Evaluation of Seismic Displacement of Reinforced Walls

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ABSTRACT: A simplified procedure to evaluate displacement of reinforced soil retaining walls with a full-height rigid facing subjected to seismic loading is proposed. By computing sliding and overturning displacements of the facing due to accumulation of residual shear deformations of subsoil and reinforced backfill, respectively, formation of failure plane in unreinforced backfill is evaluated. After its formation, the sliding component of the residual facing displacement is computed by using the Newmark’s method, in which the soil wedge above the failure plane is assumed to behave as a rigid body. In addition, the shear deformation of subsoil and reinforced backfill is assumed to continuously take place even after the formation of failure plane. The proposed procedure could simulate reasonably the results from model shaking tests conducted under a normal gravitational field.

1 INTRODUCTION

In designing reinforced soil retaining walls against large earthquake loads, we may need to accept some residual displacement to occur, which should be within a certain allowable limit. Therefore, it is required to establish procedures that can evaluate the residual displacement of walls rationally.

On gravity type retaining walls, Richards and Elms (1979) proposed to employ the Newmark’s sliding block approach in evaluating the sliding displacements of walls. Several proposals were also made by Zeng and Steedman (2000) and Okamura and Matsuo (2002), among others, on the procedures to evaluate the overturning displacement of walls.

On reinforced soil retaining walls, Bathurst and Alfaro (1997) reviewed previous relevant studies, including those based on FE analyses. Among them, Cai and Bathurst (1996) employed the Newmark’s sliding block approach as a simplified procedure. Horii et al. (1998) combined it with the consideration of the residual shear deformation of the reinforced backfill.

The above studies, however, do not fully take into account the formation of failure plane (or shear band) in the unreinforced backfill that is accompanied with the strain softening behavior along the failure plane. In the present study, therefore, based on the analysis of model test results, an attempt was made to develop a simplified procedure to evaluate displacement of reinforced soil retaining walls with a full-height rigid facing subjected to seismic loading, while considering the formation of failure plane in the unreinforced backfill.

2 MODEL TESTS

2.1 Procedures

In the model tests, as shown in Fig. 1, full-height rigid facing models having a height of 500 mm were placed on subsoil layers consisting of dense dry Toyoura sand at a void ratio of about 0.650 (Dr = 88 %), which were prepared by air pluviation using a sand hopper. They were backfilled with Toyoura sand layers that were prepared in the same manner as the subsoil layers. As reinforcements, grids of phosphor-bronze
strips as shown in Fig. 2, having a thickness of 0.1 mm and a width of 3 mm, with sand particles glued on their surfaces, were placed in the backfill at a vertical spacing of 50 mm.

These models were subjected to several steps of horizontal shaking with either 20 cycles of sinusoidal waves at a frequency of 5 Hz or irregular excitations as shown in Fig. 3, where the base acceleration level was increased at increments of about 50 gal and 100 gal, respectively.

Figure 1. Typical cross-section of reinforced soil retaining wall model with full-height rigid facing

Figure 2. Plan of model reinforcement layer

Figure 3. Typical time histories of base accelerations during irregular excitations
2.2 Test Results

Accumulation of residual displacements of the model facing in terms of tilting angle and base sliding is plotted in Fig. 4 versus the amplitude of base acceleration. In one test shown in Fig. 4a, sinusoidal excitations were applied to a model constructed on 5cm-thick subsoil layers. In the other test shown in Fig. 4b, irregular excitations were applied to another model that was constructed on 20 cm-thick subsoil layers under otherwise the same conditions. In the former test, a failure plane in the unreinforced backfill was formed gradually during two shaking steps with base accelerations in the range of 750 to 800 gals. In the latter test, on the other hand, it was formed during a shaking step with the maximum base acceleration at about 1000 gals.
Relationships between the shear stress ratio and the shear strain that were mobilized in the subsoil layers below the reinforced backfill during sinusoidal excitations in the former test are shown in Fig. 5. The shear strain was evaluated as the measured amount of base sliding of the facing that was normalized with the thickness of the subsoil layers. The shear stress ratio was evaluated based on the measured response acceleration of the reinforced backfill, while considering the earth pressure exerted from the unreinforced backfill. The earth pressure was estimated using the Mononobe-Okabe method (denoted as the MO method herein) as shown by a dotted curve in Fig. 6, where the peak angle of internal friction of the unreinforced backfill was set equal to 51 degrees, based on the relevant plane strain compression test results (Koseki et al., 2003).

3 MODELING

3.1 Shear deformation of subsoil layers

Referring to the procedures proposed for evaluating the seismic displacement of gravity type retaining walls (Koseki et al., 2004), the shear strain increment of subsoil layers during the sinusoidal excitation was separated into two components; one is mobilized due to the initial loading effect during the first cycle of each shaking step; the other is due to cyclic loading effect during the consequent cycles.
The relationships between the shear stress ratio $SR = \tau/\sigma$ and the sum of shear strain increments $\gamma_0$ induced during the first cycle of each shaking step are shown in Fig. 7a. The measured data were approximated by a polynomial equation to the forth power as shown below. It will be referred as “initial loading curve” herein.

$$\gamma_0 = 0.0146 - 0.17548 \times SR + 0.72863 \times SR^2 - 1.22896 \times SR^3 + 0.75772 \times SR^4$$  \hspace{1cm}(1)

The cyclic loading effect during the consequent cycles was analyzed in terms of the relationships between the single amplitude of shear stress ratio $SR_{amp}$ and the number of cycles $N$ to induce a specified amount of shear strain increments $\Delta\gamma_N$ as shown in Fig. 7b. The measured data were approximated by the following equations. They will be referred as “cumulative damage curves” herein. Note that $SR_{amp}$ was defined as the increment on the active side from the stress state that was mobilized immediately before the shaking.

$$\log \Delta\gamma_N = a + b \times \log SR_{amp}$$
$$a = -2.87335 + 0.97474 \times \log N$$
$$b = 1.34334 + 1.04008 \times \log N$$  \hspace{1cm}(2)

3.2 Shear deformation of reinforced backfill

In a manner similar to the above, relationships between the shear stress ratio and the shear strain that were mobilized in the reinforced backfill during sinusoidal excitations were evaluated as shown in Fig. 8. The shear strain was further decomposed into two components, $\theta_0$ and $\Delta\theta_N$, due to the initial loading effect and the cyclic loading effect, respectively. The initial loading curve for the former effect is obtained as shown in Fig. 9a, while the cumulative damage curves for the latter effect are obtained as shown in Fig. 9b. Their formulations are shown below.

$$\theta_0 = 0.0126 - 0.02449 \times SR + 0.14578 \times SR^2 - 0.32389 \times SR^3 + 0.25208 \times SR^4$$
$$\log \Delta\theta_N = a + b \times \log SR_{amp}$$
$$a = -3.15093 + 0.78226 \times \log N$$
$$b = 1.54711 + 0.78789 \times \log N$$  \hspace{1cm}(3)

3.3 Procedures of computation considering formation of failure plane in unreinforced backfill

As mentioned in 2.2, in the test with sinusoidal excitations, a failure plane was formed in the unreinforced backfill, in a gradual manner during two shaking steps with base accelerations in the range of 750 to 800 gals.

It can be seen from Fig. 4a that, after its formation, the residual sliding displacement of the facing increased in a rapid manner. In order to consider such effects, Newmark’s sliding block approach was employed to compute the amount of sliding displacement of the facing and the reinforced backfill after the formation of failure plane. The threshold acceleration $a_{thres}$ to be used in the computation was evaluated as the value to yield a safety factor equal to unity against base sliding, based on the results from pseudo-static limit-equilibrium analyses. In the analyses, the angle of internal friction of the backfill and subsoil layers at residual state was used and set equal to 43 degrees based on the relevant plane strain compression test results (Koseki et al., 2003). In addition, in evaluating the earth pressure exerted from the unreinforced backfill to the reinforced backfill after the formation of failure plane, a modified version of the MO method was employed, as shown by a solid line in Fig. 6. Refer to Koseki et al. (1998) for the details of the modified MO method.

It can be also seen from Fig. 4a that, even before the formation of failure plane, certain amounts of residual overturning and sliding displacements of the facing had already accumulated. In this study, the overturning component was computed from the shear strain of the reinforced backfill using the formulations described in 3.2, while the sliding component was computed from the shear strain and the thickness of the subsoil layers using the formulations described in 3.1. Based on these values, the maximum shear strain $\gamma_{max}$ in the unreinforced backfill were evaluated, by assuming uniform strain distributions in the affected region of the unreinforced backfill. It was also assumed that the failure plane was formed when the value of $\gamma_{max}$ exceeded 2%.
As shown in Fig. 9a, the initial loading curve for the reinforced backfill shifted upward suddenly with the formation of the failure plane. Such trend was considered in the modeling in a simplified manner by introducing a correction factor as shown in the figure.

Figure 8. Stress-strain relationships of reinforced backfill during sinusoidal excitations

Figure 9. Modelling for shear deformation of reinforced backfill; a) initial loading curve and b) cumulative damage curves

4 COMPARISON BETWEEN COMPUTATION AND TEST RESULTS

4.1 Deformation of unreinforced backfill

The computed and measured deformations of the affected region of the unreinforced backfill are plotted versus the cumulative shaking duration in Fig. 10. The maximum shear strain $\gamma_{\text{max}}$ was obtained from the horizontal strain $\varepsilon_h$ and the shear strain $\gamma$ due to the sliding and overturning displacements of the facing, respectively, while assuming for simplicity that the deformation of the unreinforced backfill accumulated under a constant volume (i.e., the vertical strain $\varepsilon_v$ is equal to $-\varepsilon_h$).

For the test with sinusoidal excitations as shown in Fig. 10a, the computed values agreed reasonably with the measured ones. This is because the above modeling for computation was made based on these test results.

On the other hand, for the test with irregular excitations as shown in Fig. 10b, the computed $\gamma$ values were in general smaller than the measured ones, resulting into underestimation of the computed $\gamma_{\text{max}}$ values as well. This may be due to the overturning displacement of the facing caused by the bearing capacity failure of the
relatively thick subsoil layers for this test, which was not considered in the computation. It should be noted that, in applying equations 2 and 4 to irregular excitations, the cumulative damage concept (Tatsuoka and Silver, 1981) was employed in terms of the respective shear strain increments due to cyclic loading.

Figure 10. Computed and measured deformations of affected region of unreinforced backfill; a) sinusoidal excitations and b) irregular excitations

Figure 11. Typical time histories of computed and measured sliding displacements; a) sinusoidal excitations and b) irregular excitations
4.2 Displacement of facing

The computed overturning and sliding displacements of the facing are compared with the measured values in Fig. 4. As is the case with the deformations of the unreinforced backfill, the computed results could reasonably simulate the test results with sinusoidal excitations as shown in Fig. 4a.

For the test with irregular excitations as shown in Fig. 4b, in order to correct for the underestimation of the computed shear strain in the unreinforced backfill as mentioned above, additional computation was made by delaying the timing of the formation of failure plane to the second cycle of the shaking step at $a_{\text{max}}$ of about 1000 gal, as observed in the actual test. After such modification, the trend of the accumulation of the residual sliding displacement could be better simulated.

Typical time histories of computed sliding displacement are compared with the measured ones in Fig. 11. Except for the increment during the first cycle with sinusoidal excitation (Fig. 11a), the trend of its accumulation during shaking could be reasonably simulated. It should be noted that, as indicated in Fig. 11, the value of the threshold acceleration $a_{\text{thres}}$ used in the Newmark’s sliding block approach was as high as 807 gal for this model configuration, suggesting the importance of considering continuously the shear deformations of subsoil and reinforced backfill even after the formation of failure plane in the unreinforced backfill.

5 CONCLUSIONS

A simplified procedure to evaluate displacement of reinforced soil retaining walls with a full-height rigid facing subjected to seismic loading is proposed. By computing sliding and overturning displacements of the facing due to accumulation of residual shear deformations of subsoil and reinforced backfill, respectively, formation of failure plane in unreinforced backfill was evaluated. After its formation, the sliding component of the residual facing displacement was computed by using the Newmark’s sliding block approach. In addition, the shear deformation of subsoil and reinforced backfill was assumed to continuously take place even after the formation of failure plane. The proposed procedure could simulate reasonably the results from model shaking tests conducted under a normal gravitational field.

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