Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1509

A simplified procedure to evaluate earthquake-induced displacement of gravity type retaining walls

Une procédure simplifiée pour évaluer les déplacements induits par des tremblements de terre sur des murs de soutènements par type de gravité

J. Koseki
Institute of Industrial Science, University of Tokyo, Japan

ABSTRACT
Based on model test results, a simplified procedure is proposed to evaluate the earthquake-induced displacement of gravity type retaining walls. Formation of failure plane in the backfill soil is evaluated based on sliding and overturning displacements of the wall due to accumulation of residual shear deformations of subsoil. After the formation of failure plane, the wall displacements are computed by using the Newmark's sliding block method. The effect of strain softening in the backfill is considered in evaluating the threshold acceleration and the threshold overturning moment to be employed in the Newmark's method. Reasonable agreements are obtained between the results from the model tests and the simulation by using the proposed method.

RÉSUMÉ
Basée sur des résultats obtenus à l'aide de modèles, une procédure simplifiée est proposée pour évaluer les déplacements induits par des tremblements de terre sur des murs de soutènements par type de gravité. La formation d'un plan de rupture dans le remblai derrière le mur est évaluée en se basant sur les glissements et les déplacements de renversement du mur dus a l'accumulation de déformations résiduelles de cisaillement dans le sous-sol. Après la formation d'un plan de rupture, les déplacements du mur sont évalués à l'aide de la méthode de glissement des blocs de Newmark. L'effet de la diminution des contraintes dans le remblai derrière le mur est considéré en evaluant l'accélération et le moment de seuil qui seront employés dans la méthode de Newmark. Les résultats obtenus avec les tests par des modèles et ceux obtenus en utilisant une simulation par la methode proposée sont comparables.

1 INTRODUCTION

Several gravity type retaining walls were damaged extensively by the 1995 Hyogoken-Nanbu earthquake, Japan (Tatsuoka et al., 1996) and the 1999 Chi-Chi earthquake, Taiwan (Huang, 2000).

In order to evaluate the sliding displacement of gravity type retaining walls during earthquakes, Richards and Elms (1979) proposed to employ the Newmark's sliding block approach (Newmark, 1965). 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 as well. However, effects of formation of failure plane in the backfill soils and shear deformation of the subsoils on the residual displacement of retaining walls have not been fully considered in these procedures.

In the present study, while considering the above effects, a simplified procedure to evaluate the earthquake-induced displacement of gravity type retaining walls in terms of sliding and overturning components was proposed, based on model test results conducted under normal gravity with different subsoil conditions.

2 MODEL TESTS

2.1 *Procedures*

The model of gravity type retaining wall tested was 53 cm high with a base width of 23 cm. In a sand box with a width of 60 cm, it was constructed on level dry sand ground with a thickness of 5 cm (Figure 1a) and subjected to 20 cycles of sinusoidal excitations at a frequency of 5 Hz, where the amplitude of the base acceleration was initially set to about 50 gals and increased at an increment of about 50 gals. Refer to Koseki et al. (2003) for the details of the test procedures.

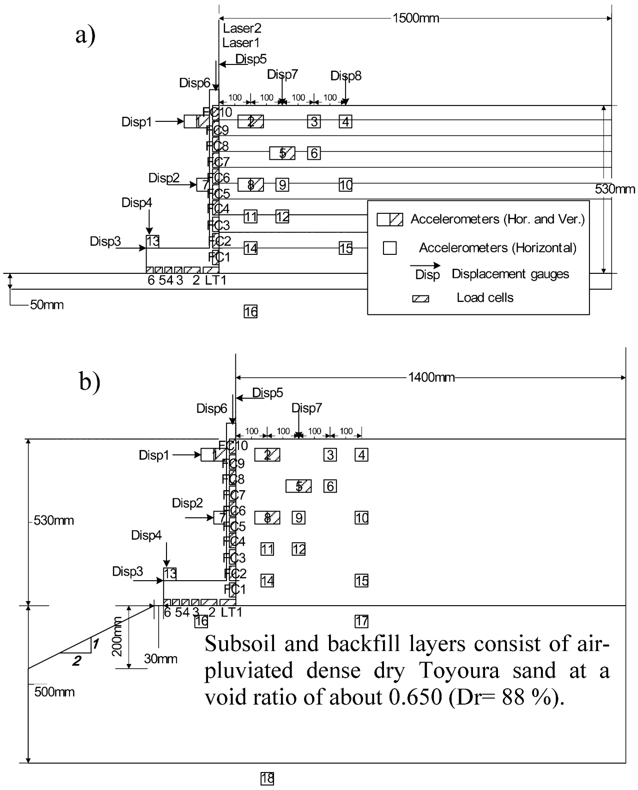

Figure 1. Typical cross-section of gravity type retaining wall models; a) with 5 cm-thick level ground and b) with 50 cm-thick sloped ground.

Under otherwise the same conditions, sinusoidal shaking tests were also conducted on two models with different ground conditions. One model was constructed on level ground with a

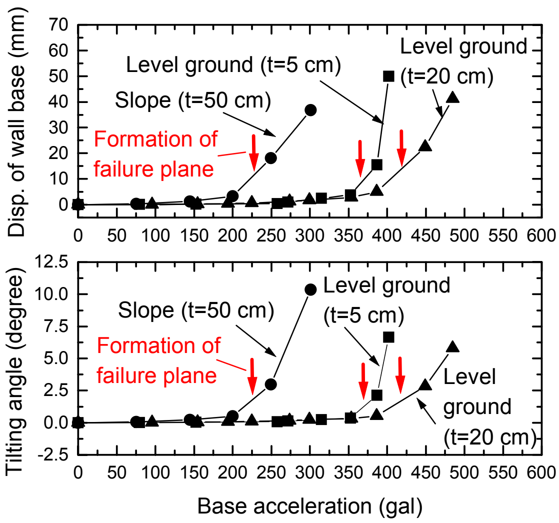

Figure 2. Relationships between residual wall displacements and base acceleration during sinusoidal excitations; a) base sliding and b) tilting angle.

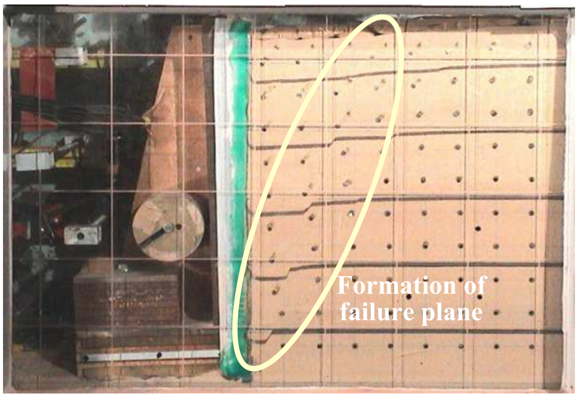

Figure 3. Formation of failure plane in the backfill for the model constructed on 5 cm-thick level ground (after a shaking step at 350 gals).

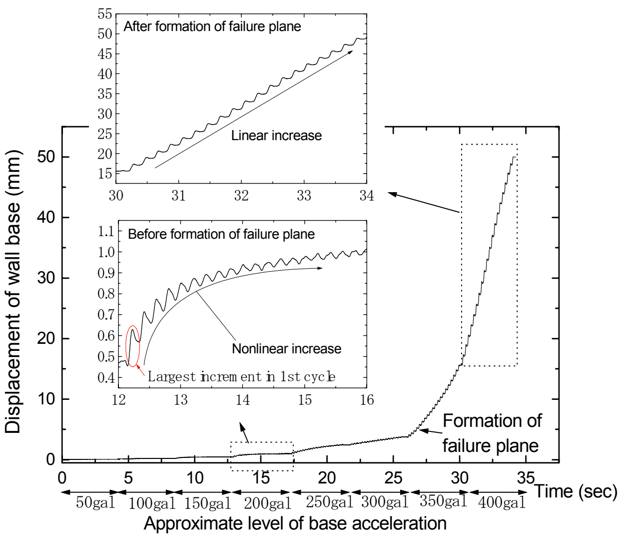

Figure 4. Time histories of base sliding for the model constructed on 5 cm-thick level ground.

thickness of 20 cm, while the other model was constructed on sloped ground having a thickness of 50 cm between its crest and the bottom of the sand box and a slope of 2:1(H:V) with a set back of 3 cm between the toe of the retaining wall and the slope crest (Figure 1b).

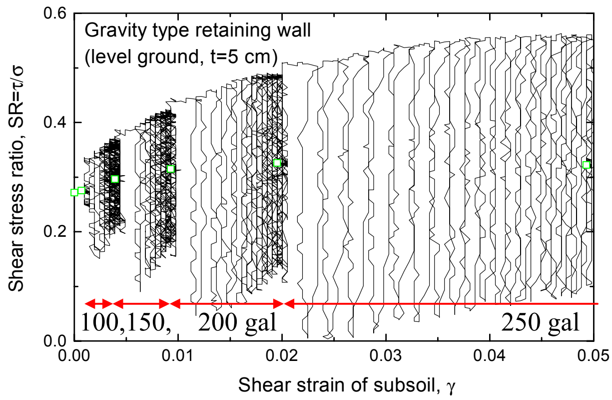

Figure 5. Stress-strain relationships of 5 cm-thick subsoil layers below the model wall during sinusoidal excitations.

2.2 *Results and discussions*

Accumulation of residual displacements of the model walls in terms of tilting angle and base sliding is plotted in Figure 2 versus the amplitude of base acceleration during sinusoidal excitations. Vertical arrows shown in Figure 2 indicate that a failure plane (or shear band) was formed in the backfill, as typically shown in Figure 3. After its formation, the wall displacements tended to accumulate significantly.

Time histories of base sliding for the model constructed on 5 cm-thick level ground for all the sinusoidal shaking steps are connected and shown in Figure 4. Typical time histories recorded before and after the formation of failure plane are also shown in the figure. Before its formation, the wall displacement accumulated in a non-linear manner. On the other hand, after its formation, the wall displacement accumulated in a linear manner.

In the present study, the former behavior was attributed to shear deformation of subsoil layers below the wall, while the latter behavior was attributed to sliding at the interface between the wall base and the subsoil layers.

It can be seen from Figure 2 that the thickness and shape of subsoil affected the properties of wall displacement. With the model constructed on 50 cm-thick sloped ground, the failure plane was formed earlier, and larger amount of tilting angle accumulated after its formation.

3 MODELING

3.1 *Shear deformation of subsoil layers*

Relationships between the shear stress ratio and the shear strain that were mobilized in the 5 cm-thick subsoil layers (level ground) below the model wall during sinusoidal excitations are shown in Figure 5. The shear strain γ was evaluated by dividing the measured amount of base sliding of the wall with the thickness of the subsoil layers. The shear stress ratio $SR=\tau/\sigma$ was evaluated based on the subsoil reactions in the shear and normal directions at the wall base that were measured with several two-component load cells.

It can be seen from Figure 5 that, during the first cycle of each sinusoidal shaking step, the increment of shear strain was larger than those during the following cycles. Similar trend can be also seen in the closed up of time history of base sliding before formation of failure plane as shown in Figure 4. This may be because the shear stress ratio during the first cycle exceeded the ever-largest value during the preceding shaking steps. Therefore, in the present study, the increment of shear strain during the first cycle of each shaking step was added together and regarded as the shear strain γ_0 induced by initial loading.

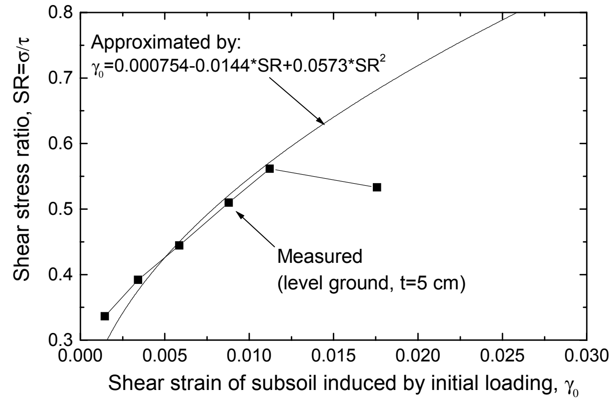

Figure 6. Initial loading curve for shear deformation of 5 cm-thick subsoil layers below model wall.

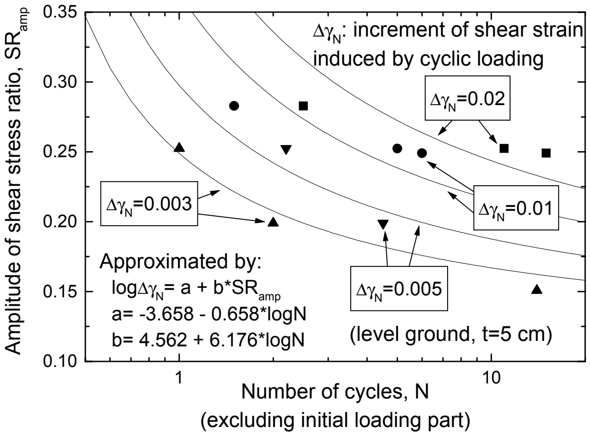

Figure 7. Cumulative damage curves for shear deformation of 5 cm-thick subsoil layers below model wall.

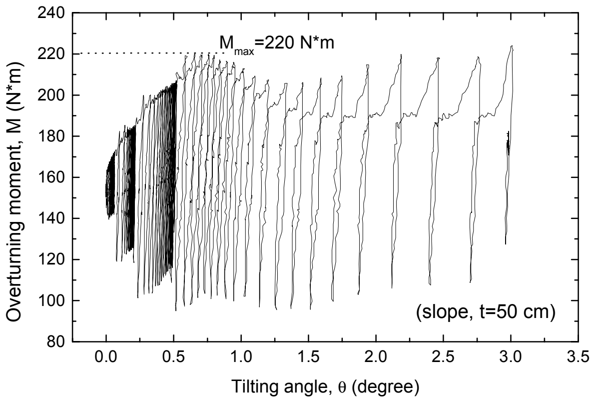

Figure 8. Relationships between overturning moment and tiltiing angle of model wall on 50 cm-thick sloped ground.

The relationship between SR and γ_0 is shown in Figure 6. It was approximated with a polynomial function as shown in the figure, which will be referred as the initial loading curve herein.

In order to evaluate the other shear strain components due to the effect of cyclic loading, the measured shear strain increments $\Delta\gamma_N$ during the cycles except for the first one were analyzed in terms of the relationships between the amplitude of shear stress ratio SR_{amp} and the number of cycles N to induce the specified amount of $\Delta\gamma_N$, as shown in Figure 7. These relationships were approximated with functions as shown in the figure and will be referred as the cumulative damage curves herein.

Note that SR_{amp} was defined as the increment of SR on the active side from the stress state that was mobilized immediately before the shaking.

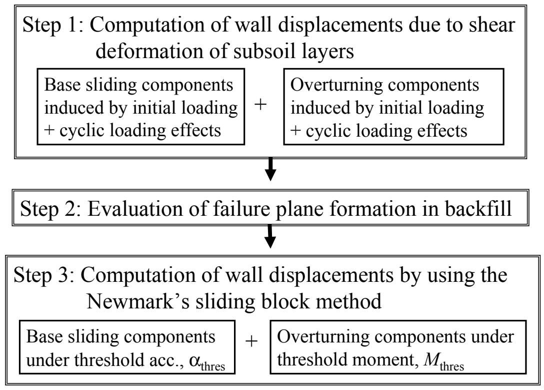

Figure 9. Summary of the proposed procedure to evaluate earthquake-induced displacement of gravity type retaining walls.

3.2 *Tilting of wall due to subsoil deformation*

The overturning moment M acting on the wall base around its heel was computed based on the measured resultant earth pressure acting on the back face of the wall, response acceleration of the wall and the mass of the wall.

Relationships between M and the tilting angle θ of the model wall on 50 cm-thick sloped ground during sinusoidal excitations are shown in Figure 8, where softening behavior was observed after exceeding the peak state at M_{max}=220 N*m. In the present study, the accumulation of θ values before this peak state was attributed to deformation of subsoil layers and modeled by separating them into two components, following the same procedure as employed in modeling the shear strain of subsoil layers described in 3.1.

3.3 *Evaluation of failure plane formation*

By applying the formulations shown in 3.1 and 3.2, the sliding displacement and the tilting angle of the model wall due to deformation of subsoil layers was evaluated using the base acceleration records.

Based on these wall displacements, the maximum shear strain γ_{max} in the backfill were evaluated, by assuming uniform strain distributions in the affected region of the backfill that was evaluated using the Mononobe-Okabe method with the threshold acceleration α_{thres} as will be mentioned in 3.4. Deformation of the backfill under a constant volume (i.e., the vertical strain ε_v is equal to $-\varepsilon_h$) was assumed for simplicity.

Based on the analysis of the model test data as well as the results from relevant plane strain compression tests, it was also assumed that the failure plane was formed when the value of γ_{max} exceeded 5 %.

3.4 *Newmark's sliding block method*

After the formation of failure plane in the backfill, the Newmark's sliding block method was employed to compute the amount of sliding and overturning displacements of the wall. For the latter component, rotation of the wall around its heel was considered. Figure 9 summarizes the proposed procedure.

The threshold acceleration α_{thres} to be used in the computation of the sliding displacement 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 backfill to the wall after the formation of failure plane, a modified version of the Mononobe-Okabe method (Koseki et al., 1998) was employed.

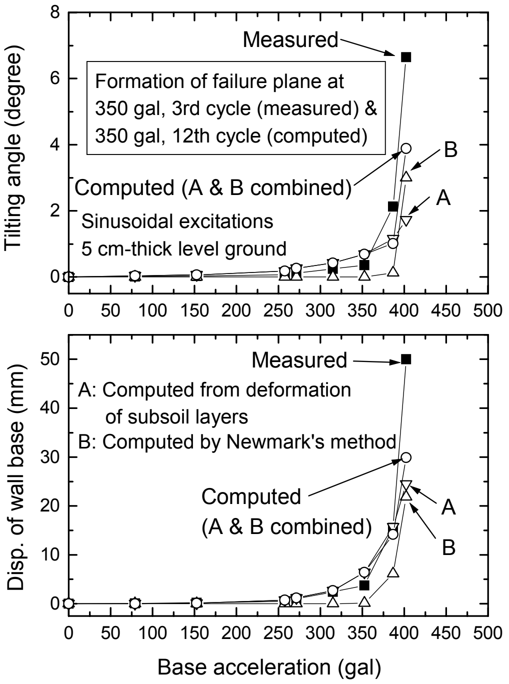

Figure 10. Comparison of residual wall displacements on 5 cm-thick level ground during sinusoidal excitations.

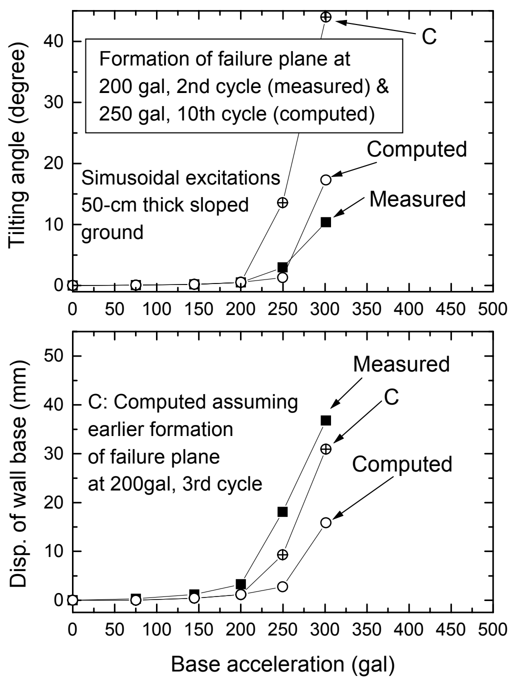

Figure 11. Comparison of residual wall displacements on 50 cm-thick sloped ground during sinusoidal excitations.

Since the bearing capacity of the model subsoil layers under different conditions could not be estimated easily, the location of the application point of the resultant force of subsoil reactions that was measured in the model tests at the moment of formation of failure plane in the backfill was used to evaluate the threshold overturning moment M_{thres}.

4 COMPARISON OF COMPUTION AND TEST RESULTS

Computed and measured wall displacements during sinusoidal excitations are compared in Figs. 10 & 11 for the model walls on 5 cm-thick level ground and 50 cm-thick sloped ground, respectively. Computed and measured moments of formation of failure plane in the backfill are also shown in these figures. In general, reasonable agreements could be obtained on these properties.

For reference, the wall displacements computed from the deformation of subsoil layers and those by the Newmark's method are separately shown in Figure 10. It can be seen that the trend of accumulation of the measured wall displacements could be simulated only by combining both methods.

Results from additional computation conducted by assuming earlier formation of failure plane are shown in Figure 11. The agreement on the sliding displacement could be improved by such modification, while it was not the case with the tilting angle.

By using the proposed procedure, simulation of model tests with irregular excitations was conducted, as reported elsewhere (Koseki et al., 2004a). It was also modified to simulate model tests on reinforced soil retaining walls (Koseki et al., 2004b).

5 CONCLUSIONS

Based on model test results, a simplified procedure was proposed to evaluate the earthquake-induced displacement of gravity type retaining walls. In the procedure, sliding and overturning displacements of the wall due to accumulation of residual shear deformations of subsoil are computed. Based on these displacements, formation of failure plane in the backfill soil is evaluated. After the formation of failure plane, sliding and overturning displacements of the wall are computed by using the Newmark's sliding block method. The effect of strain softening in the backfill is considered in evaluating the threshold acceleration and the threshold overturning moment to be employed in the Newmark's method.

Reasonable agreements were obtained between the results from the model tests and the simulation by using the proposed method in terms of wall displacements as well as the formation of failure plane.

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