Effects of earthquake characteristics on the seismic response of geosynthetic-reinforced soil walls

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ABSTRACT: Seismic design of geosynthetic-reinforced soil (GRS) walls or slopes generally uses only the peak acceleration to check external and internal stability at present. Calibrated Finite Element procedure was used in this study to check this assumption, in which a 6-meter segmental reinforced soil wall with geogrid reinforcement was analyzed using several real earthquake records. Effect of vertical seismic excitation was also investigated. The results showed that both reinforcement load and lateral facing displacement were significantly affected by the characteristics of earthquake excitations other than maximum acceleration magnitude, and that vertical earthquake component could lead to further compaction of backfill soil and reduce the residual displacement of GRS walls, but it could increase the reinforcement load due to the increase of localized stretch at reinforcement connection with facing units. The results indicated it would be more rational to take into account the amplification of seismic response as well as backfill soil compaction due to horizontal and vertical seismic loadings in the seismic design of GRS walls.

1 INTRODUCTION

Seismic design of geosynthetic-reinforced soil (GRS) walls or slopes generally uses only the peak acceleration to check external and internal stability at present (e.g. Elias et al. 2001). It is assumed that the frequency characteristic and duration of seismic excitation only have negligible influences on the seismic performance of GRS structures. Among these two factors, the duration of seismic loading has raised some interest through the use of Newmark's method to analyze GRS structures (e.g., Ling 2001). However, it is generally believed that the natural frequency of GRS structure is quite different from the frequency of seismic excitation, and thus the amplification of seismic motion due to the frequency characteristic of seismic motion are generally not considered.

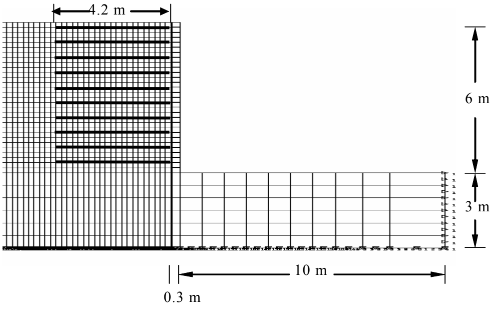


Fig. 1 Part of the Finite Element mesh

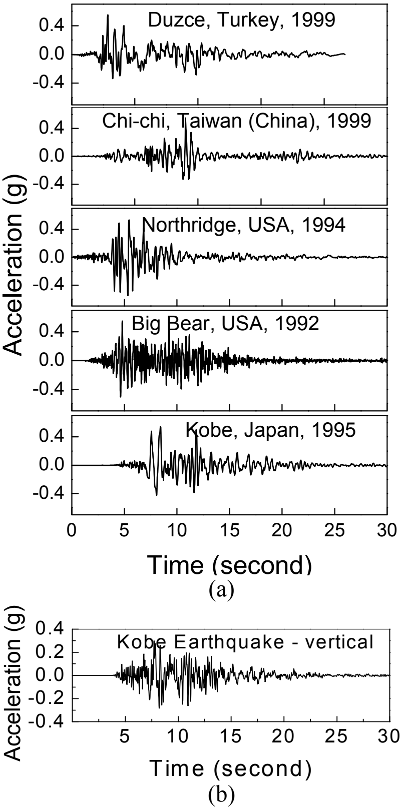
Neglecting the vertical earthquake component is another assumption in the present seismic design of GRS structures. The assumption may be valid when the vertical acceleration is much smaller than the horizontal component. However, recent earthquakes have shown that the magnitude of vertical acceleration can be quite significant.

In the present study, calibrated Finite Element procedure was used to investigate the effects of earthquake characteristics other than the maximum acceleration in the horizontal direction. Different earthquakes with the same maximum magnitude, and the same horizontal excitation with different vertical earthquake motions, were analyzed. The present study focuses on the lateral facing displacements and maximum reinforcement loads of GRS walls, which are the two most important parameters of their seismic response.

2 FINITE ELEMENT MODEL

The Finite Element analysis was conducted on a model geogrid-reinforced soil retaining wall at a height of 6.0 m with modular-block facing. The Finite Element procedure in this study involves construction sequence simulation followed by dynamic analysis with an assumption of plane strain condition. The analysis was conducted using the Finite Element program MODIFIED DYNA-SWAN-DYNE-II (Chan 1993; Liu 2002; Liu & Ling 2007).

The backfill was assumed to be a medium-dense silty sand (Ling et al. 2004), the dry unit weight of which is 15.6 kN/m^3 and the friction angle ϕ of which in triaxial compression is about 40° at an effective confining pressure of p' = 30 kPa. The foundation soil was assumed to be dense Toyoura sand (Ling and Liu 2003). They were both simulated using the generalized plasticity model for sand (Ling & Liu 2003). The reinforcement was assumed to be a HDPE geogrid, the rupture strength of which is about 55 kN/m (Ling et al. 2001; Liu & Ling 2005, 2007), and was modeled using the elasto-plastic visco-plastic bounding surface model for geosynthetics (Liu & Ling 2005, 2007). The reinforcement was assumed to be pinned to the facing blocks, with a length of 4.2 m (0.7 H) and a spacing of 0.6 m, respectively. The model parameters for the sands and geogrid are shown in Table 1 and Table 2, respectively (Ling and Liu 2003; Ling et al. 2004; Liu & Ling 2005, 2007). The interfaces between backfill soil and facing blocks as well as those between concrete blocks were simulated using thin-layer slip elements (Chan 1993; Ling et al. 2004) which express the slippage of soil-structure interface based on Mohr-Column failure criterion. Considering the fact that most geogrid reinforcements have large aperture size, the reinforcement and backfill soil were assumed to be perfectly bounded.



(a)

(b)

Fig. 2 Input accelerations

The Finite Element model was fixed at the bottom in both direction, and on the right and left boundaries in the horizontal direction. Horizontal and vertical seismic excitations were input at the bottom, assuming that the model walls were constructed on a soil foundation that was 3-meter deep and rested on bedrock. To minimize the effect of boundary reflection, large model was used, with large element size close to the side boundaries (Ling et al. 2004). Fig. 1 shows part of the Finite Element mesh. The calibration and verification of the Finite Element procedure is discussed in Liu (2009).

Different horizontal earthquake records from recent strong earthquakes were firstly analyzed, including a record from the 1992 Big Bear earthquake in USA, a record from the 1994 Northridge earthquake in USA, a component of the 1995 Kobe earthquake in Japan, a record from the 1999 Chi-Chi earthquake in Taiwan (China), and a record from the 1999 Duzce earthquake in Turkey. The maximum magnitudes of these earthquakes were all scaled to 0.55g but their duration and frequency were maintained. Fig. 2a shows the five seismic excitations used in the analysis. The second series of analysis focused on the influence of earthquake frequency, in which the Kobe earthquake was used, but its frequency was purposely lengthened or shortened while the magnitude and duration were maintained. The last series of analysis investigated the influence of vertical earthquake component, in which a vertical component of the Kobe earthquake was used in combination with the horizontal component, but with various magnitudes. Fig. 2b shows the vertical earthquake component with $a_{\max}^{v}$ = 0.3g. In the first two series, no vertical excitation was considered.

Table 1 Material constants of the soils

Material constants	Back-Fill soil	Found-ation soil	Material constants	Back-Fill soil	Found-ation soil
ϕ_0 (°)	39.4	43.7	β_0	20	15
$\Delta\phi$ (°)	0.5	4.9	α	0.47	0.5
M_g	1.4	1.25	H_0/P_a	500	50000
M_f	0.645	0.688	H_{u0}/P_a	800	40000
G_0/P_a*	500	9400	r	5.0	3.0
K_0/P_a	550	9700	r_u	0.0	1.0
k_s	0.01	0.015	r_d	600	3000
β_{10}	3.1	1.0			

*: P_a is the atmospheric pressure

Table 2 Material constants of geogrid

J_e (kN/m)	A (kN/m)	$\bar{J}_p$ (kN/m)	h_0^L (kN/m)	B (kN/m)	h_k^L (kN/m)
1300	240	40	200	-45	180
h_0^U (kN/m)	n_0	κ	η	c_1 (kN/m)	c_2 (kN/m)
1500	3.8	14	2.2e9	52	0.52

3 RESULTS AND ANALYSIS

3.1 Effects of Horizontal Earthquake Characteristics

Figs. 3a and 3b show the effects of horizontal earthquake excitations on the maximum reinforcement load and residual lateral displacement, respectively. With the same maximum acceleration input ($a_{\max} = 0.55$ g), responses of the GRS model wall were quite different, with that of the 1999 Duzce Earthquake the largest and that of the 1992 Big Bear Earthquake the smallest. The difference in the reinforcement load was as large as 54% and that in the lateral facing displacement was more than 6 times.

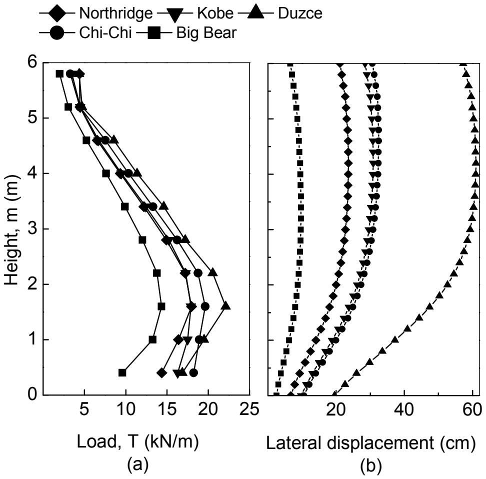


Fig. 3 Effects of horizontal earthquake excitations

Such result is not surprising. As can be seen in Fig. 2a, the frequency of the Duzce Earthquake is much smaller than that of the others, and since most GRS walls or slopes have small natural frequency, the response due to the Duzce Earthquake was sure to be much larger. In fact, if observing Fig. 2a and Fig. 3 carefully, one can find that the trend of seismic response exactly followed the input frequency. It should be emphasized that the excitations used in the analysis were all real earthquake records, while the height of the model reinforced soil wall can be commonly found; hence such response difference can be expected in the field.

In the second series of analysis, the frequency of the horizontal Kobe earthquake was purposely shortened or lengthened to investigate the effect. Fig. 4 shows the relationships between the dominant frequency and the corresponding maximum reinforcement load and lateral facing displacement. In the range of frequency investigated, the seismic response decreased with an increase in the dominant frequency and from the trend, it can be seen that only when the dominant frequency was very large and far away from the natural frequency of the GRS wall, the effect of earthquake characteristics other than maximum acceleration was minimum. In the frequency range of 1~2 Hz, which is commonly encountered in earthquakes, the differences in the maximum reinforcement load and maximum lateral facing displacement for the model wall analyzed were still very large. The difference of course depends on the parameters of GRS structures but the influence of earthquake characteristics other than maximum acceleration magnitude would be similar.

3.2 Effects of Vertical earthquake Excitation

Most earthquakes have considerably large vertical components, which can be seen in the ground motion database of the Pacific Earthquake Engineering Research Center (http://peer.berkeley.edu/nga/). In this series of analysis, the horizontal component of Kobe earthquake used above was input to the model GRS wall together with a vertical earthquake component, which is also a record from the earthquake. The magnitude of the vertical excitation component was varied in order to investigate its effects on the seismic response of the GRS model wall.

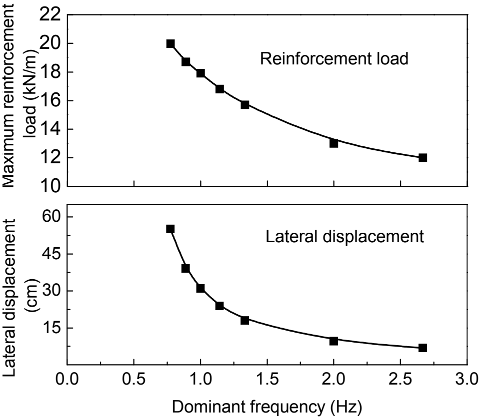


Fig. 4 Effect of input frequency using the Kobe earthquake as the base case

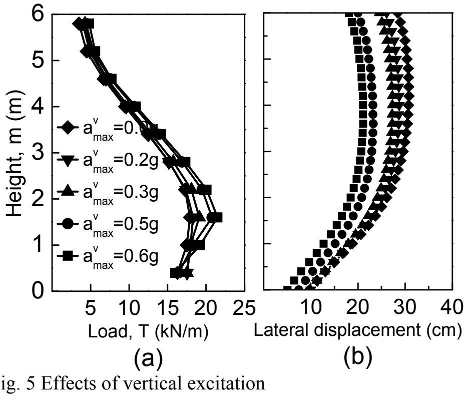


Fig. 5 Effects of vertical excitation

Figs. 5a and 5b show the comparison of maximum reinforcement load and residual lateral displacement, respectively. Interestingly, the vertical acceleration component has opposite effect on the reinforcement load and lateral facing displacement. With an increase in the vertical acceleration, the maximum reinforcement load increased, while the lateral facing displacement decreased.

The mechanism behind such responses can be found in the effect of compression wave (P-wave) on soil behavior. Under vertical excitation (P-wave), soil tends to compact. Such compaction in the backfill and foundation soils led to two outcomes in the GRS wall. On the one hand, the soil densified and its stiffness increased, hence reduced the shear deformation of soil and the residual lateral facing displacement; on the other hand, the compaction of the reinforced soil stretched the reinforcement connection with the facing units, hence leading to larger reinforcement load. The increase of reinforcement load due to vertical excitation was also observed in the large-scale model test of Ling et al. (2005).

Such increase of reinforcement load due to local stretching at facing connection can be expected for GRS walls in which the reinforcement layers are soundly connected to stiff facing units, such as the model wall used in the present study and the test walls in Ling et al. (2005). It should be pointed out that due to the continuum characteristics of the Finite Element procedure, the relative compression between the backfill soil and facing could not be fully captured. The difference in reinforcement load could be considerably larger than that shown in Fig. 5a and the possibility of connection rupture was quite large due to the local stretching.

4 CONCLUSION

Calibrated Finite Element procedure was used to analyze the influence of earthquake characteristics on the seismic response of GRS walls. The following conclusion can be obtained from the Finite Element study.

1) Both reinforcement load and lateral facing displacement were significantly affected by the characteristics of earthquake excitations other than maximum acceleration magnitude;
2) Vertical earthquake component could lead to further compaction of backfill soil and reduce the residual displacement of GRS walls, but it could increase the reinforcement load due to the increase of localized stretch at reinforcement connection with facing units.

The results from this study show that in the seismic design of GRS walls or slopes, the amplification of seismic responses should be considered; and in the design of GRS walls with stiff facing units together with rigid reinforcement-facing connection, the increase in reinforcement connection load due to relative compaction between backfill soil and facing should also be taken into account.

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