16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1432

Registration Code: S-B1464615834

THE EFFECT OF SEISMIC STABILITY OF RETAINING WALL ON SEISMIC EARTH PRESSURE

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Abstract

In recent years, there has been serious damage to retaining walls (RWs) because of large earthquakes. Seismic earth pressure, which is one of the important external forces acting on RWs during an earthquake, is largely affected by the dynamic interaction between the wall and the backfill; the detailed mechanism of this effect has not been clarified well. In the current seismic design procedure, the Mononobe-Okabe theory is often used for evaluating the seismic earth pressure. Although this theory is simply based on the pseudo-static approach, many researchers have mentioned that this theory is applicable under a small seismic load (around 200 gal).

In this study, therefore, a series of shaking table model tests were performed to investigate the effect of seismic stability (bearing condition) of the RW on seismic earth pressure.

The experiment was conducted for four cases (Case1 - 4). A RW model that was either completely fixed or elastically supported was used in all cases except for Case 4, in which a gravity-type RW model (one-tenth scale) was used. The RW model used for Cases 1-3 were made of aluminum and were 715 mm high and 40 mm thick. Two-component load cells which can measure both the normal and shear component of seismic earth pressure were positioned at nine locations in the direction of the height on the RW surface. The gravity-type RW of Case 4, on the other hand, was 530 mm high, and two-component load cells were positioned at 10 locations in the direction of the height and at six locations on the bottom surface of the RW footing.

The model used for Cases 1-3 did not simulate the actual RW; in fact, these model experiments were conducted under more simplified conditions in order to evaluate the impact of the seismic stability (bearing conditions) of the RW on the seismic earth pressure, with the focus on obtaining accurate measurements of seismic earth pressure. On the other hand, in Case 4, the focus was on simulating the seismic earth pressure acting on the actual gravity-type RW, where the model specification (height, width and center of gravity) and the yield seismic intensity was set as similar as possible to those of an actual RW.

The experiments revealed that the seismic earth pressure (intensity, phase property, distribution) is largely affected by the seismic stability of the RW. By considering the dynamic response of RWs, the seismic earth pressure under large earthquake loads can be calculated more rationally than by the Mononobe-Okabe theory. This result have already applied to the seismic design procedure of retaining structures under large earthquake, which is written precisely in the new design standard of railway retaining structures in Japan (2012).

Keywords: seismic earth pressure, retaining structure, seismic stability

1. Introduction

In recent years, there has been serious damage to retaining walls (RWs) because of large earthquakes (Fig. 1). The Hyogoken-Nanbu earthquake in Japan on January 17, 1995, for example, caused serious damage to conventional masonry and concrete gravity-type RWs for railway embankments [1].

The seismic earth pressure, which is one of the important external forces acting on RWs during an earthquake (Fig. 2), is largely affected by the dynamic interaction between the wall and the backfill; the detailed mechanism of this effect has not been clarified well. For example, seismic earth pressure acting on (a) the stable retaining wall and (b) unstable retaining wall should be different even under the same seismic input motions (Fig. 3).

In the current seismic design procedure, the Mononobe-Okabe (M-O) theory [2, 3] is often used for evaluating the seismic earth pressure. This method is very convenient for practical design because very few parameters are used for calculations. Hence, it is used not only for railways, but also for road and harbor structures; it has also been used overseas.

Although this theory is simply based on the pseudo-static approach, many researchers have mentioned that this theory is applicable under a small seismic load (around 200 gal=cm/s^2). This result was confirmed by Ichihara et al. (1973) and Sherif et al. (1982) by conducting shaking table model tests where the dynamic response of RWs was negligible [4, 5]. However, Whitman (1990) pointed out that these model tests were carried out under conditions similar to those assumed in the M-O theory, and this is why the experimental results agreed mostly with the M-O theory. [6]

The peak ground acceleration that was recorded during recent major earthquakes in Japan approached or exceeded 800 gal, particularly after the 1995 Hyogoken-Nanbu earthquake. Therefore, in Japan, it has become necessary to design an important earth structure against such high levels of near-fault earthquake effects. By

Fig. 1 – Damaged retaining walls during the Hyogoken -Nambe Earthquake

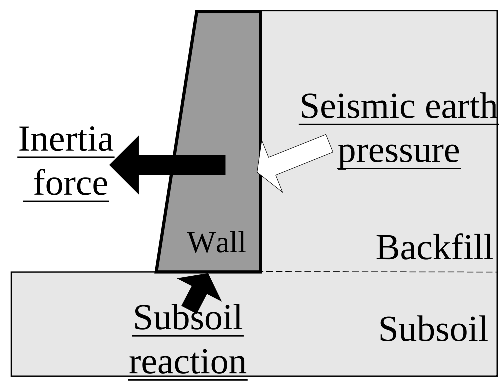
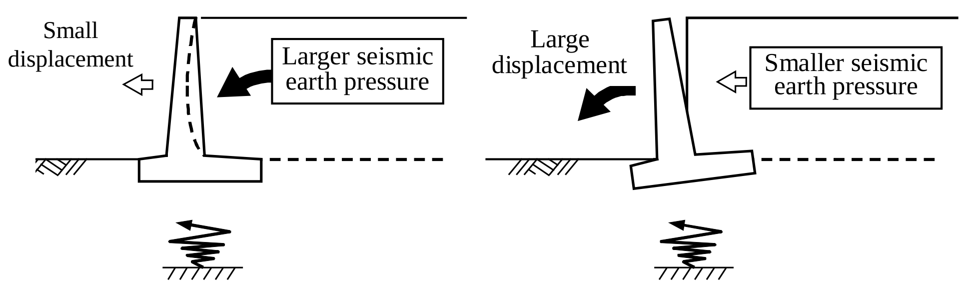


Fig. 2 – External forces acting on retaining walls during earthquake



a) Seismic earth pressure acting on the stable retaining wall

b) Seismic earth pressure acting on the unstable retaining wall

Fig. 3 – Relationship between the stability of the retaining wall and seismic earth pressure

using such a large seismic load, we observe that the M-O theory often derives an unrealistically large seismic earth pressure, and sometimes, the seismic loads exceeds the applicable limit of this theory. This often causes practical problems in designing a retaining structure or evaluating the seismic stability of an existing retaining structure. Therefore, it has become necessary to evaluate the seismic earth pressure rationally under a large seismic load in order to establish the practical design procedure of a retaining structure.

In recent years, modified M-O method (Koseki et al., 1998a, [7]) that considers the effects of strain localization and strain softening in the post-peak behavior of well-compacted backfill soils has been adopted for design of railway structures and highway bridges against high seismic loads. [8, 9] (R.T.R.I., 2012 and J.R.A., 2002). On the other hand, Watanabe et al. [10, 11] (1999, 2003) found through the shaking table model tests that the seismic earth pressure is largely affected by the dynamic response of RWs. Further, the seismic earth pressure measured under large seismic load was smaller than the modified M-O method by using the maximum base acceleration and the peak value of the backfill soil strength.

Considering these facts, the authors intended to propose a practical evaluation method for earth pressure resulting from seismic motions and conducted very simple shaking table model tests. This paper describes the experiments, and in particular, focusing on the effects of bearing conditions (degree of stability) of the RW on the seismic earth pressure.

2. Testing Procedures

2.1 Model of retaining wall and backfill

Model tests were conducted by using a shaking table at the Railway Technical Research Institute, Japan. A rigid soil container (length: 2050 mm, width: 600 mm, and height: 1400 mm) was fixed to this table.

The experiment was conducted for four cases. A RW model that was completely fixed or elastically supported was used in all cases except for Case 4, in which a gravity-type RW model (one-tenth scale) was used.

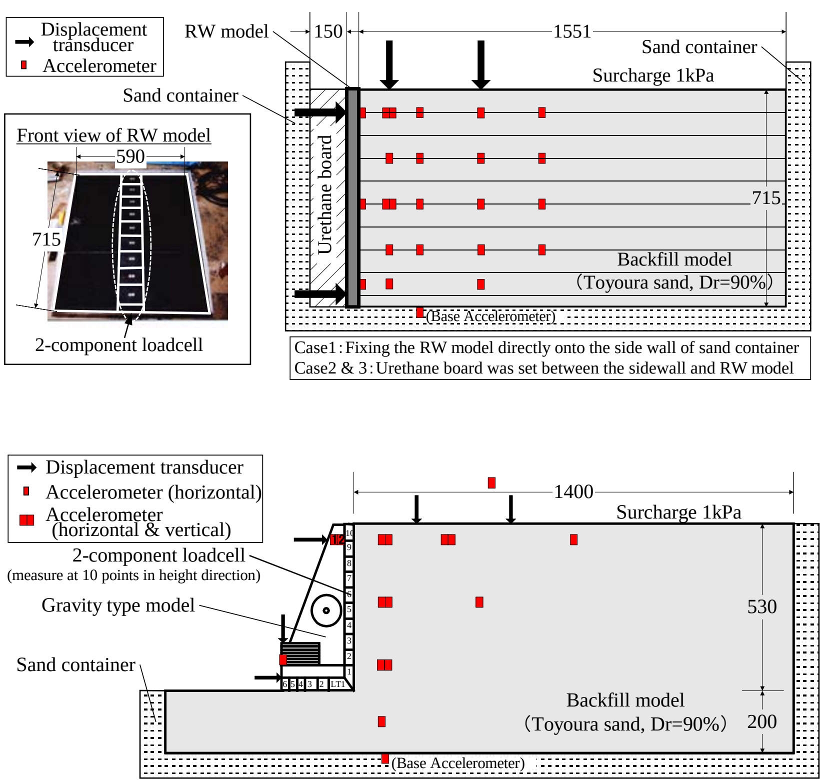


Fig. 4 –Cross-section of model retaining wall and location of measuing instruments

(Upper: Cases 1 to 3, lower: Case 4, unit : mm)

The RW model used for Cases 1–3 were made of aluminum and were 715 mm high and 40 mm thick. As shown in Fig. 4, both normal and shear components of thrust force were monitored with nine two-component loadcells that were set along the center line of the wall surface (Case1-3).

The gravity-type RW of Case 4, on the other hand, was 530 mm high, and two-component load cells were positioned at 10 locations in the direction of the height and at six locations on the bottom surface of the RW footing.

The backfill 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 prepared by using a sand hopper and keeping the falling height constant. The average relative density of 90% was achieved by this method.

The stress condition is different between the prototype and 1-g shaking table model. Therefore, this study focuses on relative comparison of the seismic earth pressure acting on several RW models having different seismic stability. The model used for Cases 1–3 did not simulate the actual RW; in fact, these model experiments were conducted under more simplified conditions in order to evaluate the impact of the bearing conditions of the RW on the seismic earth pressure, with the focus on obtaining accurate measurements of seismic earth pressure. On the other hand, in Case 4, the focus was on simulating the seismic earth pressure acting on the actual gravity-type RW. The geometric shape and specifications (height, width, and center of gravity) of this model was set by referring to that of typical ones having a height of about 5 m in Japan, while reducing their size to a scale of almost one-tenth. The critical seismic coefficient (overturning, sliding and overturning) which follows the relevant design procedures almost corresponds to that of the gravity type RW which is generally designed for the railway structure in Japan (Watanabe et al., 2003, [11]).

The testing conditions for all cases are listed in Table 1. The RW model was fixed directly onto the sidewall of an soil container for Case 1, while a elastic material (urethane board) was set between the sidewall of the soil container and the RW model (Fig. 4). Highly elastic urethane board was used in Case 2 to ensure that the backfill soil did not reach an active state during shaking. In Case 3, on the other hand, a urethane board with lower elasticity than that in Case 2 was used to ensure that the backfill soil did not reach an active state before shaking (against static earth pressure) but reaches the active state during shaking (the upper edge of the RW is displaced by 0.5% to 1% with respect to the wall height). The result of static loading test for these urethane board conducted in advance indicated that the elasticity of urethane board used in Case 2 was about four times that of

Table 1 – Testing conditions and input earthquake motion of all tests

	Supporting conditions of retaining wall model	Input earthquake motion
Case1	Completely fixed to the sidewall of sand container	Sinusoidal wave (5Hz、10 waves) Increased in increments of 100gal
Case2	Elastic support (High elastic urethane board)	
Case3	Elastic support (Low elastic urethane board)	
Case4	Gravity-type retaining wall (set on subsoil layer 200 mm thick)	Sinusoidal wave (5Hz、20 waves) Increased in increments of 50gal

the one used in Case 3.

The gravity-type retaining (Case 4) wall was set on supporting ground (200 mm thick), while the RW was set directly on the bottom surface of the soil container (Case 1 - 3).

2.2 Application of seismic loads

Seismic loads were applied by shaking the soil container horizontally by means of regular base acceleration (Sinusoidal waves of frequency 5 Hz). Its amplitude and time scale were adjusted so that the base acceleration had a prescribed maximum amplitude. Each model was subjected to several shaking steps, where the maximum amplitude of the base acceleration was initially set at 100gal (Case1 -3, 10 waves) or 50gal (Case4, 50 waves) and increased at an increment of 100gal (Case1 -3) or 50gal (Case4).

The shaking table test was conducted up to an excitation of 1,000 gal for Cases 1–3, but the experiment was terminated at 550 gal in Case 4 since the residual displacement of the RW became large.

3. Test results and Discussion

3.1 Residual displacement of the wall

The relationship between horizontal displacement near the top of the wall and base acceleration is shown in Fig. 5. The horizontal displacement immediately before the start of shaking table tests was about 0.06 to 0.09% (horizontal displacement / RW height), indicating that the backfill did not reach the active state for Cases 2 and 3 in which an elastic material (urethane board) was used. The displacement increased almost linearly in Cases 2 and 3 as the acceleration increased, but the displacement increased rapidly around 200gal – 300gal in Case 4. This is because in Cases 2 and 3, the resistance of urethane installed on the back of the RW increased elastically in association with the displacement of the RW. On the other hand, in Case 4, horizontal displacement suddenly increased due to the loss of bearing capacity near the tow of the base footing. Refer to reference document [11] for details on the resistance characteristics of the gravity-type RW against external forces.

3.2 Dynamic characteristic of seismic earth pressure

Fig. 6 shows the time history of the resultant normal force of the seismic earth pressure, horizontal displacement near the top of the wall, and horizontal acceleration for Cases 2 and 4. All the data were measured during the shaking step at 500 gal. In Case 2, the seismic earth pressure increased when the inertial force was oriented to the active direction (negative acceleration), while inversely, the seismic earth pressure decreased when the inertial force was oriented to the passive direction (positive acceleration). This shows that the inertial force and the seismic earth pressure are "in-phase" and same tendency was also observed in Case 1. This is due to the "collision" between the wall the backfill when the inertial force was oriented to the active direction, since

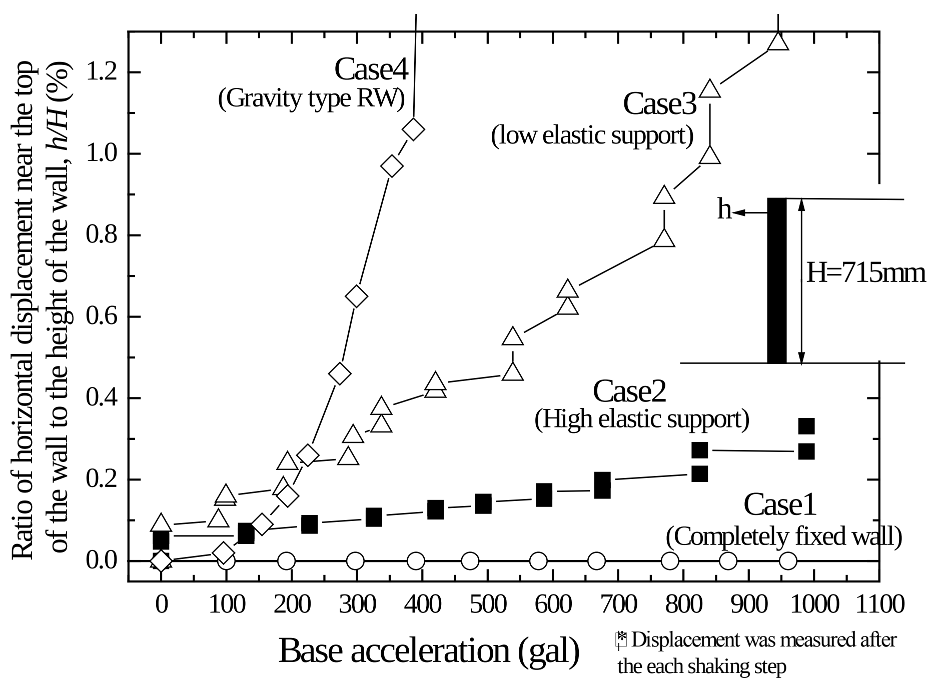


Fig. 5 – Accumulation of residual horizontal displacement near the top of wall

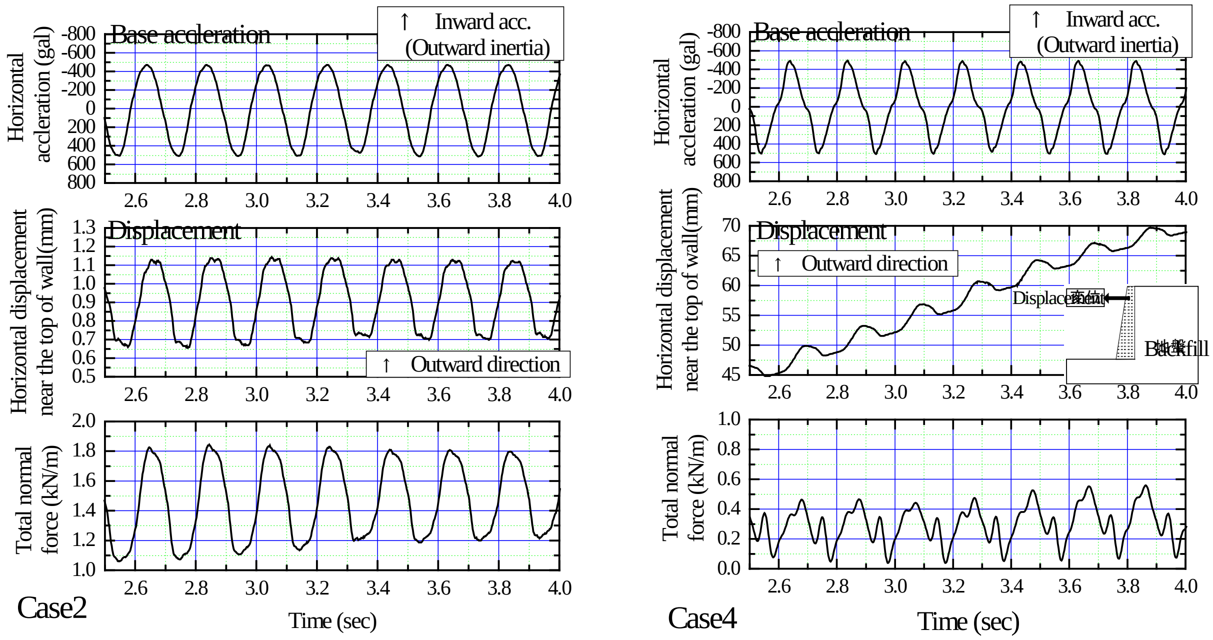


Fig. 6 –Time history of horizotal acceleration, displacement and total normal force of the seismic earth pressure

the RW was highly stable.

In Case 4, on the other hand, the seismic earth pressure increased not only when the inertial force was oriented to the active direction, but also when it was oriented to the passive direction. It can also be seen from this figure that the resultant force was larger in Case 2 than in Case 4, although the model was subjected to almost the same seismic excitation.

These difference characteristics of seismic earth pressure are caused by the different degree of seismic stability of the RW in Cases 2 and 4. In Case 4, when the inertia force was oriented to the active direction, the RW moved outward more than the backfill, and the seismic earth pressure, which should have been mobilized by the “collision” between the wall and the backfill, did not increase after the outward displacement of the RW. On the other hand, larger seismic earth pressure was mobilized by this “collision” in Case 1, where the RW model fixed completely to the soil container. A similar tendency where the dynamic characteristics of seismic earth pressure were changed by the seismic stability of RW was also found in shaking table tests using different RW models [10] and same gravity-type RW models set on the different supporting ground model. [12]

These tests results revealed that the dynamic characteristics of seismic earth pressure was significantly affected by the seismic stability of the RW and cannot be obtained only by the force equilibrium of the soil wedge using the maximum response acceleration as assumed by the M-O theory.

3.3 Comparison of seismic earth pressure distributions

The seismic earth pressure distributions measured in each shaking table tests are shown in Fig. 7. The earth pressure measured in each height when the base acceleration inducing an outward inertia force (active state) took the maximum value in each shaking step was plotted for all the cases. The seismic earth pressure was largest for Case 1, it decreased in the order of Case 1 > 2 > 3 > 4, indicating that large earth pressure acts on a RW having high seismic stability. The shape of the seismic earth pressure distribution reveals that the earth pressure increased almost on the same level at all heights in Cases 1 and 2 with a high degree of stability, while the distribution for Case 3 and 4 was triangular as assumed by the design standard. The seismic earth pressure in the lower layers primarily increased with the increase of the base acceleration. This may be due to strain softening behavior along the failure plane in the backfill soil which was slightly observed for Case 3 and clearly observed for Case 4, indicating that backfill had reached an active state in these cases. On the other hand, the seismic earth pressure was mobilized mainly by the simple shear deformation of the backfill soil for Case 1 and Case 2 where

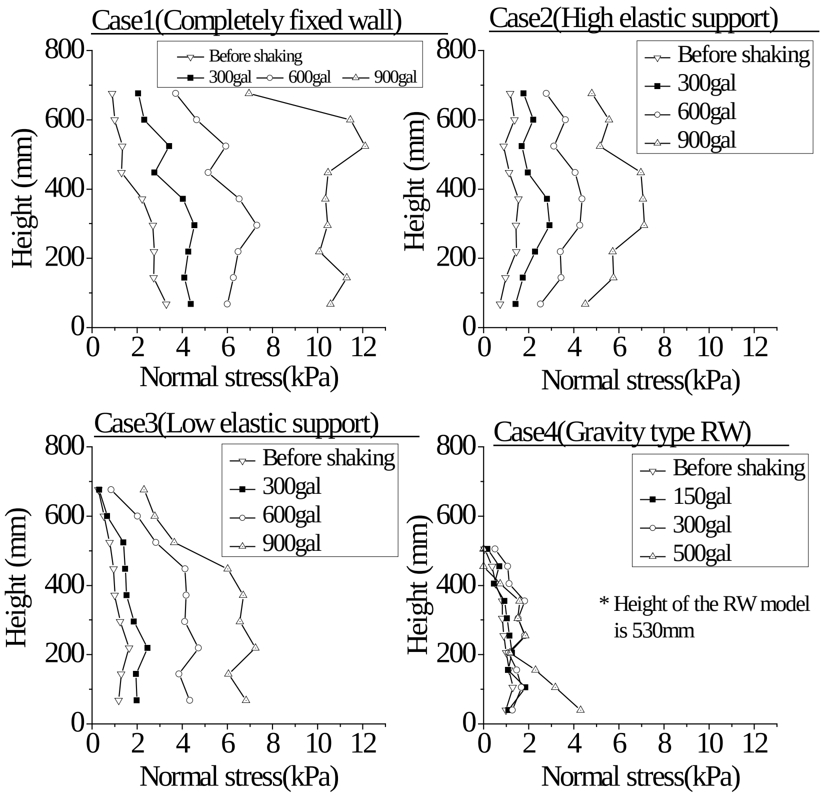


Fig. 7 – Comparison of seismic earth pressure distribusions

the displacement of the RW was less compared with Cases 3 and 4. This condition is similar to that assumed by the response displacement method which is often used to derive the earth pressure acting on an open cut tunnel or box culvert, etc. The increase of the seismic earth pressure is therefore seemed to be quite large in the middle and upper ground layers where the responses of the retained ground are large.

3.4 Relationship between seismic earth pressure, acceleration and the displacement of the walls

The relationship between the seismic earth pressure coefficient, K_a, and base acceleration is shown in Fig. 8, while that between the seismic earth pressure coefficient and the displacement of the RW is shown in Fig. 9. The values for seismic earth pressure used here was also measured when the base acceleration inducing an outward inertia force took the maximum value in each shaking step. Furthermore, the theoretical values for seismic earth pressure which was obtained from the modified M–O method have also been plotted, for comparison, in Fig.8. In order to obtain the theoretical values using modified M-O method, the shear resistance angle ϕ of the backfill was set to be equal to ϕ_{peak} (=51°) and ϕ_{res} (=43°) obtained from the relevant plane strain compression (PSC) tests which were conducted under a low confining pressure (10 kPa) (Koseki et al., 1998b, [13])

This figure reveals that the seismic earth pressure acting on the model in Case 1 (a completely fixed wall) is much larger than in the other experiments, and it exceeds the values derived from modified M–O method.

Furthermore, in Cases 1 to 3, the seismic earth pressure increases as the acceleration increases. However, it reaches an upper limit with excitations of 300 gal or more in the case of the gravity-type RW (Case 4), and it can be seen that the seismic earth pressure hardly increases beyond this point even when the acceleration continues to increase. This is because the seismic earth pressure depends on the degree of stability of the RW, as shown in Fig. 3. In other words, when the resistance of the RW against the external forces (inertial force and seismic earth pressure) is large (small displacements) as in the case of the RW models in Cases 1 to 3, greater seismic earth pressure can act on the wall. On the other hand, when the resistance is small (large displacements) as in Case 4,

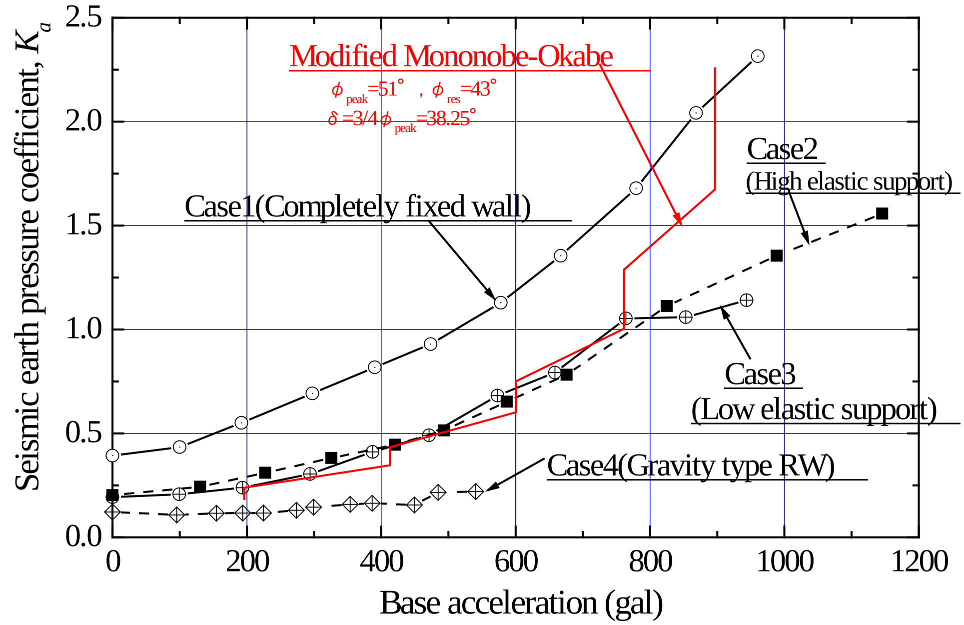


Fig. 8 – Relationship between seismic earth pressure coefficient and horizontal acceleration

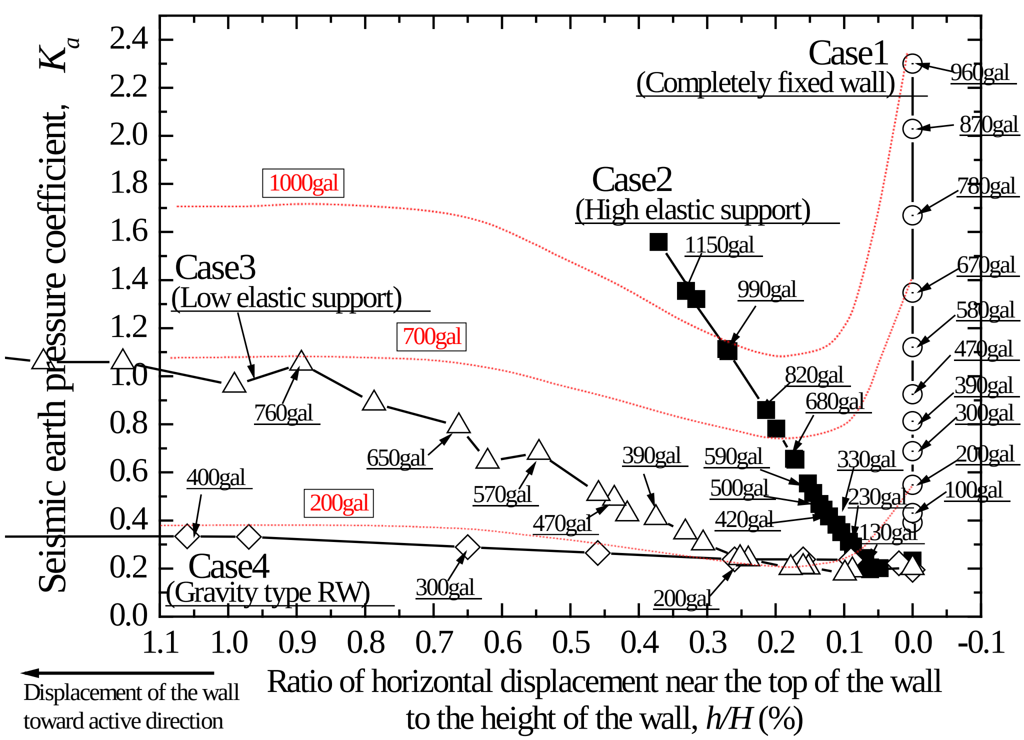


Fig. 9 –Relationship between seismic earth pressure coefficient and the displacement of the retaining wall

only small seismic earth pressure can act on the wall. Considering these aspects, the seismic earth pressure curves plotted for same acceleration level (200gal, 700gal and 1000gal) are also shown as red line in Fig. 9, where the seismic earth pressure coefficient was plotted with respect to the displacement of the RW, and it shows how the seismic earth pressure changes with the displacement of the RW and increase of acceleration. Details will be discussed in the next section.

3.5 Qualitative interpretation of actually measured seismic earth pressures

The seismic earth pressure is affected significantly by the displacement of the RW even when the wall and backfill soil are subject to same acceleration level, as shown in Fig. 9. This tendency can be interpreted qualitatively using the schematic diagram shown in Fig. 10.

The earth pressure temporarily decreases significantly with the displacement of the RW in the active direction, as shown in the skeleton curve for the static field in Fig. 10a. This is because the shear strength (φ_{mod}) mobilized along the failure plane reaches its maximum (φ_{peak}), and the earth pressure at this point is equivalent to the active earth pressure (Fig. 10a). When the RW moves outward (toward the active direction), the shear strength (φ_{mod}) decreases (strain softening behavior, Fig. 10b), and the earth pressure increases (Static skeleton curve in Fig. 10a). This tendency has been confirmed in a static loading test using the gravity-type RW model used in this

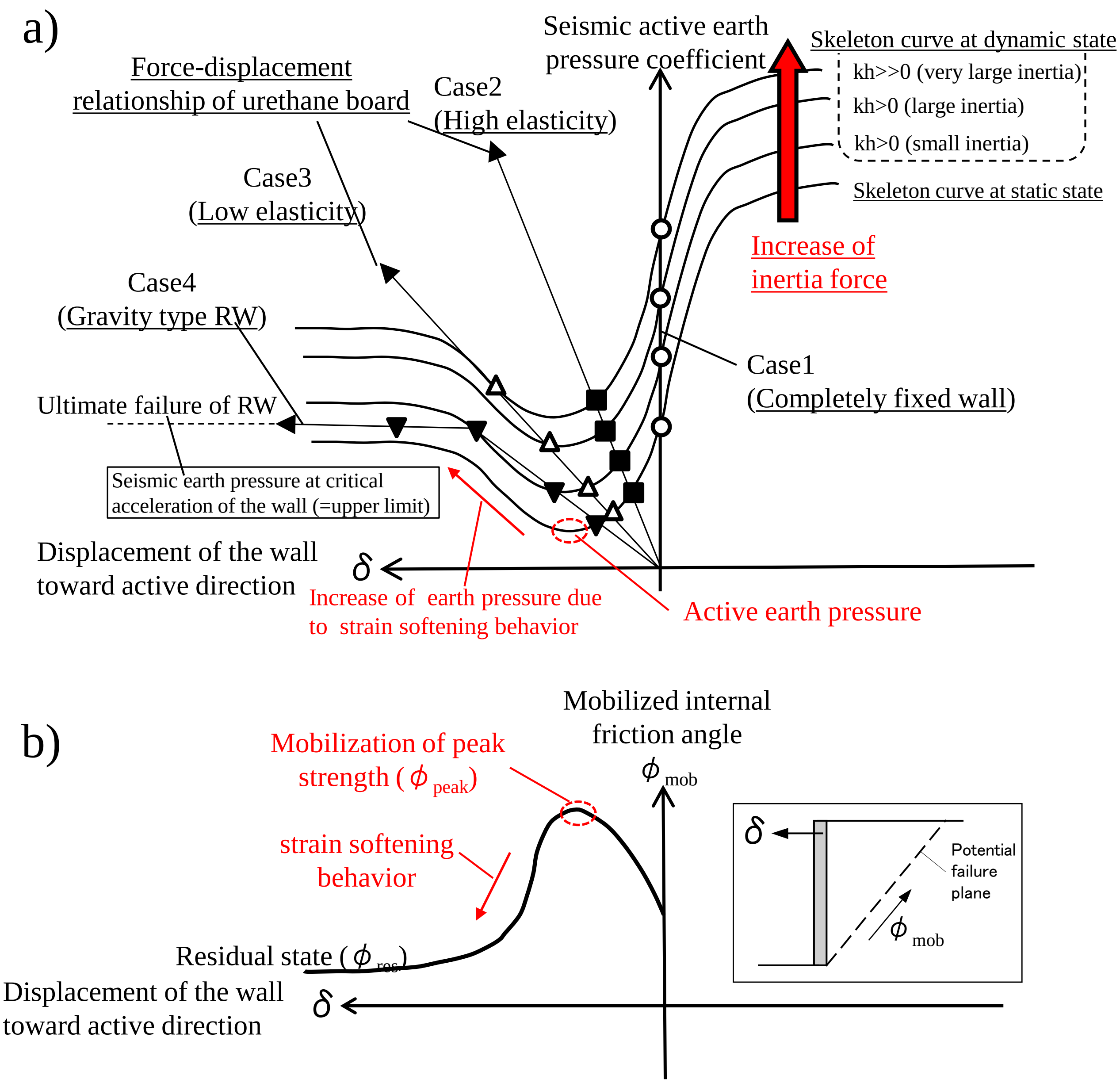


Fig. 10 – Schematic diagrams showing the relationships between the seismic earth pressure coefficient and the wall displacement

research (Case 4) [14]. The inertia force shifts the entire skeleton curve upward since the seismic earth pressure which is mobilized by the collision between the wall and backfill soil increases with the increase of inertia force.

The urethane boards that support the RW, on the other hand, exhibited larger resistance force with the increase of outward displacement of the RW (i.e., the degree of compression of urethane). The straight line in Fig. 10a shows the force-displacement relationship of urethane under the assumption that the urethane is an elastic body. Two resistance lines that correspond to the elasticity (modulus of elasticity) of urethane boards are shown in this figure. The seismic earth pressure acting on the RW corresponds to the intersection of the skeleton curve of the earth pressure and the resistance line of urethane board. The earth pressure, therefore, increases with the increase of the acceleration as shown in Fig. 10a (Case 1: symbol ○; Case 2: symbol ■; Case 3: symbol △), indicating that the seismic earth pressure in each acceleration level varies with the stability of the RW.

Although the present examination is based on the assumptions that,

(a) the shape of the skeleton curve of the earth pressure does not get deformed regardless of the static or dynamic field,
(b) the urethane boards used in the experiments are perfect elastic body,

similar qualitative trends can be seen between Fig. 10a and Fig. 9 when the measured points of the seismic earth pressure coefficient under same acceleration was connected in a curve (red line in Fig. 9).

As in Case 4, the seismic earth pressure does not increase when the displacement increases largely. This is because the resistance of the RW reaches “upper limit”, as indicated by the ▼symbol in Fig.10a, and the seismic earth pressure cannot exceed the “upper limit” of the resistance of the RW. This indicate that maximum seismic earth pressure is equivalent to the “upper limit” of the resistance force, such as the bearing capacity, and displacement of the wall increases rapidly after seismic earth pressure move outward.

4. Seismic earth pressure under a large seismic loads

The shaking table model tests revealed that the resultant force of seismic earth pressure was smaller than that obtained by using the M-O theory especially for RW suffering from large outward displacement. This is mainly due to the applicable limit of the M-O theory where the dynamic response of the RW is ignored. On the other hand, it was found that the seismic active earth pressure has an “upper limit,” which is determined by the bearing capacity of the RW.

Therefore, it should be suggested that the resultant force of seismic earth pressure under the large seismic load for a practical design can be evaluated by applying the critical acceleration to the M-O theory. Watanabe et al. (2012) also shows that the angle of failure plane in the backfill, which determines the shape and volume of soil wedge, can also be obtained by applying the critical acceleration to the M-O theory [12].

This result have already applied to the seismic design procedure of retaining structures under large earthquake, which is written precisely in the new design standard of railway retaining structures in Japan (2012).

5. Conclusion

In this study, a series of shaking table tests of the RW model under different bearing conditions (seismic stability) were performed to examine the impact of the bearing conditions of the RW on the seismic earth pressure. The experiments reveals that the resultant force and the distribution of seismic earth pressure, phase relationship between acceleration and seismic earth pressure are affected significantly by the seismic stability of RW (in other word dynamic response characteristic of RW), even when the wall and backfill soil are subject to same earthquake input motion. It was also revealed that the seismic earth pressure cannot exceed the “upper limit” of the resistance of the RW, indicating that maximum seismic earth pressure is equivalent to the “upper limit” of the resistance force, such as the bearing capacity of the supporting ground.

These test results indicates that the seismic earth pressure cannot be obtained only by the force equilibrium of the soil wedge using the maximum response acceleration as assumed by the M-O theory.

It is necessary to carry out more precise experiments or numerical analysis to investigate the relationship between the seismic earth pressure and dynamic response characteristic of RW in detail. However, it is possible to evaluate rationally the maximum resultant force of the seismic earth pressure, which is the most important factor for the practical seismic design of retaining structure, by taking the larger value between (a) the maximum resistance force (such as bearing capacity) and (b) M-O theory using maximum acceleration.

For example, when the RW which is sufficiently stable against the seismic input motion, it is possible to obtain the resultant force of seismic earth pressure by using simply the M-O theory. This corresponds to the experiment results through Case 2 and Case 3. On the other hand, when the RW is not stable against the seismic input motion, the seismic earth pressure does not exceed the maximum resistance force, as seen in Case 4. In this case, the RW usually suffers from large residual displacement, which should be evaluated by other method rationally.

These research outputs have already been applied to the seismic design procedure of retaining structures under large earthquake, which is written precisely in the new design standard of railway retaining structures in Japan [8].

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