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RESIDUAL EARTH PRESSURE ON A RETAINING WALL WITH SAND BACKFILL SUBJECTED TO FORCED CYCLIC LATERAL DISPLACEMENTS

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ABSTRACT

A pair of about 11 m-high soil retaining walls of an U-shaped underground reinforced concrete (RC) structure in Tokyo exhibited a large residual inward (i.e., toward the active side) displacement with potential structural damage, which became 18 cm between the tops of the two walls about three years after its completion. Noticeable settlements of the backfill were observed behind the walls. A series of small-scale model tests was performed in the laboratory to understand this field behaviour. The results from in-situ investigation and model tests showed that this wall behaviour can be attributed to a gradual increase in the residual lateral earth pressure, resulting from cyclic lateral displacements of the walls caused by a small number of relatively large seasonal thermal cyclic displacement of the RC wall facing and bottom slab of the structure, not by a great number of relatively small daily displacement. Three factors for the mechanism of this wall behaviour (i.e., ratcheting, cyclic hardening and cyclic loading-induced residual deformation of the backfill) were identified and analyzed based the model test results. The settlement in the backfill observed in the model tests is consistent with the field behaviour.

1. INTRODUCTION

An U-shaped underground reinforced concrete (RC) structure that was constructed as an open-cut to accommodate over-passing roads has two about 11 m–high soil retaining walls on the opposite sides with the backfill of sandy soil (**Figure 1**; Sugimoto et al., 2003; Sumiyoshi et al., 2005). Two side roads were constructed on the backfill immediately behind the RC walls. During the construction of the structure, the two walls were supported with horizontal steel struts. After the backfill was filled and then the steel struts were removed, the 5th section of the walls started exhibiting overturning displacements toward the active side, which gradually increased with time. The wall displacement was actually rotation about the bottom of the facing. **Figure 2a** shows the time-histories of the lateral displacement measured between the tops of the two walls (at

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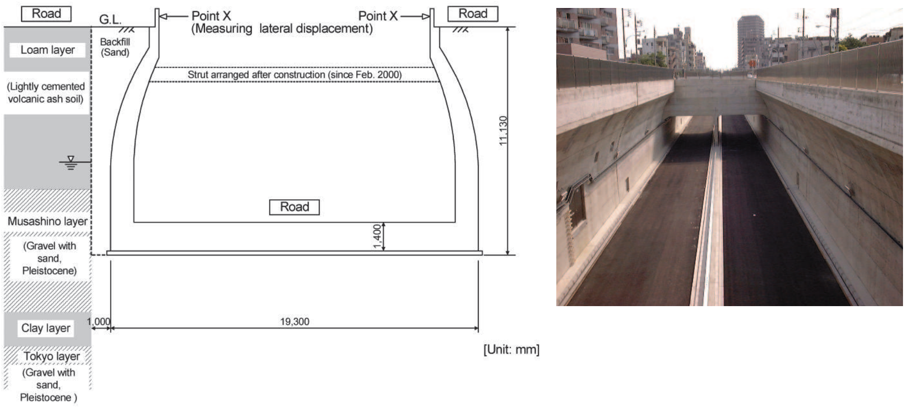

Figure 1. Cross-section of the RC U-shaped soil retaining wall at the 5^{th} section (Sugiyama et al., 2003; Sumiyoshi et al., 2005)

point X in Fig.1) and the surrounding temperature. The displacements toward the active side between the tops of the two walls became 18 cm about three years after the completion of the structure with a possibility of structural damage if the residual displacement would continue increasing. Moreover, the backfill behind the walls exhibited noticeable settlements that increased as approaching the back of the walls. The in-situ investigation and numerical back analysis of the deformation of the walls indicated that the residual lateral earth pressure continued increasing at a decreasing rate with time after the removal of the struts and the earth pressure coefficient, *K*, acting on the facing reached 0.72 (Sugimoto et al., 2003). To prevent the structural damage, a permanent strut was installed February 2000, as shown in Fig. 1.

Figures 2b and **2c** show the relationships between the lateral displacement between the tops of the two walls and the surrounding temperature (presented in Fig. 2a) during a single day and about two years (Sumiyoshi et al., 2005). It may be seen that the wall top cyclically displaced in the lateral direction corresponding to daily and seasonally temperature changes. The average double amplitude (*DA*) of seasonal cyclic displacement of a single wall, δ, was about 20 mm × 0.5= 10 mm compared to the wall height, *H*, equal to 11 m; i.e., $\delta(DA)/H$ = about 0.09 %, which was much larger than that of daily cyclic displacement for a single wall equal to about 1.6 mm × 0.5= 0.8 mm; i.e., $\delta(DA)/H$ = about 0.07%. Based on these facts, it was considered that this wall behaviour was caused by cyclic thermal deformation (i.e., contraction and expansion) of the RC wall facing and bottom slab of the structure due to daily or seasonal changes in the temperature. It was not known however whether a great number of relatively small daily cyclic wall displacement or a small number of relatively large seasonal cyclic wall displacement or both is (are) the cause for the gradual increase in the residual earth pressure. Furthermore, the mechanism of the increase in the residual earth pressure by forced cyclic lateral wall displacement with relatively small amplitude was not known.

In view of the above, a series of model loading tests on a small-scale retaining wall was performed in the laboratory to investigate the following issues:

1) The effects of the amplitude of cyclic wall displacement and the number of cyclic loading on the development of residual earth pressure and associated residual active wall displacement.
2) The mechanism of the development of residual earth pressure by cyclic lateral wall displacements; and
3) The comparison of the wall behaviour between when subjected to forced cyclic lateral displacements and when subjected to monotonic active and passive displacements.

2. MODEL TEST PROCEDURES

A 505 mm-high model wall made of a full-height rigid facing was set up in a plane strain sandbox (1,800 mm-long × 400 mm-wide × 800 mm-high: **Figure 3**). The bottom of the facing was placed on a pair of hinge structures, which were the center of wall rotation. The back face of the model facing was made rough by gluing sandpaper #150. The model wall was equipped with nine two-component (shear and normal) load cells to measure the distribution of the earth pressure, which will be reported in the near future. The facing was cyclically displaced laterally at a constant rate of 0.4 mm/min at a hinge located 115 mm below the top of the facing. The model backfill (1,295 mm-long × 595 mm-high × 400 mm-wide) was prepared by pluviating air-dried particles of Toyoura sand throughout air using multiple sieves. The target initial relative density, D_r, was 90 % (γ_d = about 1.60 g/cm^3). Horizontal thin layers of colored Toyoura sand were arranged in the model backfill to observe the deformation of the backfill (including shear bands) through the transparent Acrylic sidewall of the sand box.

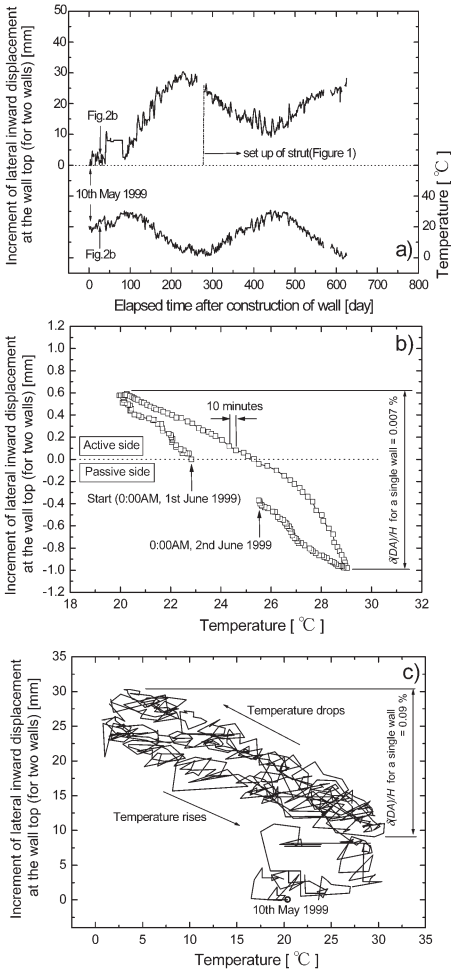

Figure 2. a) Time-histories of lateral displacement between the wall tops at point X in Fig.1 (for two sides of wall) and surrounding temperature; and their relations during: b) a single day & c) for about two years.

Several amplitudes of cyclic lateral wall displacement for a single wall in a range of $\delta(DA)/H$ from 0.02 % to 0.5 %, which nearly covers the daily and seasonal values of the prototype wall, were applied to the model wall from the K_0-state. The following two types of wall rigidity were assumed:

Rigid wall: The model facing was cyclically loaded with zero residual displacement, which means that the model wall is rigid against changes in the earth pressure. The results in this case are reported in this paper.

Elasto-plastic wall: Actual prototype walls exhibit residual active displacements when subjected to a residual increase in the lateral earth pressure (as shown in Fig. 2a). The results from the model tests assuming a non-rigid wall having elasto-plastic displacement characteristics will be reported in the near future.

The settlements of the crest of the backfill were measured at in total five locations with laser displacement transducers (Fig. 3). The lateral load acting to the facing was measured with two load cells arranged at the top and bottom hinges (Fig. 3). The earth pressure coefficient, $K = 2 \cdot Q/(\gamma_d \cdot H^2)$, where Q is the total earth pressure per wall width; γ_d is the unit weight of the backfill (= about 1.60 g/cm^3); and the wall height (= 505 mm).

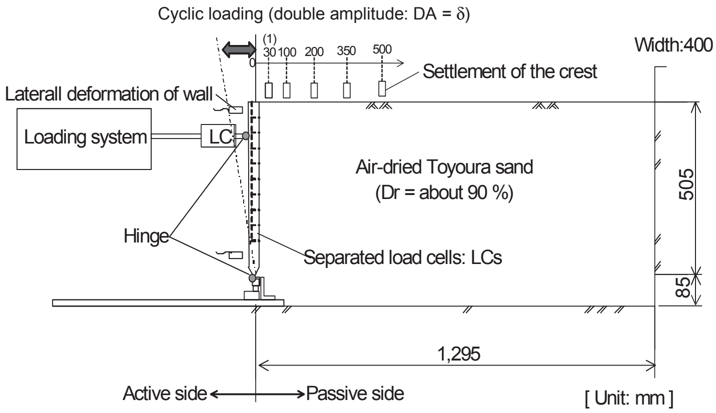

Figure 3. Model retaining wall.

3. TEST RESULTS AND DISCUSSIONS

Overall behaviour of the model wall when subjected to forced lateral cyclic displacements

Figures 4a and **4b** show two typical time-histories of total earth pressure coefficient, K, when $\delta(DA)/H$ = 0.02 % and 0.08 %, more-or-less simulating the average daily and seasonal cyclic displacements of the prototype wall. The values of K were obtained from the measurements of the load cells at the top hinge where cyclic lateral displacements were applied and the bottom one on which the facing was placed. **Figures 5a** and **5b** show the relationships between the K value and δ/H, corresponding to Figs. 4a and 4b. **Fig. 5c** is a close-up of the major part of Fig. 5b. In these figures, the results from two

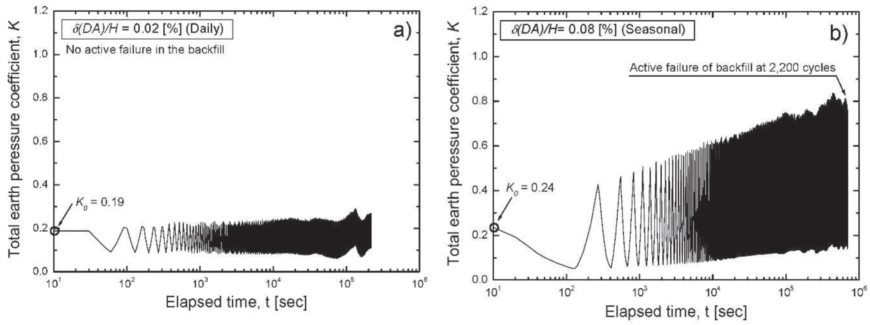

Figure 4. Time-histories of total earth pressure coefficient K: a) $\delta(DA)/H$ = 0.02 % (simulating daily cyclic loading) as double of daily cyclic loading, and b) $\delta(DA)/H$ = 0.08 % as seasonally cyclic loading (simulating seasonal cyclic loading).

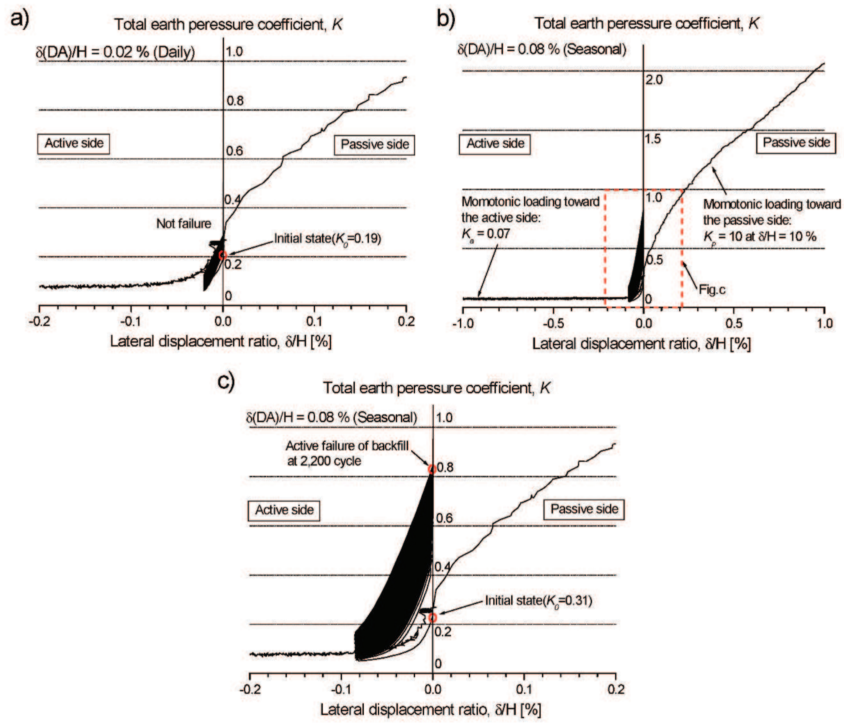

Figure 5. Relationships between K and δ/H (positive at the passive side): a) $\delta(DA)/H$ = 0.02% (simulating daily cyclic loading), and b) & c) $\delta(DA)/H$ = 0.08% (simulating seasonal cyclic loading).

monotonic loading (ML) tests that were continued towards the active and passive failure states are also presented. It may be seen from Figs. 4 and 5 that the development of residual earth pressure by cyclic wall displacements depends on the amplitude of cyclic lateral displacement. The maximum value of K in each cycle, K_{max}, when $\delta(DA)/H$ = 0.08 % increased at a high rate, while the minimum value, K_{min}, also increased noticeably. When $\delta(DA)/H$ = 0.02 %, on the other hand, the increase in the K_{max} and K_{min} values is much smaller despite a larger number of cyclic loading for a given period (about four times). This result indicates that a smaller number of relatively large cyclic lateral displacement, as the seasonal changes with the prototype wall (Fig. 2), has much larger effects on the development of residual earth pressure than a larger number of relatively small cyclic lateral displacements, as the daily change with the prototype wall.

When $\delta(DA)/H$ = 0.08 %, the maximum of K, K_{max}, exceeded the K_0 value already during the first passive loading process and the K_{max} value continued increasing towards the passive earth pressure coefficient, K_p, attained at δ/H= 10 % in the ML test. Although it is far below K_p, the K_{max} reached even 1.0 after many cycles. This result suggests that the earth pressure coefficient, K, of the prototype wall (Fig. 1) may reach 1.0 within its lifetime. When subjected to such large earth pressure, walls designed based on the active earth pressure either exhibits large, perhaps intolerably large, active displacements when the wall is non-rigid, or is structurally damaged when the wall is rigid. Indeed, the prototype wall (Fig. 2) was designed based on K= 0.3 – 0.4 (Sugiyama et al., 2003).

Figure 6 shows the time-histories of the settlement of the backfill crest 30 mm from the back of the model facing (point 1 in Fig. 3). The settlement when $\delta(DA)/H$ = 0.08 % was very large and is consistent with the field observation (i.e., Sumiyoshi et al., 2005).

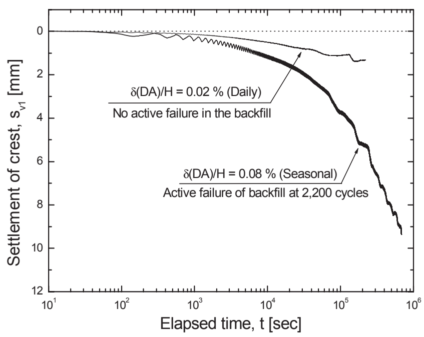

Figure 6. Time-histories of settlement at the backfill crest (30 mm from the back of model facing), the rigid facing.

The effect of cyclic amplitude of wall deformation on the increase of earth pressure

Figure 7 summarises of the relationships between the K_{max} value at the respective number of cycle (*N*) and $\delta(DA)/H$ from the cyclic loading model tests on the rigid wall. The value of K_0 is also indicated in this figure. The solid data points indicate the moment when the active failure plane developed in the backfill was noted. It may be seen that the values of K_{max} increases by cyclic loading at a rate that increases with an increase in $\delta(DA)/H$. In Fig. 7, the results from the 1g model tests by England et al. (2000), similar to those performed in the present study, and those from centrifuge tests by Ng et al. (1998), both using Leighton Buzzard silica sand with particle sizes between 90 – 150 µm,

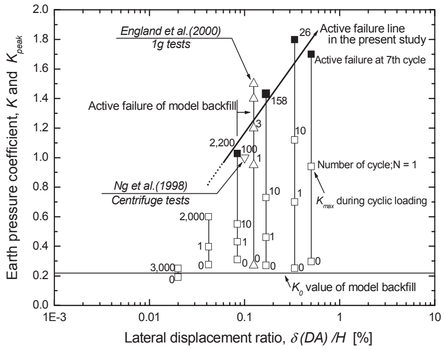

Figure 7. Relationships between K and $\delta(DA)/H$: comparison between the present study model loading tests and the previous studies for rigid wall.

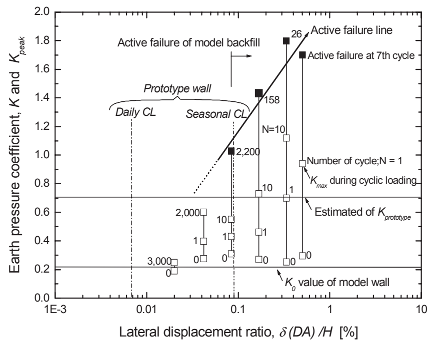

Figure 8. Relationships between K and $\delta(DA)/H$: comparison between the present study model loading tests for rigid wall and the prototype wall.

are also plotted. These previous studies were performed linked to the thermal loading problem of integrated bridge. The results from the present study (1g on Toyoura sand) and the previous studies are consistent with each other.

Figure 8 compares the results from the present study with the behaviour of the prototype wall, for which the estimated maximum residual value, $K_{prototype}$, is equal to 0.72, and the average daily and seasonal values of $\delta(DA)/H$ for single wall are equal 0.007 % and 0.09 %, are indicated. In the model tests on the rigid wall, the development of residual earth pressure was very small even after many cycles when $\delta(DA)/H$ was less than about 0.02, while the development when $\delta(DA)/H$ = about 0.1 % was significant, similar to the prototype wall. Therefore, considering also the trends of the settlement of the backfill (Fig. 6), it can be concluded that the development of relatively large residual active displacement and associated settlement with the prototype wall can be attributed to seasonal thermal displacements of the wall.

Mechanism of the development of residual earth pressure by cyclic wall displacement

The increase in the residual earth pressure by cyclic lateral wall displacements, which results into the development of residual active wall displacements when the wall is not rigid, are due to a mechanism consisting of the following three factors (**Figure 9**):

1) ratcheting in the backfill deformation;
2) cyclic hardening of backfill; and
3) cyclic loading induced residual deformation of backfill.

The first factor, the ratcheting in the backfill deformation, is illustrated in **Figure 10**, namely:

1) The facing displacement toward the active side results into a settlement of the active zone in the backfill (Fig. 10b). The first event of this process is denoted by relation **a** → **b** in Fig. 9.
2) When the wall is subsequently forced to displace toward the passive side, the active zone in the backfill cannot return to the original location due to different mechanisms

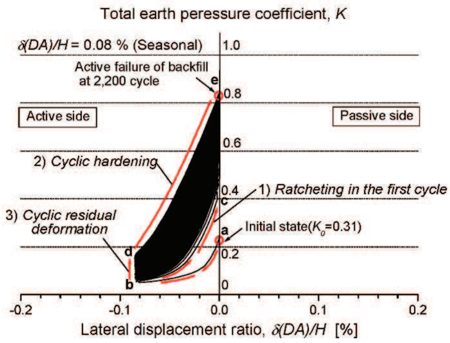

Figure 9. Three factors of the mechanism for an increase in the residual earth pressure when subjected to cyclic lateral displacements, illustrated using the test results presented in Fig. 5c.

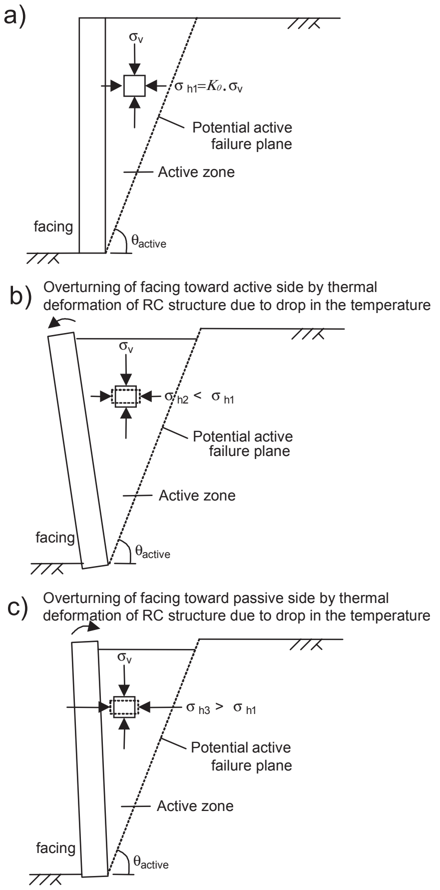

Figure 10. Ratcheting mechanism in the wall subjected to cyclic lateral displacements.

between the active and passive earth pressure developments, which results in an increase in the lateral earth pressure (Fig. 10b). The first event of this process is relation **b** → **c** in Fig. 9.

3) The ratcheting process described above is repeated during subsequent cycle loading at a rate that decreases with an increase in the number of loading cycles.

It seems that most of the passive wall displacement, which takes place subsequently to the preceding active wall displacement is absorbed by the deformation of the backfill outside the active shear band (having a thickness of order of ten times the mean diameter), while large part of the active wall displacement is absorbed by the deformation of the active shear band. Then, cyclic displacements of wall either in the fixed range of displacement when the wall is rigid, or in a range shifting toward the active side when the wall is non-rigid result into a gradual increase in the active displacement of the active zone. This means that, even if the maximum displacement during the cyclic loading is smaller than the displacement when active failure takes place in a continuous active ML test, the maximum earth pressure can exceed the K_0 value increasing towards the passive value while the active failure takes place in the backfill. In fact, in the cyclic loading tests with a displacement $\delta(DA)/H$ ranging between 0.08 and 0.5 %, an active failure shear band, as observed in the continuous active ML test, developed despite that the maximum earth pressure observed in the cyclic loading tests was far larger than the active earth pressure observed in the continuous active ML test. The angle of active shear band that developed in these cyclic loading tests was independent of $\delta(DA)/H$, and close to the one observed in the continuous active ML test.

The second factor, cyclic hardening of backfill, can be noted by a significant increase in the stiffness of the backfill by cyclic loading (i.e., a change from relation **b** → **c** to relation **d** → **e** in Fig. 9). By this factor, the maximum earth pressure coefficient, K_{max}, increases by cyclic loading even when the minimum value, K_{min}, remains constant. This factor is due to such material property that the stress-strain behaviour of unbound granular material becomes more elastic, thus the stiffness increases, when subjected to continuous cyclic straining for a fixed range of strain (Tatsuoka et al., 2003).

The last factor, cyclic loading-induced residual deformation of backfill, can be noted from an increase in the minimum value of K, K_{min}, by cyclic loading (i.e., from point **b** to pint **d** in Fig. 9). It is considered that, if the wall is subjected to cyclic earth pressure for a fixed range of K below 1.0, the active residual displacement increases during cyclic loading. It seems that this trend of behaviour results from such property of soil that the residual shear strain increases when subjected to cyclic shear stresses in the direction of currently acting neutral shear stress.

4. CONCLUSIONS

From the full-scale behaviour of a prototype structure and the results of model loading tests, the following conclusions can be derived:

1) The earth pressure can increase gradually when a RC soil retaining wall is subjected to cyclic lateral displacement caused by thermal deformation of the wall structure due to cyclic changes in the temperature even if the cyclic wall displacement is relatively small and remains on the active side. In the case of the prototype structure reported in this paper, a small number of relatively large seasonal temperature change was responsible for the development of relatively large residual active displacement of the wall while the effects of a great number of daily relatively small temperature changes can be considered negligible.
2) Even when the wall is subjected to cyclic lateral displacements that remain on the active side, the earth pressure can exceed the K_0 value while increasing towards the passive value while the backfill can exhibit active failure.
3) The mechanism for the development of residual earth pressure, and also residual active wall displacements when the wall is not rigid, by cyclic lateral wall displacements consists of three factors; namely, ratcheting in the backfill deformation, cyclic hardening of the backfill and cyclic loading-induced residual deformation of the backfill.

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