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Seismic stability of preloaded and prestressed reinforced soil structure against strong shaking

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ABSTRACT: To substantially increase the vertical stiffness and reduce the vertical residual compression of geotextile-reinforced soil (GRS) structures subjected to long-term traffic load, the preloading and prestressing (PLPS) method has been proposed. The seismic stability of PLPS GRS structures was investigated by performing shaking table model tests using sinusoidal waves with horizontal acceleration of 700 gals. The use of a newly developed device, called the ratchet system, is very effective in increasing the seismic stability of the structures by maintaining high prestress when the backfill tends to contract and preventing the expansion of the backfill. These functions effectively prevent the occurrence of resonant state while restraining the bending deformation of the structure, which are essential for the high seismic stability of the structure.

1 INTRODUCTION

A new construction technology, called the preloading and prestressing method, has been proposed so as to substantially increase the vertical stiffness and decrease the vertical residual compression of geosynthetic-reinforced soil (GRS) structures against long-term traffic load (Figure 1; Tatsuoka et al., 1996; Uchimura et al., 1996, 1998). That is, the deformation of the backfill is made essentially elastic by applying sufficiently large vertical preload to the backfill and, while the structure is in service, the stiffness of the backfill is kept sufficiently high by not fully unloading the preload, but maintaining sufficiently high prestress. Shinoda et al. (1999) performed laboratory model tests and showed that the transient and residual deformation of the backfill against cyclic load, such as traffic load, could be made very small by means of the PLPS method.

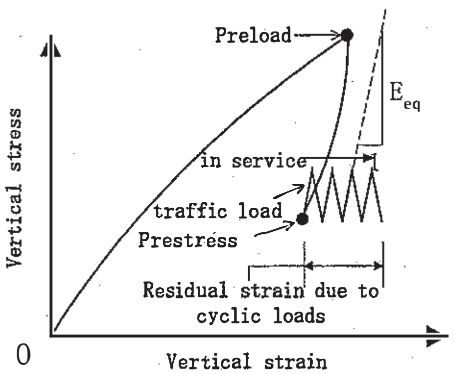

Figure 1. Stress-strain behaviour of PL/PS soil structure (not to scale).

In the summer of 1996, the first prototype PLPS GRS bridge pier was constructed in Fukuoka City, Japan, to support a pair of railway bridge girders (Figure 2). The backfill of the pier is densely compacted well-graded crushed gravel, reinforced with geogrid layers with a vertical spacing of 15 cm. Since having been opened to service the summer of 1997 until now (March 2001), the pier has shown nearly zero residual settlement against about 120 train passing per day (Uchimura et al., 2001).

The maximum transient compression of the backfill by each train passing is only about 0.02 mm, which is equivalent to a vertical strain of as small as

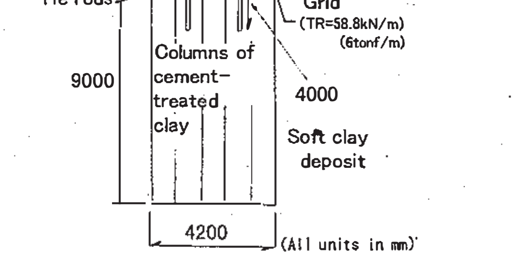

Figure 2. First prototype PLPS GRS bridge pier (Uchimura et al., 2001).

about 0.001 % in the backfill. This strain value is within the elastic limit strain of the material (Tatsuoka et al., 1997). It is one of the keys for the success of the PLPS method that the transient strain has been kept as small as above by attaining a high stiffness of the backfill, which was realized by the PLPS procedure. One end of the bridge is supported by an abutment, which is a GRS structure that is similar to the pier, constructed using the same backfill material and reinforcement as the pier, but without PLPS. In comparison to the PLPS GRS pier, the GRS abutment exhibited a total residual settlement of 12 mm until now, despite that the load by the same train passing applied to the abutment is nearly a half of that applied to the pier. This relatively large residual settlement was due to a much larger maximum transient settlement of about 0.2 mm, which is equivalent to a strain of about 0.01 %, exceeding the elastic limit strain. These different behaviours of the pier and abutment indicate that the PLPS method is very effective in reducing the vertical transient and residual settlement of GRS structures.

Another important required property of such PLPS GRS structures as this pier is the capability of surviving high seismic load. To have a better insight into the seismic stability for PLPS GRS structures and to develop the relevant seismic design methodology, a series of shaking table model tests were performed (Shinoda et al., 2000a, b). The functions of a new device, called the ratchet system, which was developed to substantially increase the seismic stability of GRS structures were evaluated.

2 TEST METHOD

The models of GRS structures were 55 cm-high and 35 cm times 35 cm in cross-section (Figure 3). This relatively slender dimension was selected to investigate into the behavior of PLPS GRS structures in a rather critical use. The backfill of the models was a compacted 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). The backfill was compacted to a relative density of 90 %, reinforced with 12 grid layers with a vertical spacing of 5 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 gravel bag models with a diameter of about 5 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 displacement transducers were set at the top platen and the mid-heights of the second, sixth and eleventh sub-layers from the bottom of the model.

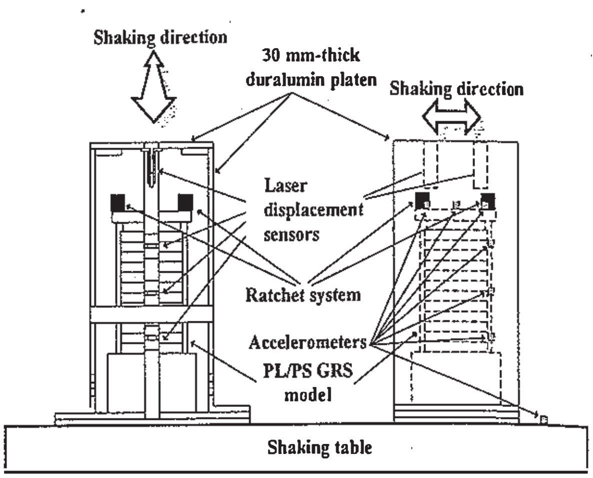

Figure 3. GRS structure model placed on a shaking table.

Vertical preload 30kPa was applied to the backfill by using four steel tie rods fixed to the top and bottom reaction steel platens, which was then decreased to the initial prestress of 15 kPa. These preload and prestress values were determined considering the model similitude. Each tie rod was equipped with a load cell to measure the tension. To examine the deformation of PLPS reinforced structure during strong shaking, a series of shaking table tests were performed using sinusoidal waves with horizontal acceleration of 700 gals and a frequency of 5 Hz at the table.

The results from the following two tests, among many others that were performed in the present study, will herein be reported.

In the first test, a pier model was not equipped with a ratchet system on the top of each tie rod (Figure 4; the ratchet system is explained later), but the tie rods were fixed to the top reaction platen with nuts. Due to a relatively high stiffness of the tie rods, the tie rod tension decreases at a high rate when the backfill exhibits vertical compression by creep and cyclic loading. The consequence of the reduction of tie rod tension could be serious for the seismic stability of structure. That is, the initial natural frequency n structures under undamaged conditions of a PLPS GRS should be designed to be sufficiently higher than the predominant frequency ω of considered seismic load to avoid the resonant state during a seismic event. The resonant state can be avoided also by making n of the structure sufficiently lower than the ω value of the input motion. This method will, however, be penalized by too large cyclic deformation, which may result into a large compression of the backfill. With an initial ratio ω/n smaller than unity, a rapid and significant decrease in n during cyclic loading may result into the transient resonant state, which may result into excessive deformation or even the total collapse of the structure.

In the second test, a ratchet system was used to fix the top end of each tie rod to the top reaction platen (Figure 4). This system was developed to alleviate the above-mentioned problem. In the present study, after the prestressed condition was reached, a ratchet system was fixed to the top end of each tie rod before the start of shaking test.

3 RATCHET SYSTEM

The ratchet system was designed to show a low stiffness, under high prestress conditions, when the backfill tends to vertically contract by whatever cause, such as creep deformation and shaking-induced compression. This low stiffness is attributed to a low stiffness of a relatively long spring attached between the top end of each tie rod and the top reaction platen (Figure 4b). In this case, the tie rod tension decreases only slightly even when the backfill contracts relatively largely. On the other hand, the ratchet system can exhibit a very high stiffness, increasing largely the tie rod tension, when the height of the backfill tends to increase by whatever cause, such as bending deformation of the structure or dilatancy during monotonic or cyclic loading. The high stiffness of the system is attained by locking the displacement of the top end of each tie rod relative to the top reaction platen (Figure 4c). It is to be noted that the bending deformation of the backfill, as illustrated in Figure 5a, is one of the most dangerous causes for the failure of such slender GRS structures. By these two functions of the ratchet system described above, the bending deformation of the structure can be effectively restrained, as illustrated in Figure 5b and shown below.

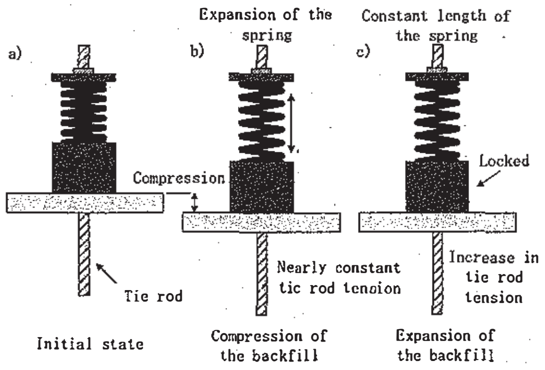

Figure 4. Behaviour of the ratchet system when the backfill tends to vertically contract and expand.

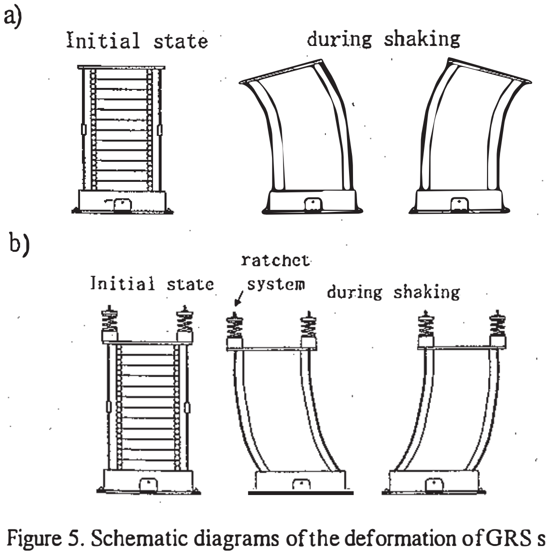

Figure 5. Schematic diagrams of the deformation of GRS structure; a) without a ratchet system; and b) with a ratchet system.

4 TEST RESULTS

Figure 6 shows the time histories of horizontal acceleration at the top platen and the shaking table, the average prestress acting at the top of the backfill (equal to the sum of the tension acting in the four tie rods and the weight of the top reaction platen divided by the cross-section of the backfill), the rotation angle of the top platen and the averaged vertical compressive strain of the backfill. The averaged vertical prestress in the test not using ratchet systems decreased to nearly zero already by an elapsed time of five seconds from the start of shaking (Figure 6b). A large rotation at the top plate was then induced (Figure 6b), indicating a large bending deformation of the backfill. This behavior was due to a large reduction in the stiffness of the backfill caused by a substantial decrease in the prestress.

It may be seen from Figure 6b, on the other hand, that the ratchet system functioned very well in keeping the prestress and restraining the bending deformation of the model despite very strong shaking. Importantly, the averaged prestress did not become lower than the initial value at any moment during the shaking test, but it became very large transiently in each cycle by restraining the backfill expansion, resulting into a very small rotation of the top platen and a small settlement of the backfill.

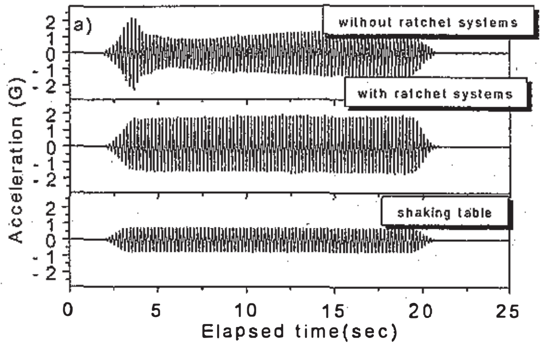

Figure 6. Time histories of; a) horizontal acceleration at the top platen and the table.

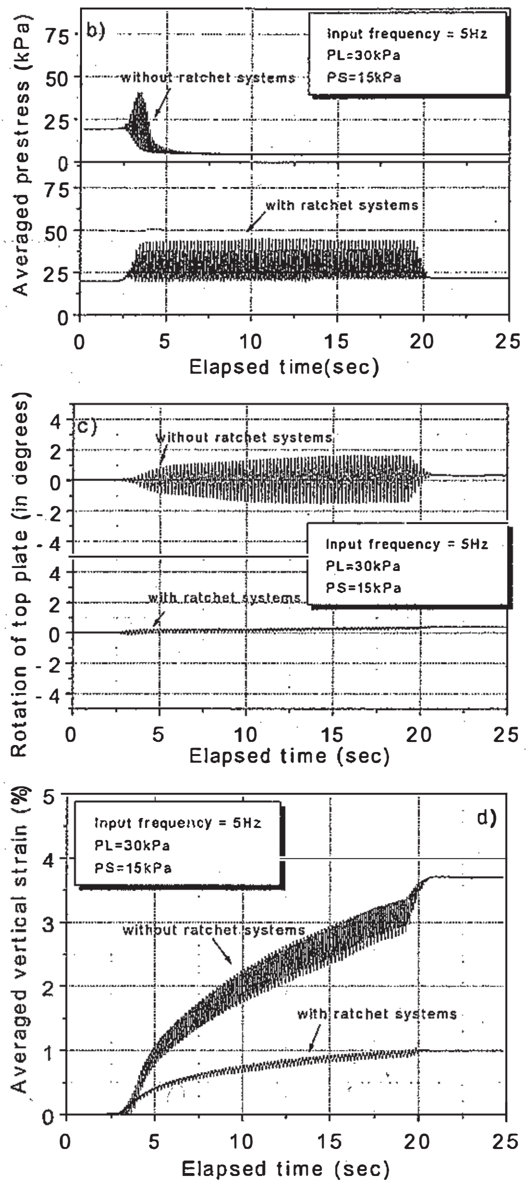

Figure 6 (continued). Time histories of; b) average prestress; c) rotation of the top plate; and d) averaged vertical strain.

5 DYNAMIC RESPONSE CHARACTERISTICS

The dynamic response characteristics of the models were very complicated, mainly because they were not stationary due to continuing changes in the stiffness of the backfill caused by shaking-induced changes in the tie rod tension and associated deformation of the backfill.

For the first approximation, the response characteristics of the models were analyzed based on the theory of a single degree of freedom. The time histories of the response ratio L and the phase difference φ between the top platen of the structure and the shaking table were measured in the respective test. These quantities are given theoretically as:

$$L=\sqrt{\frac{1+4h^2(\omega/n)^2}{\left\{1-(\omega/n)^2\right\}^2+4h^2(\omega/n)^2}} \tag{1a}$$

$$\tan\varphi=\frac{2h(\omega/n)^3}{1-\left(1-4h^2\right)(\omega/n)^2} \tag{1b}$$

where h is the damping ratio (unknown), ω is the given input frequency (equal to 5.0 Hz) and n is the non-constant natural frequency of the structure (unknown).

Figures 7a and 7b show the theoretical relationships between L and ω/n and between φ and ω/n for different h values obtained based on Eqs. 1a & 1b. The transient values of the damping ratio h and the frequency ratio ω/n for respective measured values of L and φ were obtained by solving Eqs. 1a & 1b with a process of iteration.

The relationships between the measured value of L and the estimated value of ω/n and between the measured value of φ and the estimated value of ω/n are presented in Figures 7a and 7b. It can be seen that the model without using the ratchet system exhibited the transient resonance while the value of ω/n was increasing, which was associated with a substantial decrease in the tie rod tension due to shaking-induced vertical deformation of the backfill (Figure 6). The increase in the ω/n value was enhanced by the decrease in the stiffness of the backfill due to the non-linearity of stiffness. This observation is well consistent with the fact that the single amplitude of shear strain γ_{sa} at the top of the model showed noticeably a high value at the resonant state and the γ_{sa} value was very high, close to that during resonance, even when the ratio ω/n exceeded the value at resonance (about unity) (Figure 7c).

On the other hand, the model using the ratchet systems did not exhibit the resonance, because the ratio ω/n was kept always lower than unity. The value of γ_{sa} was therefore was kept much smaller (Figure 7c). This behaviour was due to the positive functions of the ratchet system (i.e., maintenance of high prestress and restraining of the expansion of backfill).

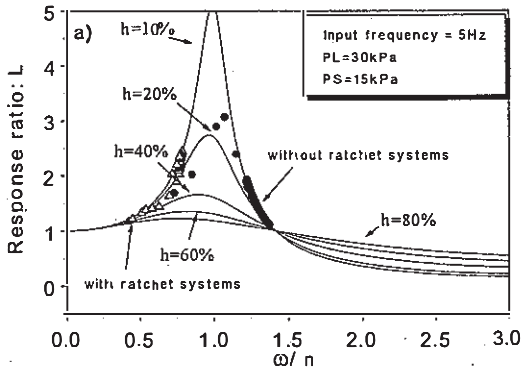

Figure 7. Theoretical and measured response curves; a) response ratio plotted to the ratio of the input frequency to the natural frequency (to be continued).

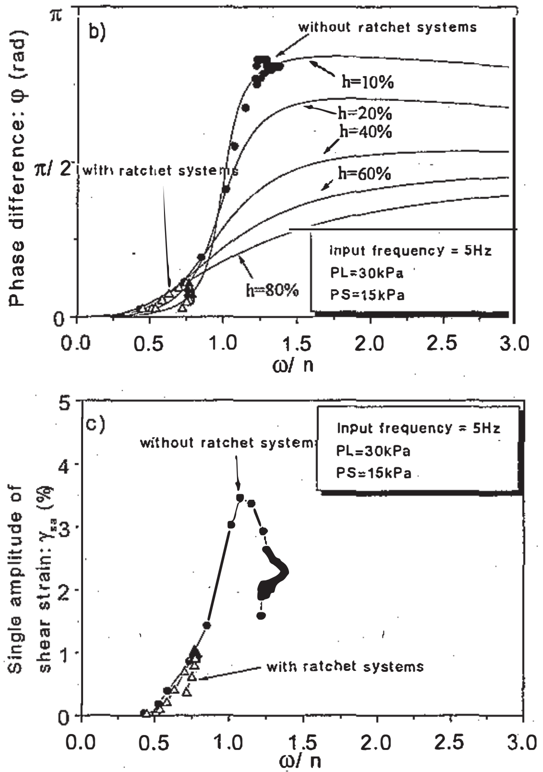

Figure 7 (continued). Theoretical and measured response curves; b) phase difference and c) dynamic shear strain of backfill, plotted to the ratio of the input frequency to the natural frequency.

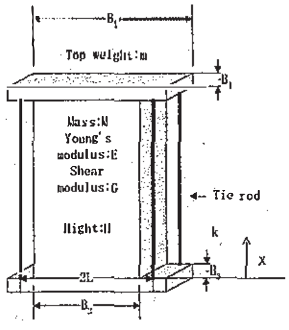

Figure 8. Model configurations to compute the natural frequency of the model.

6 STIFFNESS OF THE BACKFILL DURING SHAKING

In the seismic design of PLPS GRS structure, the initial natural frequency and those during shaking should be evaluated with a reasonable accuracy so as to avoid the occurrence of resonance during a given design seismic load. To that end, a simplified method was developed based on the following assumptions:

1) the backfill is a uniform isotropic linear elastic material having a constant Young's modulus E, shear modulus G with a total mass of M (Figure 8);
2) the major deformation mode of the backfill is bending and shearing as a simple beam; and
3) 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).

From the condition that the maximum kinematic energy is equal to the maximum strain energy, an equation is derived to obtain the natural frequency n of the model. Figure 9 shows the ranges of the theoretical relationship between the natural frequency n and the shear modulus G of the backfill for the two tests obtained by this procedure. The shear modulus G of the backfill at each cycle during shaking was back-calculated by substituting the respective natural frequency n that was estimated by assuming that the PLPS reinforced pier model deformed as a single degree of freedom system (Figure 7a).

Figure 10 shows the relationships between the shear modulus G back-calculated as above and the corresponding measured single amplitude shear strain γ_{sa} for the two tests (with and without using the ratchet systems). The shear stress τ that is indicated in Figure 10 is equal to the shear modulus G multiplied by γ_{sa}. Figure 11 shows the relationships between the back-calculated shear modulus G and the corresponding measured normal stress (i.e. aver-

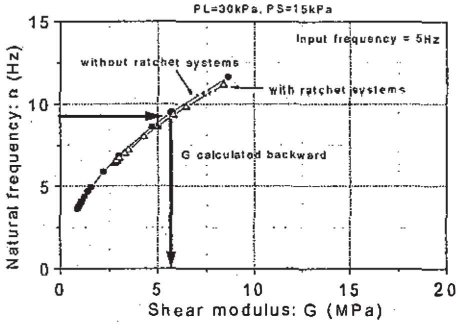

Figure 9. Theoretical relationship between the natural frequency and the shear modulus of the backfill with the ranges estimated for the two tests (with and without using ratchet systems).

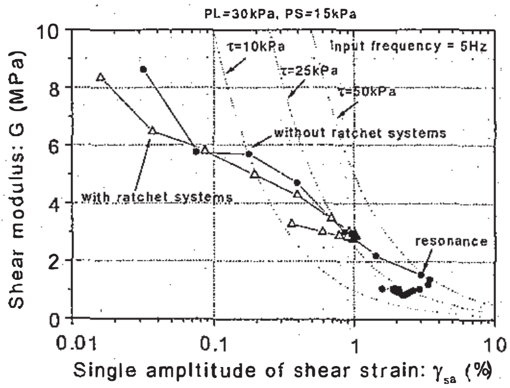

Figure 10. Relationship between the back-calculated shear modulus of the backfill and the measured shear strain in the test with and without ratchet systems.

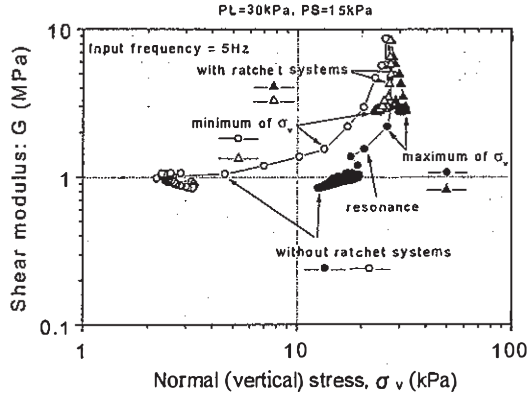

Figure 11. Relationship between the back-calculated shear modulus of the backfill and the measured vertical stress in the test with and without ratchet systems.

aged vertical stress on the backfill)σ_v. The maximum and minimum values of σ_v in each cycle are plotted against the respective shear modulus G. It is clearly seen that in the test without using the ratchet systems, the increase in the shear strain is associated with a large decrease in the shear modulus, which is associated with a substantial decrease in the vertical stress σ_v and a large increase in the shear strain due to large shear stresses τ as a result of resonance.

On the other hand, in the test using the ratchet systems, the shear strain γ_{sa}' was kept relatively small, which was associated with high shear modulus values and relatively low shear strain values due to the non-occurrence of resonance (Figure 10), which was associated with high vertical stress values kept high during strong shaking (Figure 11). These data clearly show that the ratchet system can maintain high prestress and thereby can restrain low shear strains by keeping high shear modulus values while avoiding the resonance state.

7 CONCLUSIONS

The following conclusions can be derived from the test results:

1) The initial natural frequency n_i under undamaged conditions of a given PLPS GRS structure should be designed to be sufficiently higher than the predominant frequency ω_n of design seismic load so as to avoid the resonant state.
2) With an initial ratio ω_n/n_i smaller than unity, a rapid and significant decrease in the natural frequency n during cyclic loading may result into the occurrence of transient resonant state, which may result into excessive deformation or even the total collapse of the structure.
3) Therefore, the natural frequency n should not decrease largely from the initial value n_i (which is larger than ω_n) so that the n value does not approach ω_n. To this end, the tie rod tension should be maintained to a sufficiently large value during shaking. The use of ratchet systems is effective for this purpose.
4) The ratchet system also does not allow the height of the backfill to increase, which is effective in restraining the bending deformation of the backfill, which is very dangerous deformation mode to be avoided.

It will be also important to ensure that the structure can survive the resonant state, in case it takes place. For the above, the tie rod tension should not decrease largely to a near-zero value even at the resonant state.

PLPS GRS structures equipped with ratchet systems described in this paper can be constructed as permanent important structures having a high stiffness for long-term repeated load, such as traffic load as well as a seismic stability.

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