and rib thickness is 0.1 cm. The tensile force is 17.4 KN/m at 2 % elongation on MTS tensile tester. The arrangement of reinforcement is lateral isometric. The vertical spacing is 15 cm. The laying length is 1.26 m. Backfill sand use standard sand. The relative compactness is 0.7. The physical properties of standard sand are shown in Table 2.

### 3.3. Sensor arrangement

Figure 3 shows the specimen design diagram. 12 accelerometers are arranged in the reinforced and unreinforced zone of A2, A4, A6, A8, A10, and A12 to test the dynamic response of backfill. The instrument layout in the test is shown in Figure 4.

### 3.4. Test conditions

In order to understand the seismic behavior of the RSRW, the peak acceleration of loading gradually increased in the test case until the RSRW was damaged. In the test, the input unidirectional horizontal
seismic motions were Wolong motion (WL) and El-centro motion (EL). The duration time is 58.5 s. Peak acceleration and time compression can be adjusted as required, and the time-history curve of seismic motion is shown in Figure 5.

Before the change of energy level of input peak acceleration, white noise was input to sweep the frequency of the model. The test condition is shown in Table 3. After each working condition, the data was checked, and the external damage of the model was recorded and photographed. All acquisition channels were return-to-zero and the model was regarded as a new model for the next working condition until the model was destroyed.

![Figure 5. Input time history of earthquake acceleration.](image)

Table 3. Loading cases of model test.

| Case number | Input wave | PGA/g | Similarity ratio | Case code |
|-------------|------------|-------|------------------|-----------|
| 1, 2        | WL, EL     | 0.05  | 4                | WN        |
| 3, 4        | WL, EL     | 0.1   | 2                | WL0.1g, EL0.1g |
| 5, 6        | WL, EL     | 0.2   | 1                | WN        |
| 7, 8        | WL, EL     | 0.2   | 2                | WL0.2g, EL0.2g |
|             | White Noise| 0.05  | 1                | WN        |
| 9, 10       | WL, EL     | 0.4   | 4                | WL0.4g, EL0.4g |
| 11, 12      | WL, EL     | 0.4   | 2                | WL0.4g, EL0.4g |
|             | White Noise| 0.05  | 1                | WN        |
| 13, 14      | WL, EL     | 0.6   | 4                | WL0.6g, EL0.6g |
| 15, 16      | WL, EL     | 0.6   | 2                | WL0.6g, EL0.6g |
|             | White Noise| 0.05  | 1                | WN        |
| 17, 18      | WL, EL     | 0.8   | 4                | WL0.8g, EL0.8g |
| 19, 20      | WL, EL     | 0.8   | 2                | WL0.8g, EL0.8g |
|             | White Noise| 0.05  | 1                | WN        |
| 21, 22      | WL, EL     | 1.0   | 4                | WL1.0g, EL1.0g |
| 23, 24      | WL, EL     | 1.0   | 2                | WL1.0g, EL1.0g |
|             | White Noise| 0.05  | 1                | WN        |
| 25, 26      | WL, EL     | 1.2   | 4                | WL1.2g, EL1.2g |
| 27, 28      | WL, EL     | 1.2   | 2                | WL1.2g, EL1.2g |
|             | White Noise| 0.05  | 1                | WN        |
| 29          | WL         | 1.6   | 4                | WL1.6g    |
| 30          | WL         | 1.6   | 2                | WL1.6g    |
|             | White Noise| 0.05  | 1                | WN        |
| 31          | WL         | 2.0   | 4                | WL2.0g    |
| 32          | WL         | 2.0   | 2                | WL2.0g    |

4. Experimental results and analysis

4.1. Model destruction Phenomenon

The wall displacement gradually increases as the peak acceleration increases. First, there is a slight "bulge" in the middle of the wall, and the mortar on the wall surface begins to fall off. Then the top model blocks are over-displaced under WL 2.0 g (scaling factor: 1/2), the top model blocks are all dropped, and the model is destroyed. The result reflects the seismic performance of RSRW. The specific damage is shown in Figure 6.
4.2. Horizontal displacement and settlement

Settlement at the top sand of the RSRW under seismic loading is showed in Figure 7. It can be seen that backfill settlement value is relatively small when peak acceleration is relatively small, and the settlement of backfill under different working cases is not much different, or even basically unchanged. The settlement value of backfill increases gradually with the increase of peak acceleration, Visual observation of settlement is given in Figure 8.

In order to understand the settlement of internal backfill soil intuitively, blue sand is laid every 15 cm during the construction. The blue sand position and block position of each layer are recorded on the plexiglass after each working case, as shown in Figure 9. Due to the large number of working cases and large amount of data recorded, only the blue sand settlement and displacement of top panel are listed, as shown in Figure 10 and Table 4. When the peak acceleration is small, the settlement is very small, which is invisible to the people. The peak acceleration increases continuously, the settlement gradually increases, and the blue sand gradually turns into a circular arc. The settlement of the blue sand of other layers was observed, which was basically consistent with the blue sand of the top layer. Similarly, it can be seen from Table 4 that the displacement of the top panel is very small with the peak acceleration small. The peak acceleration increases and the horizontal displacement increases until the top blocks fell down.
4.3. Acceleration amplification

The ratio of the peak acceleration in the backfill to the acceleration at the foundation level is defined as the amplification factor. The acceleration at the foundation is measured by the accelerometer on the table. Figure 11 shows acceleration response of reinforced soil zone in A2-N under the WL and EL (scaling factor: 1/4).

Figure 12 and 13 shows acceleration amplification under WL and EL (scaling factor: 1/4 and 1/2). It can be seen that the amplification factor exists in different height of RSRW. When the inputted peak acceleration is small, the acceleration amplification effect at the top of the RSRW is most significant. As the peak acceleration increases, the overall acceleration amplification attenuates, and the attenuation of the top acceleration amplification is the most obvious. When the inputted peak acceleration is greater than 0.8g, the acceleration amplification effect at the top wall is less than 1. Figure 12 (a) shows the acceleration amplification coefficients are range in 0.80~1.46 under WL at different peak acceleration. Figure 12 (b) shows that the amplification coefficients under EL is...
0.79–2.07. Figure 13 (a) shows that the range of acceleration amplification factor under WL is 0.71–1.53, Figure 13 (b) shows that the acceleration amplification factor under EL is 0.91–1.76.

![Figure 11. Acceleration response of A2-N (scaling factor: 1/4).](image1)

![Figure 12. Acceleration amplification distribution along height (scaling factor: 1/4).](image2)

![Figure 13. Acceleration amplification distribution along height (scaling factor: 1/2).](image3)

The trend of acceleration amplification changes is consistent with the results of Cai et al. [8]. The main reasons of acceleration amplification factor at the top wall less than 1 are that with the increase of the peak acceleration, the displacement of the top wall, the top settlement of the soil and the strain of the geogrid causing the energy dissipation under seismic motions, thus reducing the amplification effect. The greater the peak acceleration, the more obvious the seismic energy dissipation effect of the RSRW. And when the inputted peak acceleration is greater than 0.8g, the acceleration amplification effect at the A2-N is most significant, the main reasons are that the displacement of the bottom wall is small, the support effect of the reinforcement is significant, and the settlement between layers is small, which make less energy dissipation relative to other positions. At the same time, comparing the different scaling factor and seismic waves of the above figure, it can be known that the range of
acceleration amplification effects is inconsistent because the seismic motion spectrum characteristics of different types and scaling factors are different.

4.4. Comparison analysis

Table 5 is the shaking table test conducted by domestic experts [9-12] on RSRWs with different panel forms. It can be seen from this table that the RSRWs of different panel forms have good seismic behavior, and no significant damage occurs when the peak acceleration is 0.50 g or less.

| Panel                  | Model                        | Input seismic wave          | Test results         |
|------------------------|------------------------------|-----------------------------|----------------------|
| Whole Panel            | Panel : 0.7 m (height) × 0.05 m (width), total length: 1.4 m | Shifang pant: 0.2 g, 0.3 g  | No obvious damage    |
|                        |                              | Songpan: 0.2 g, 0.3 g, 0.5 g |                      |
|                        |                              | Taft: 0.3 g                 |                      |
| Block wrapping/Block bands| Each layer is 0.2 m, model height: 2.0 m | Darui: 0.085 g, 0.312 g, 0.616 g, 0.7 g |                      |
|                        |                              | EL (N-S): g, 0.8 g, 0.9 g, 1.0 g |                      |
|                        |                              | Kobe: 0.3 g                 |                      |
| Soilbag                | Geogrid with 6 layers, model height: 2.0 m | Darui: 0.085 g, 0.312 g, 0.616 g |                      |
|                        |                              | EL (N-S): 0.17 g, 0.34 g, 0.51 g, 0.68 g |                      |
| Gabion                 | Each layer is 0.4 m, model height: 2.0 m | ELCE-NS: 0.17 g, 0.34 g, 0.51 g, 0.68 g |                      |
|                        |                              | HACHI-EW: 0.09 g, 0.18 g, 0.27 g, 0.36 g |                      |

As shown in Figure 12, Figure 13 and table 5, it is suggested to revise the provisions of the code that "reinforced soil retaining wall should not be used in zone where design basic ground motion peak acceleration to be greater than or equal to 0.2 g", so as to facilitate the further promotion and application of the flexible structure of reinforced soil retaining wall in the field of highway transportation.

5. Conclusions and discussions

The dynamic response of the modular-block RSRW under earthquake action is studied, and the failure mode, failure process and acceleration response of the reinforced soil retaining wall are observed by the large-scale shaking table test. The following conclusions are obtained:

(1) Under the action of the earthquake, the retaining wall panel has a slight bulging in the middle of the retaining wall, and the mortar on the wall surface falls. In the case of WL2.0 g (scaling factor: 1/2), the displacement of the top model blocks is so large that the top model blocks are all dropped, and the model is destroyed. Backfill settlement and horizontal displacement of wall panel increased with peak acceleration increase.

(2) The acceleration has an amplification effect along the wall height, and the acceleration amplification factor decreases with the increase of the peak acceleration. When the peak acceleration is greater than 0.8 g, the magnification of the top wall is gradually less than 1, the nonlinear dynamic response of soil and the energy dissipation effect of RSRW is remarkable.

(3) The spectrum characteristics of different types and scaling factor is different, the range of acceleration amplification factor is different.

(4) The test of RSRW with different panel type shows that the seismic behavior of RSRW is excellent. In order to promote the application of reinforced soil structure in the field of highway transportation, it is suggested to modify some provisions in the code of road seismic design.

Although some findings of this study, such as the acceleration amplification may be intuitive, others are not as obvious and were revealed for the first time in this study. These include the face displacement, the reinforcement strain distribution and dynamic soil pressure. Regarding post-earthquake investigations of RSRW, new technologies should be considered, such as drones [13]. The acceleration amplification effect can only determine that the seismic effect of RSRW is excellent, and it is not a good way to quantify the damage of RSRW under dynamic loading. As for the damage degree of RSRW, there are quantify methods mainly based on displacement control index, but the methods are not perfect, and further research is still needed. For post-earthquake repairs, multiple methods need to be considered, such as reinforcement of steel-concrete composite structures [14-16].
Acknowledgements
The authors appreciate the support of the National Natural Science Foundation of China (No.51778144), Earthquake Technology Spark Program of China (XH204402), Graduate Innovation Funding Project of Hebei Province (CZXXSS2020150) and Graduate Innovation Funding Project of the Fundamental Research Funds for the Central Universities (ZY20200301, ZY20200311).

Reference
[1] Li Guangxin. 2016 Earthquake and earth reinforcement [J] China Civil Engineering Journal 49 (7) 1-8
[2] Kyle Rollins, Christian Ledezma, Gonzalo Montalva 2014 Geotechnical aspects of April 1,M8.2 iquique, Chile earthquake [R] Geotechnical extreme events reconnaissance (GEER) association report No. GEER - 038. Version 1.2: October 22, 2014
[3] Andrew C. Sander, Patrick J. Fox, Ahmed Elgamal 2014 Full-Scale Seismic Test of MSE Retaining Wall at UCSD [C] Geo-Congress
[4] Robret M.Koerner, George R.Koerner. 2018 An extended data base and recommendations regarding 320 failed geosynthetic reinforced mechanically stabilized earth (MSE) walls [J] Geotextiles and Geomembranes 46 904-912
[5] YANG Guang-qing. 2018 Design and Engineering Application of Reinforced Soil retaining Walls [R] Taiyuan The Training of Geosynthetic material Reinforced Soil retaining Wall Structure and Engineering Application
[6] Specification of Seismic Design for Highway Engineering (JTGB02-2013) [S] Beijing: China Communications Press 2013
[7] Iai, S. 1989 Similitude for shaking table tests on soil-structure-fluid model in 1g gravitational field Rep Port and Harbour Research Institute 27 No 3 Japan Ministry of Transport, Tokyo
[8] Cai Xiao-guang, Li Si-han, Huang Xin 2018 Shaking Table Tests on Dynamic Characteristics of Two-stage Reinforced Soil retaining Wall [J] China J. Highw Transp 31(2) 200-207
[9] Zhu Hong-wei, Yao Ling-kan, Chen Xiao-long, et al. 2016 Seismic Behavior and Design Recommendations of Ecological Bags Reinforced Retaining Wall [J] Chinese Journal of Geotechnical Engineering 34(11) 2072-2080
[10] Li Yun, Yang Guo-lin, Lin Yu-liang 2009 Dynamic characteristics of reinforced gabion walls subjected to horizontal seismic loading [J] Chinese Journal of Geotechnical Engineering, 31(12) 1930-1935
[11] Wang Li-yan, Sun Tian, Chen Su. 2015 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, 48(2) 103-110
[12] Zhu Hong-wei, Yao Ling-kan, Zhang Xu-hai. 2012 Comparison of dynamic characteristics between netted and packaged reinforced soil retaining walls and recommendations for seismic design [J] Chinese Journal of Geotechnical Engineering 34(11) 2072-2080
[13] Micelli, F., Cascardi, A. 2020 Structural assessment and seismic analysis of a 14th century masonry tower. Engineering Failure Analysis 107 104198
[14] Sheng Peng, Chengxiang Xu, Mengxiao Lu. et al. 2018 Experimental research and finite element analysis on Engineering structures seismic behavior of CFRP-strengthened seismic-damaged composite steel-concrete frame columns”, Engineering Structures 155 50-60
[15] Cheng-Xiang Xu, Sheng Peng, Jie Deng. et al. 2018 Study on seismic behavior of encased steel jacket-strengthened earthquake-damaged composite steel-concrete columns Journal of Building Engineering 17 154-166
[16] Chengxiang Xu, Sheng Peng, Chenfei Wang. et al. 2020 Influence of the degree of damage and confinement materials on the seismic behavior of RC beam-SRC column composite joints Composite structures 231 111002