Seismic design of retaining wall considering the dynamic response characteristic

Conception sismique des murs de soutènement compte tenu des caractéristiques de réponse dynamique

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ABSTRACT: Under the previous design standard, retaining wall and bridge abutment are classified under same category as a retaining structure and same seismic design procedure is applied in Japan. However, there is a difference in the dynamic response characteristic in that the effect of seismic earth pressure is larger than inertial force for a retaining wall while inertial force is the main external force for a bridge abutment. In this study, therefore, we performed a series of shaking table model tests in order to evaluate difference of dynamic response characteristic of each structure. The experiments revealed that the dynamic response characteristic of retaining wall is largely affected seismic ground motion characteristics, while the dynamic amplification is not significant. On the basis of the test results, a seismic design method using the Newmark method was proposed for the retaining wall. This new methods provides reasonable displacement compared to the test results of shaking table tests and the actual residual displacement of the damaged railway retaining wall after the 1995 Hyogo-ken nambu earthquake. This proposed method was employed in the new railway design standard for retaining structure in Japan which was revised into performance-based design in January, 2012.

RÉSUMÉ : Au Japon, conformément aux normes de conception antérieur, les murs de soutènement et les piliers de pont sont classés dans la même catégorie des structures de soutènement et les mêmes processus de conception s'appliquent. Toutefois, les caractéristiques de réponse dynamique présentent une certaine différence. Au cours de cette étude, nous avons procédé à une série d'essais de modèles sur table à secousses afin d'évaluer la différence des caractéristiques de réponse dynamique de chaque structure. Les expériences montrent que les caractéristiques de réponse dynamique des murs de soutènement sont fortement affectées par la pression sismique des terres et les caractéristiques de déplacement sismique des terres alors que l'amplification dynamique est négligeable. Sur la base des résultats des essais, nous avons proposé l'utilisation de la méthode de Newmark pour les murs de soutènement, Cette nouvelle méthode assure un déplacement raisonnable par rapport aux résultats des essais sur table à secousses et le déplacement résiduel réel du mur de soutènement endommagé après le tremblement de terre de la préfecture de Hyogo-Ken Nambu. Cette méthode est désormais utilisée au Japon par la nouvelle norme de conception de chemins de fer pour les structures.

KEYWORDS: seismic design, retaining structure, Newmark method, dynamic response characteristic

1 INTRODUCTION.

1.1 *Design standards for railway retaining structures*

Several types of retaining structures are used in railways. In addition to conventional structures, recent years have seen the introduction of new types of structure like reinforced-soil retaining walls and reinforced-soil bridge abutments as technical progress is achieved in reinforced earth construction methods.

Conventional type retaining walls and bridge abutments are categorized as "soil-retaining structures" and design procedures for them were indicated in the railway structure design standard (2000). Seismic design regulations were also indicated in the railway structure design standard (1999) which were compiled based on experience drawn from the 1995 Hyogo-ken nambu earthquake. The railway structure design standard (earth structures, 2007) on the other hand provided the design method for reinforced-soil structures such as reinforced-soil retaining walls and reinforced-soil bridge abutments, because the reinforced-earth construction method, originally applied to earth structures was applied to higher-grade structures, which allow little deformation against severe earthquakes.

The design method for retaining structures used in railways therefore appeared in different design standards for these reasons. Choice of a conventional retaining structure or a reinforced-soil structure is made considering the importance of the intended structure, its required performance and the construction site conditions. Consequently, suggestions have been made indicating that it is necessary to cover these structures in the same design standard, which offers a means to assess their performance with an equivalent index.

Pursuant to the above objective, the Railway Technical Research Institute (R.T.R.I), under the guidance of Ministry of Land, Infrastructure and Transportation, revised the soil

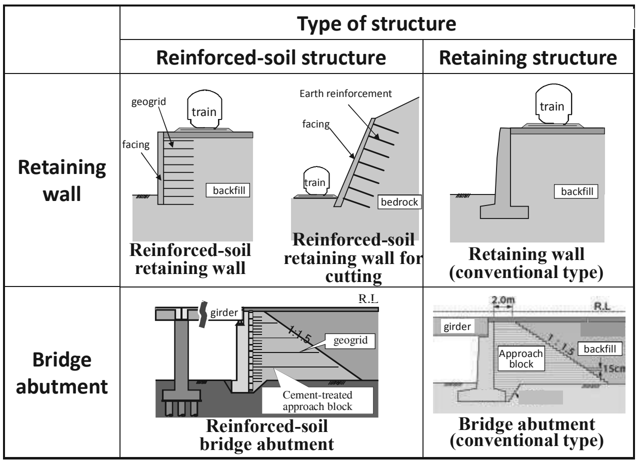

Figure 1 Structures covered under the new soil retaining structure standard (R.T.R.I, 2012)

retaining structure standard (2012), which now corresponds to a performance based design method. Structures covered under this new standard are shown in Figure 1. The revised standard now offers a harmonized method covering both conventional retaining structures and reinforced-soil structures.

1.2 *Problem with seismic design method in the previous seismic standard*

In the previous seismic standard (1999), one design method applies to both conventional retaining walls and bridge abutments. However, the dynamic response characteristics differ during earthquakes in that the effect of seismic earth pressure is greater than inertial force in the case of retaining walls while for bridge abutments inertial force exerts the main influence.

The method to obtain residual displacement for conventional retaining walls and conventional bridge abutments according to the previous seismic standard is shown in Figure 2. The load - displacement relationship of a foundation and a wall is calculated by static nonlinear analysis independently, and a 'constant energy law' is used to calculate the maximum response displacement considering plastic behavior of them. Verification of the performance of a foundation's stability and residual deformation of wall members were evaluated with a plastic ratio (ratio of maximum response displacement to maximum linear response displacement).

Even though the 'constant energy law' offers the advantage of being a simple calculation, it cannot take into account the displacement characteristics of a retaining structure, which tends to accumulate in a single direction (active direction), and largely affected by seismic ground motion characteristics (duration and number of seismic motions).

In view of the above, it is preferable to separate the design methods for conventional retaining walls and bridge abutments in order to consider the dynamic response characteristics and the purpose of application of each structure.

In this study, therefore, a series of shaking table model tests were performed in order to evaluate the dynamic response characteristics of each structure. Based on the test results, a seismic design method for retaining walls was proposed. This paper shows the test results mainly of retaining wall.

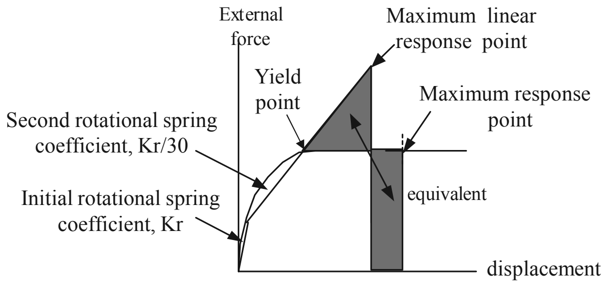

Figure 2 Calculation of plastic ratio of retaining structure by 'constant energy law' (R.T.R.I, 2000)

2 SHAKING TABLE TESTS ON THE RETAINING WALL MODEL

2.1 *Model retaining wall and backfill*

Model tests were performed using a shaking table at the Railway Technical Research Institute. A rigid soil container (length: 2050 mm, width: 600 mm, and height: 1400 mm) was fixed to the table. A 530 mm-high and 938 N in weight gravity-type RW model was used in this study. The geometric shape of this model was fixed in reference to the standard shape of such examples in Japan, which are about 5 m in height, and then reducing the size to a scale of almost one-tenth. The backfill model and subsoil model was made of air-dried Toyoura sand (D_{50}=0.23 mm, G_s=2.648, e_{max}=0.977 and e_{min}= 0.609). The sand layers were produced using a sand hopper and a constant falling height. This method helped achieve an average relative density of 90%. There was no subsoil model in front of the base footing in order to simplify the model. Watanabe et al.(2003) have summarized the details of the model preparation.

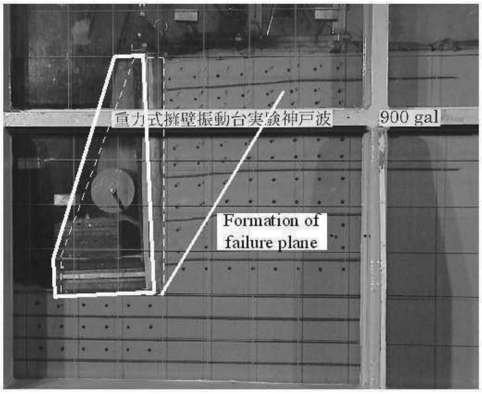

Figure 3 Residual displacement of retaining wall model and formation of failure plane in the backfill soil

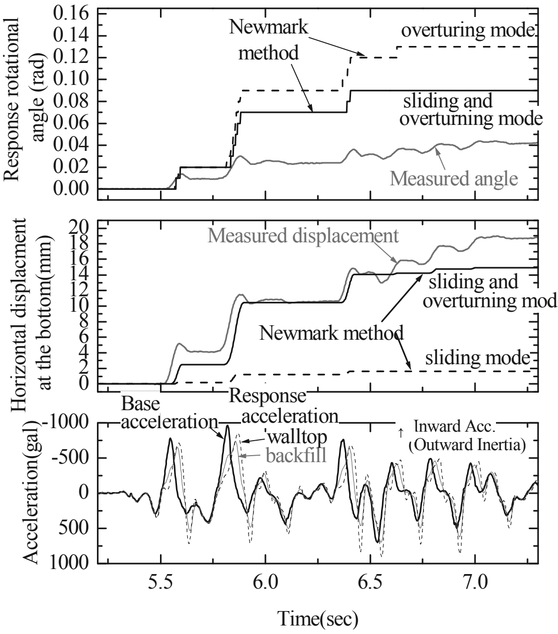

Figure 4 Time history of rotational angle, horizontal displacement and acceleration

2.2 *Dynamic response characteristic of the retaining wall*

Figure 3 shows the residual displacement of the wall and the residual deformation of the backfill after shaking. The major failure pattern was overturning, which was associated with the bearing capacity failure of the subsoil. One inclined failure plane was clearly observed in the backfill soil. This overturning was mainly caused by the loss of bearing capacity near the toe of base footing. This was confirmed by the output of 7 loadcells which were arranged at the bottom of base footing. (Watanabe et al. 2003). Horizontal displacement of the bottom end of the retaining wall was 19mm and horizontal displacement of the top end of the retaining wall was 36mm (rotational angle was 0.04rad) after shaking (Figure 4).

Figure 5a shows the relationship between overturning moment being applied to a retaining wall by inertia force and seismic earth pressure and response rotational angle of the retaining wall. Figure 5b also shows the relationship between horizontal external forces (inertial force and seismic earth pressure) and horizontal displacement at the top of the retaining wall. These figure shows clearly that the displacement is accumulated rapidly around when the moment and external

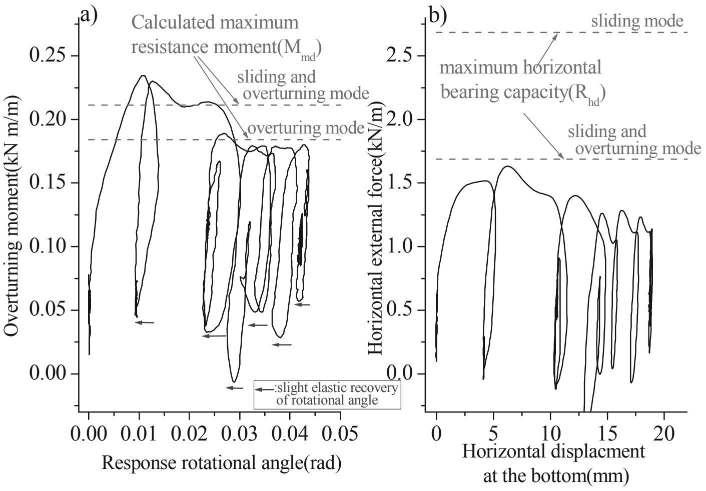

Figure 5 Relationship between overturning moment (external force) and response rotational angle (horizontal displacement)

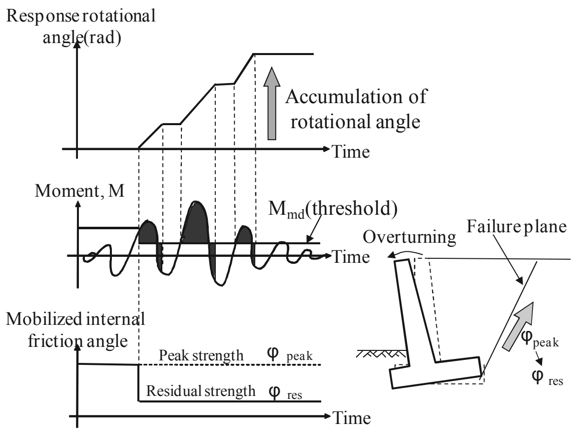

Figure 6 Newmark method for retaining wall (overturning mode)

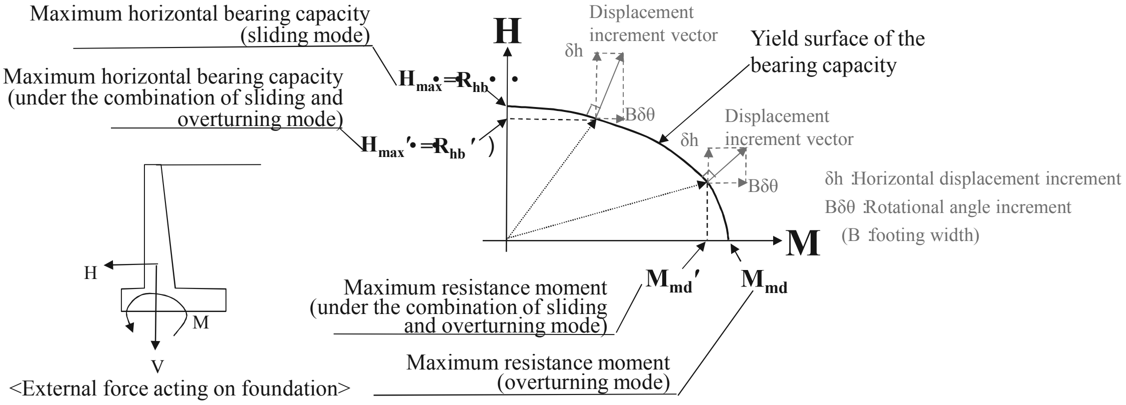

Figure 7 Yield surface of bearing capacity and the associated flow rule

force reaches the maximum value. This maximum value has been identified as being generally consistent with the maximum resistance moment (M_{md}) and the maximum horizontal bearing capacity (R_{hd}) of a retaining wall as shown in Figure 5 (see below for detail). On the other hand, recovery of displacement (elastic behavior) was small when the external forces were applied in the backward direction (passive direction). It can be said that the displacement increment of the retaining wall to the active direction is largely affected by seismic ground motion characteristics (duration and number of seismic motions).

3 A NEW METHOD TO EVALUATE THE RESIDUAL DISPLACEMENT OF RETAINING STRUCTURES.

3.1 *Retaining wall*

Based on the test results, a seismic design method using the Newmark method (Newmark, 1965) was proposed for the retaining wall (Figure 6).

The Newmark method has various advantages in that (1) the theory is very simple and has very few analytical parameters while still providing an adequate result; (2) seismic ground motion characteristics can be directly considered, and (3) the strength characteristics and strain softening behavior of the backfill soil can be taken into account.

According to experience gained in the wake of past disasters and model experiment results, overturning modes (rotational mode) are common in the seismic response of retaining wall foundations. Therefore, the Newmark method is indicated as the method for calculating the response rotational angle of a retaining wall in the new design standard. However since a considerable eccentricity/inclined load at the base footing is often caused by seismic earth pressure, this effect should be considered when calculating the maximum resistance moment (M_{md}' in Figure 7) of the foundation. Furthermore, an overturning mode does not necessarily occur independently but can also be simultaneously accompanied by a sliding mode when a spread foundation-type retaining wall has a low center of gravity or when the passive resistance force at the front side of base footing is small. However, such failure mode combinations cannot be taken into direct consideration since the Newmark method uses a different motion equation for sliding modes and overturning modes. Therefore, the combination of a sliding mode and an overturning mode is determined if the horizontal external force exceeds an horizontal stability level when the response of the retaining wall reaches the maximum. The displacement caused by the major failure mode is calculated by the Newmark method and the displacement caused by the minor failure mode is calculated from the yield surface of the bearing capacity considering the associated flow rule (Figure 7).

3.2 *Bridge abutment*

Although the details of a study for bridge abutments have been omitted due to space limitations in this paper, the effect of inertial force and dynamic amplification was significant for bridge abutments (Nishioka et al, 2011). This is because the bridge abutment sustains the heavy bridge girder at the top. This dynamic response characteristic is similar to that of a bridge pier. In view of the above, a seismic design method was proposed, which models the bridge abutment as a single-degree-of-freedom system. This design method is almost similar to bridge pier, however, seismic earth pressure acting on the backface of bridge abutment is also considered.

4 TRIAL CALCULATION OF RESIDUAL DISPLACEMENT OF RETAINING WALL

4.1 Damaged railway retaining wall during 1995 Hyogo-ken nambu earthquake

The railway retaining wall selected for the trial calculation is a cantilever type retaining wall in Ishiya River District, which suffered critical failure during the 1995 Hyogo-ken nambu earthquake (Figure 8). The retaining wall is 7m in height, and has a spread foundation. According to detailed investigations after the earthquake, the major displacement mode of this retaining wall was overturning, and an 800mm horizontal displacement was observed at the top end of the retaining wall.

A number of subsoil parameters were obtained such as the N value from standard penetration tests performed after the earthquake. In addition, backfill soil material was determined based on field density tests and drained tri-axial tests on reconstituted samples.

Recorded seismic ground motion, such as N-S components from Kobe Marine Meteorological Observation Station, was employed in the trial calculation, considering the orientation of the retaining wall. The residual horizontal displacement at the top end of the retaining wall, which was calculated from the Newmark method (overturning mode), was 570mm. Even though the amount was slightly less than the actual value (800mm), the result was closer to the actual value than the calculated values obtained with the current seismic standard based on the energy constant law (353mm). This is because the energy constant law only considers maximum acceleration, and is unable to consider seismic ground motion characteristics such as duration and number of seismic motions.

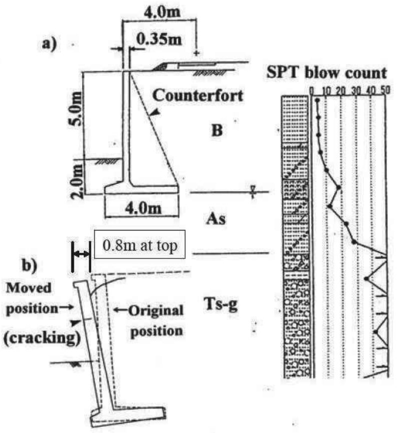

Figure 8 Damaged railway retaining wall after the 1995 Hyogoken-Nanbu earthquake (Tatsuoka et al. 1998)

4.2 Shaking table test results of gravity type retaining wall model

The time history of the horizontal displacement and rotational angle obtained from the Newmark method are shown in Figure 4 and compared to their measured values. Cases of coupled displacement mode (sliding and overturning modes) occurred during shaking table tests, however trial calculations were made for one case in which the failure mode combination (sliding mode and overturning mode) was considered and one case in which the failure mode combination was not considered.

Where coupled displacement mode was not considered, the Newmark method underestimated the sliding mode (horizontal displacement) and overestimated the overturning mode (rotational angle). In the sliding mode, the horizontal force and moment actually act simultaneously, resulting in a decrease of the maximum horizontal bearing capacity (R_{hd}' in Figure 7) as shown in Figure 5. That is why the horizontal displacement is underestimated. On the other hand, in the overturning mode, the overestimation of the rotational angle compared to the experimental value is mainly due to the correction coefficient for inclined loads ($I\gamma$) which is used to determine the maximum resistant moment (M_{md}' in Figure 7). This correction coefficient was obtained through experiments performed by Meyerhof (1953), however, there may be an applicable limit in the case where the ratio of horizontal force to vertical force is large due to the effect of inertial force and seismic earth pressure such as is the case with retaining walls. The above result shows the limit to dealing with sliding and overturning modes independently in cases where the retaining wall is suffering from the effects of the failure mode combination.

Notwithstanding, when considering the coupled displacement modes sliding and overturning, it is clear that the horizontal displacement is consistent with the experimental value (Figure 4). The rotational angle value is also generally reproduced in the experiment though still overestimated. This is because slight recovery of rotational angle (elastic behavior, Figure 5a) was ignored in the Newmark method when the external forces were applied in the backward direction (passive direction), and the maximum resistant moment (M_{md}') was still underestimated which corresponds to the residual strength of the bearing capacity.

5 CONCLUSION

A series of model shaking tests were carried out on conventional retaining wall, and its dynamic response characteristics was evaluated. The dynamic response of the retaining wall was largely affected by the seismic ground motion characteristics (duration and number of seismic motions), whereas response acceleration amplification was insignificant.

Based on these test results, a proposal was made for retaining wall seismic design method based on the Newmark method. The yield surface of the bearing capacity was used in the proposed method in order to consider the failure mode combination (sliding and overturning). The seismic design method proposed in this study was confirmed as being generally able to reproduce experiment results and cases of past damage.

The proposed seismic design methods have been employed in the new railway design standard for retaining structures in Japan, which was revised into a performance-based design in 2012.

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