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High seismic stability of preloaded and prestressed reinforced soil structure

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ABSTRACT: A preloading and prestressing (PLPS) method is proposed to substantially decrease the transient and residual vertical compression of geosynthetic-reinforced soil (GRS) structures subjected to long-term traffic load. A series of shaking table tests were performed to evaluate the seismic stability of PLPS GRS structures. It is shown that by using a newly developed device (called the ratchet system) in addition to the PLPS procedure, the seismic stability of PLPS GRS structures becomes extremely high. The ratchet system can not only maintain high prestress when the backfill tends to contract but also prevent the expansion of the backfill, both effectively restraining the shear and bending deformations of the structure subjected to seismic load.

1 INTRODUCTION

Geosynthetic-reinforced soil (GRS) retaining walls (RWs) are now widely used, mainly because of their high cost-effectiveness as well as their satisfactorily high performance (Bathurst & Alfaro 1997, Tatsuoka et al. 1998, Koerner and Soong 2001). This fact can be attributed to the fundamental advantages of reinforced soil RWs in the stability mechanism over conventional type RWs (including gravity type and cantilever RWs). It is also very effective to use a full-height rigid (FHR) facing and to connect the reinforcement layers to the back of the facing to increase the seismic stability of reinforced soil RWs, as validated by high seismic performance of a number of reinforced soil RWs of this type during recent severe earthquakes (Tatsuoka et al. 1996, 1997b & c, White and Holtz 1997) and model shaking table tests (Tatsuoka et al. 1998). Previous researchers have shown that the seismic performance of these GRS RWs was substantially better than that of conventional gravity type RWs, while it was equivalent to, or even better than, that of conventional cantilever type RC RWs (Murata et al. 1994, Koseki et al. 1998, 2001). Conversely, most of the existing modern bridge abutments and piers are RC or steel structures, except for a limited number of reinforced backfill abutments directly supporting bridge girders. The current limited use of GRS bridge abutments is mainly due to their potential high deformability.

To alleviate a potentially high deformability of reinforced soil subjected to long-term static load and cyclic load such as traffic load, a preloaded and prestressed (PLPS) GRS method was proposed (Fig. 1: Tatsuoka et al. 1997a & c; Uchimura et al. 1996, 1998). In this procedure, sufficiently large vertical preload is applied to the reinforced backfill by introducing tension into metallic tie rods that penetrate the reinforced backfill with ends fixed to the bottom and top reaction blocks (Fig. 1). Taking advantages of high vertical compressive strength of reinforced backfill, large vertical preload can be applied without damaging the backfill (Shinoda et al. 2001a). In addition, the stiffness and strength of backfill while the structure is in service is always kept sufficiently high by maintaining sufficiently high prestress. By this PLPS procedure, the transient deformation of reinforced backfill subjected to traffic load could become very small, essentially elastic, and thereby the long-term residual deformation could become very small (Shinoda et al. 2001a). Wu (2001) has also pointed out that preloading and prestressing could significantly improve the deformability of a GRS structure.

It has also been found that the stability and rigidity of reinforced soil structures subjected to seismic load increases with the increase in the pressure level (i.e., prestress) (Shinoda et al. 2001b). When such a PLPS reinforced soil structure as descri-

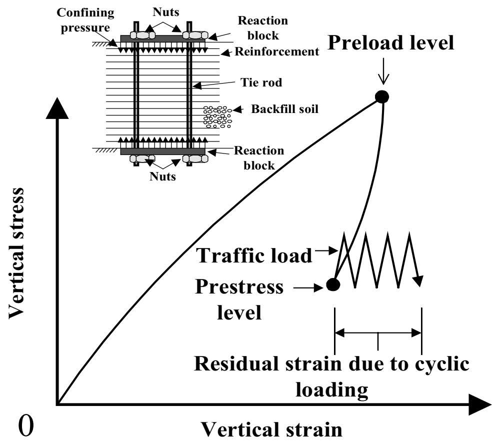

Figure 1. Schematic diagram showing the stress-strain behaviour of PLPS GRS structure (not to scale).

bed above is slender and the prestress has decreased to a very low level, the structure subjected to high-level seismic load may exhibit large bending deformation. In that case, the height at both sides of PLPS reinforced soil structure may largely increase and decrease cyclically. When the height of backfill increases largely, the vertical stresses in that backfill zone may become temporarily very low or even nearly zero. Then, the shear strength and stiffness of that backfill zone may become very low, resulting in excessive shear deformation of backfill. For this reason, it is necessary to keep sufficiently small the bending deformation of PLPS reinforced backfill structures during seismic loading by some measures. To this end, Shinoda et al. (2001c) proposed to fix the top end of the tie rods to the top reaction block placed on the backfill by using a newly developed device, called the ratchet connection system.

Reported herein are a part of the results from a series of shaking table model tests with various prestress levels using or not using a ratchet connection system, showing particularly high performance of the ratchet system.

2 RATCHET CONNECTION SYSTEM

The ratchet connection system (Fig. 2a) has been developed to achieve the following two functions:

- When the backfill tends to exhibit vertical compression, such as creep deformation and transient and residual compression by shaking-induced shear and bending deformation, the ratchet system is unlocked (Fig. 2b) while a relatively long and relatively soft spring that is attached between the top end of each tie rod and the top reaction platen extends according to the vertical compression of backfill. In this way, the stiffness of each tie rod system becomes very low while the prestress level is kept high, close to the initial level.

- On the other hand, when the backfill tends to exhibit dilatancy of backfill or expansion by bending deformation of backfill or both, the ratchet system is locked (Fig. 2c), which makes the stiffness of the tie rod system very high, exerting the original stiffness of the tie rods. In this way, the tie rod tension increases largely responding to the trend of increase in the backfill height.

For such slender reinforced soil structures, the bending deformation of backfill is one of the most dangerous deformation modes leading to the ultimate failure of the structure. By these two functions of the ratchet system described above, large bending deformation as well as large shear deformation of the backfill can be effectively restrained (Fig. 2d). The mechanical details of the ratchet connection are described in Shinoda et al. (2001c).

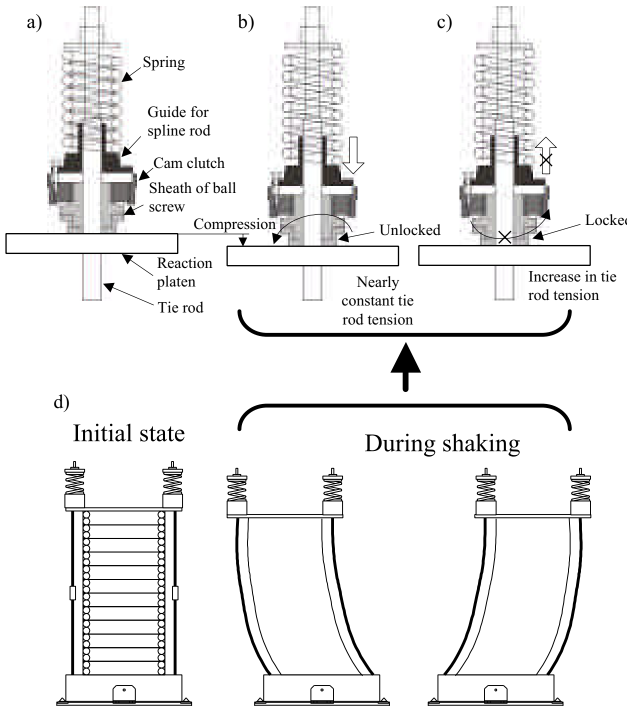

Figure 2. Restraining of bending deformation of PLPS soil structure by using ratchet connections; a) initial state, b) & c) during shaking, and d) typical behaviour during shaking.

3 SHAKING TABLE TEST PROCEDURES

Shinoda et al. (2001b) performed a series of shaking table tests using an input motion consisting of high-amplitude sinusoidal waves to validate the effectiveness of using a ratchet connection system in increasing the seismic stability of reinforced soil structures. The maximum horizontal table acceleration was equal to 700 gals with a frequency *f* equal to either 5 Hz or 10 Hz. The GRS structure models were 55 cm-high and 35 cm by 35 cm in cross-section (Fig. 3). The backfill was a well-graded gravel of crushed sandstone (D_{50}= 2.52 mm; U_c= 5.41; FC= 0 %; e_{max}= 0.986; and e_{min}= 0.481) compacted to a relative density of 90 % while reinforced with 12 grid layers with a vertical spacing of 4.6 cm. Each grid layer consisted of 34 phosphor bronze strips (3.5 mm-wide, 0.2 mm-thick and 350 mm-long), 17 in each perpendicular direction, with an aperture of 8 mm. The periphery of each sub-layer of the backfill was protected with two layers of model gravel bags with a diameter of about 2.3 cm. A square steel platen of 5 cm in thickness and 45 cm times 45 cm in cross-section with a weight of 282 N was placed on the top of the completed reinforced backfill. Horizontal accelerometers and displacements were measured at the top platen and the mid-heights of the second, sixth and eleventh sub-layers from the bottom of the model. Each tie rod was equipped with a load cell to measure the tension.

An average vertical stress of either 30 kPa or 60 kPa or 90 kPa was first applied to the backfill as preload by using four steel tie rods. The top and bottom ends of the tie rods were fixed to the top reaction steel platen and the pedestal of the model. Two types of tie rod connection, “rigid connection” and “ratchet connection”, were used. Each tie rod was fixed rigidly to the top reaction platen by using a nut (the rigid connection) or a ratchet system (the ratchet connection). The vertical stress was then decreased to the prescribed initial prestress, which was either 15 kPa or 30 kPa or 45kPa while keeping the ratio of the preload to the initial prestress equal to 2.0. This ratio was found relevant to make very small the residual vertical compression of backfill subjected to long-term vertical cyclic load as traffic load (Shinoda et al. 2001a). These preload and prestress levels were determined by considering the model similitude for a scaling factor ? (the ratio of the length of prototype to that of model) equal to 6.

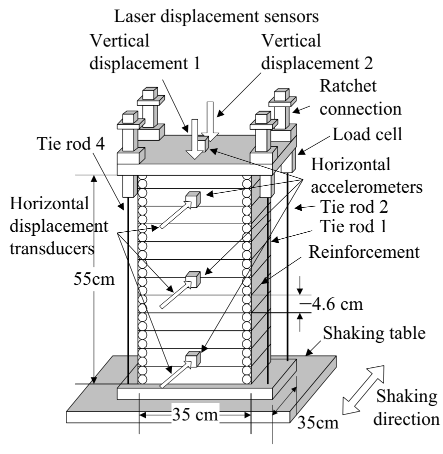

Figure 3. PLPS GRS model with measurement systems.

4 TEST RESULTS

Figure 4 shows the results from the following four tests performed with various preload and prestress levels at an input frequency of 5 Hz; 1) two tests conducted on models with rigid and ratchet connections at an initial prestress level (PS) of 15 kPa to validate the effect of ratchet connection; and 2) two tests conducted on models having a ratchet connection at PS= 30 kPa and 45 kPa to evaluate the effect of the initial prestress level. The following trends of behaviour may be seen from Figure 4:

- The response acceleration at the top of the model with a rigid connection changed largely during shaking (Fig. 4a), which was due to a large change in the natural frequency of the model caused by a large loss of prestress (Fig. 4c) and an associated increase in the shear strain in the backfill during shaking. In the three tests with a ratchet connection, on the other hand, the response acceleration was kept rather constant throughout shaking, showing that the stress conditions in the backfill were essentially constant throughout each test because of proper functioning of the ratchet connection.
- With a rigid connection, the lower bound of prestress started decreasing immediately after the start of shaking (Fig. 4c). Corresponding to the above, the rotation of the top platen of

the model became very large (Fig. 4b) as a result of very large bending deformation of backfill. Because of the above, the residual compression of the backfill was much larger than that of the model with a ratchet connection. This behaviour was due to the following two factors: a) the tie rods became unable to effectively restrain the expansion of backfill because of full loosening of the tie rods (Fig. 4b); and b) the stiffness of backfill became very low due to a substantial decrease in the prestress and a additional decrease due to the non-linearity of the stiffness of backfill (Fig. 4c).
- In all the tests using a ratchet connection, the peak and minimum levels of prestress during shaking were rather constant (Fig. 4c) and the rotation at the top of backfill was very small (Fig. 4b). The effects of initial prestress on the rotation of the top of the backfill were not systematic. The reasons for the above are not known.
- The amplitude of prestress during shaking decreased with the increase in the prestress, which was due to a smaller response acceleration of the model at a higher prestress level. Because of the above and because of a decrease in the shear strain in the backfill associated with an increase in the shear modulus of backfill by an increase in the prestress, the residual compression of backfill significantly decreased with the increase in the initial prestress (Fig. 4d).

In summary, to attain a higher seismic stability of PLPS reinforced soil structures, a higher initial prestress is preferable as far as the structure is not damaged during the preloading stage and the initial natural frequency of structure is sufficiently higher than the predominant frequency of design seismic load.

5 SHEAR MODULUS OF BACKFILL

In the seismic design of PLPS GRS structures, the initial natural frequency and those during shaking of the respective structure should be evaluated with a reasonable accuracy so as to avoid a resonance during a given design seismic load. To that end, a simplified method was developed based on the following assumptions:
- The backfill is a uniform isotropic linear elastic material having constant Young's modulus and shear modulus;
- The major deformation mode of the backfill is bending and shearing as a simple beam.
- The rotation of the top platen is zero due to the full restriction of tie rods (this assumption is relevant before the tie rod tension becomes very small for structures using a rigid connection and at the all the time for structures using a properly functioning ratchet connection).

From the condition that the maximum kinetic energy is equal to the maximum strain energy for a given structure, an equation is derived that provides the natural frequency of the model. The average shear modulus *G* of the backfill at each moment during shaking was back-calculated by substituting the respective natural frequency that was evaluated from measured values of response ratio and phase difference between the shaking table and the top of the model while assuming that the PLPS reinforced pier model behaved as a single degree of freedom system. The details of this procedure are described in Shinoda et al. (2001b, c).

Figure 5a shows the relationships between the average shear modulus *G* back-calculated as above and the corresponding measured single amplitude shear strain γ_{sa} obtained from the two tests with rigid and ratchet connections. The respective shear stress τ indicated in Figure 5a is equal to the average shear modulus *G* multiplied by the corresponding value of γ_{sa}. Figure 5b shows the relationships between the back-calculated shear modulus *G* and the corresponding measured average vertical stress σ_v at the bottom of the backfill (excluding the periphery gravel bags) that was obtained from vertical load measured with

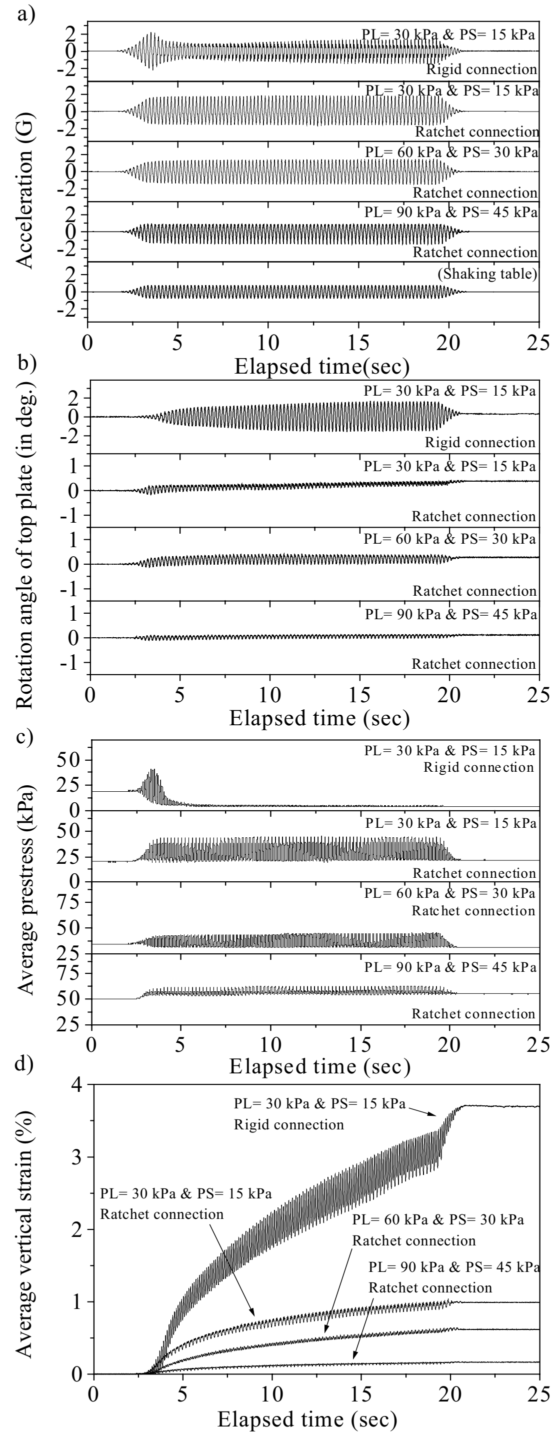

Figure 4. Time histories of a) horizontal acceleration at the top platen (the top four) and the table (the bottom); b) rotation angle of the top platen; c) average prestress; and d) average vertical strain at the bottom of the backfill from four tests with rigid and ratchet connections.

load cells equipped at the bottom of the backfill. The maximum and minimum values of σ_v in each cycle are plotted against the respective average shear modulus *G*.

The following trends of behaviour can be seen from Figure 5:
- In the test with a rigid connection, the shear strain increased largely associated with a large decrease in the average shear modulus *G*. This behaviour was due to; a) a substantial decrease in the vertical stress σ_v; and b) a large increase in the shear stress τ as a result of transient resonance.

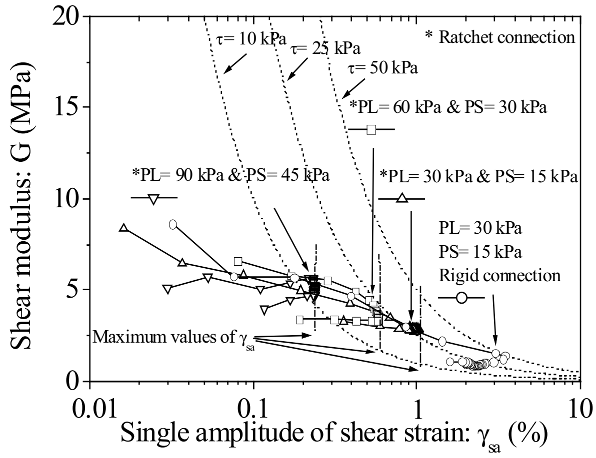

Figure 5a. Relationships between the back-calculated shear modulus of the backfill and the measured shear strain in the tests with and without a ratchet connection system.

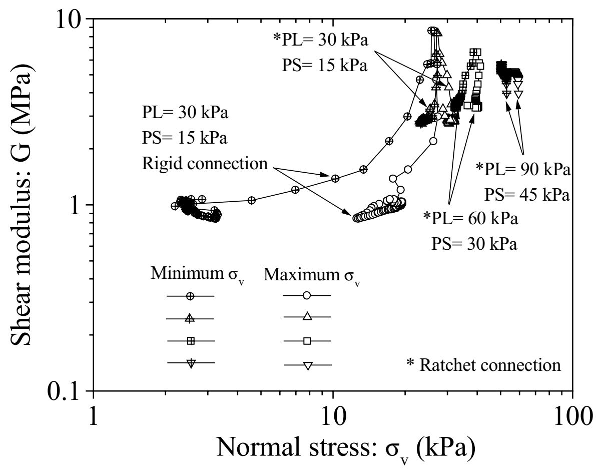

Figure 5b. Relationships between the back-calculated shear modulus of the backfill and the measured vertical stress in the tests with and without a ratchet connection system.

- In the test using a ratchet system, the maximum shear strain γ_{sa} was much smaller. This behaviour was due to the maintenance of relatively high shear modulus associated with that; a) the vertical stress was kept high during shaking (Fig. 5b); and b) the shear stress was kept relatively low because of the non-occurrence of resonance (Fig. 5a). This trend was more evident with a higher initial prestress.

6 CONCLUSIONS

The test results presented in this paper showed that by using a ratchet connection system, the prestress can be kept high when the backfill tends to exhibit compression and the height of the backfill is not allowed to increase. These two functions are essential to restrain the shear and bending deformations of the backfill subjected to high seismic load. The results of the present study suggest that PLPS GRS structures equipped with a ratchet connection system can be constructed as permanent important structures having a high stiffness for long-term repeated load, such as traffic load, as well as a high seismic stability.

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