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Seismic stability of geosynthetic-reinforced soil bridge abutment (model experiments)

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ABSTRACT: A series of shaking table tests were performed to validate a high seismic stability of preloaded and prestressed geosynthetic-reinforced soil bridge abutment. A well-graded gravel was used as the backfill supporting a relatively heavy model bridge girder, while the backside unreinforced backfill was made of Toyoura sand. It is shown that a large drop in the prestress and cyclic expansion of the backfill, of which both may seriously damage the structure, can be effectively prevented by connecting the top ends of the tie rods used for preloading and prestressing by means of a newly developed ratchet connection system. It is shown that the dynamic behaviour of plane strain and three-dimensional models were similar.

1 INTRODUCTION

A number of geosynthetic-reinforced soil (GRS) structures have been constructed as bridge abutments directly supporting girders in Japan to achieve a high const-effectiveness as well as equivalent or even better performance compared with conventional RC structures (e.g., Tatsuoka et al. 1997b). The preloaded and prestressed (PLPS) method has been proposed so that GRS bridge abutments could support longer and heavier girders (Figure 1: Tatsuoka et al. 1997a; Uchimura et al. 1996, 1998). In this method, large vertical preload is applied to the backfill by means of tie rods placed between the top and bottom reaction blocks. The preload is then released to prescribed prestress level and the top ends of the tie rods are fixed to the reaction block. The preloading makes the deformation of the backfill essentially elastic and the prestressing keeps the stiffness of the backfill sufficiently high. Then, a full-height rigid RC facing is constructed at the wall face before opening to service.

After the 1995 Hyogo-ken Nambu Earthquake, it was specified in a number of design codes for civil engineering structures in Japan, including bridge abutments, that civil engineering structures should survive very high seismic load such as the highest one experienced during that earthquake (so-called Level II seismic load). To ensure a high seismic stability of PLPS GRS structures, the ratchet connection system has been developed: i.e., by fixing the top ends of the tie rods to the top reaction block by means of a ratchet connection system, the tie rod tension is kept nearly constant even when the backfill contracts, while the backfill is not allowed to expand vertically. Shinoda et al. (2000) performed model shaking table tests and showed that the seismic stability of independent slender PLPS GRS structures, such bridge piers, becomes very high by means of the PLPS method together with the ratchet connection system.

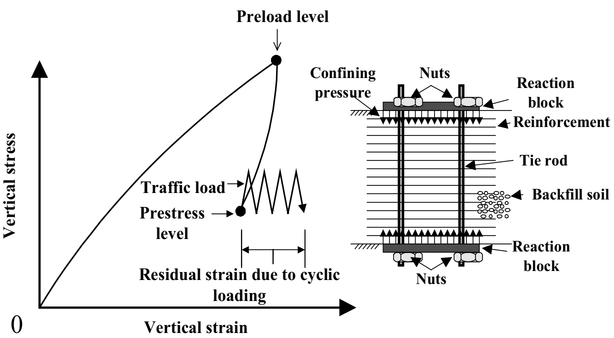

Figure 1. Procedures of preloading and prestressing.

A series of model shaking table tests were performed in the present study to validate that the above is also the case with GRS bridge abutments directly supporting a bridge girder and unreinforced backfill behind.

2 TEST METHOD

2.1 *Models of bridge abutment*

Plane strain models: Plane strain models of GRS bridge abutment were constructed in a 600 mm-wide sand box on a shaking table (Figure 2). The model sub-soil was an about 250 mm-thick layer of compacted well-graded gravel of crushed sandstone (D_{max}= 100 mm, γ_d=1.9 gf/cm^3). The backfill of the abutment zone was an air-dried well-graded gravel (D_{max}= 50 mm) compacted to a relatively low density, 1.7 gf/cm^3 (D_r= 60%) (n.b., In another series of tests, models having a denser gravel backfill were prepared and it was found that they performed much better than those reported herein. This result will be reported elsewhere). A model bridge girder, which was as heavy as 197.5 kg, was placed on the top reaction block (200 mm-long, 600 mm-wide) through a hinge connection that was placed on the PLPS gravel backfill. The gravel backfill was reinforced with 12 layers of model geogrid made of phosphor bronze strips (3.5 mm-wide, 0.2 mm-thick and 600 mm-long) with an aperture of 100 mm (in the longitudinal direction) and 50 mm (in the transversal direction). The front ends of the reinforcement were connected to the back of a wooden full-height rigid facing. To simulate the ordinary embankment conditions, a less stable backfill zone was constructed behind the triangle gravel backfill by pluviating through air air-dried fine sand (Toyoura and) at a relative density of 75 %. Four steel tie rods were set vertical penetrating the gravel backfill with the lower ends fixed to a bottom reaction block beneath the backfill and the top ends fixed to the top reaction block by using a ratchet connection system. Vertical preload of 40 kPa and prestress of 20 kPa, determined considering the model similitude (Shinoda et al. 2001), were applied by using these tie rods.

Three-dimensional (3D) models: With the plane strain models, free dynamic behaviour may be hindered by possible effects of friction between the backfill and the sidewalls of the sand box activated during preloading. To validate more reliably a high dynamic stability of PLPS GRS structures, therefore, 3D models (Figure 3) with the side faces of the gravel backfill abutment separated from the sidewalls of the sandbox while protected with small sand bags placed at the shoulder of each subsoil layer were prepared. The other test arrangements were the same as the plane strain models.

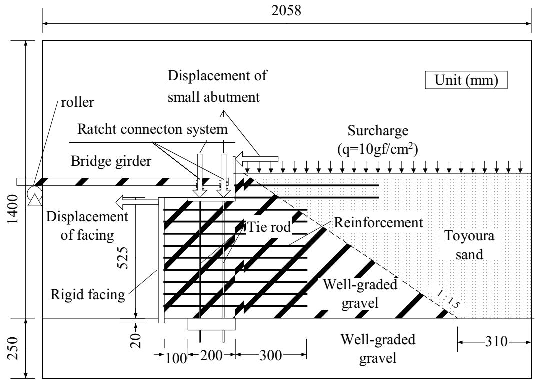

Figure 2. Plane strain model of PLPS GRS bridge abutment

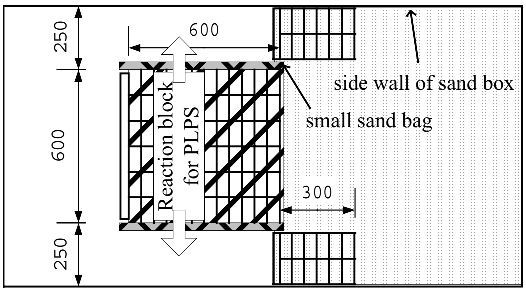

Figure 3. 3D model of PLPS GRS bridge abutment

2.2 *Ratchet connection system (Figure 4a)*

The ratchet connection system, consists of a spring and a ratchet mechanism, designed to have the following two functions:
Function 1: The system exhibits a low stiffness of the spring under high prestress conditions when the backfill tends to exhibit vertical compression by whatever cause, such as creep deformation and shaking-induced compression (Figure 4b).
Function 2: The system exhibits a very high stiffness of the tie rods by locking the top end of tie rod when the backfill tends to expand by whatever cause, such as bending deformation of the structure or dilatancy by shear deformation (Figure 4c). Restraining the bending deformation of the PLPS backfill supporting a girder is particularly important, because the vertical stress in the backfill zone at the backside of bending decreases substantially by large bending deformation, resulting in a substantial decrease in the strength and stiffness of the backfill.

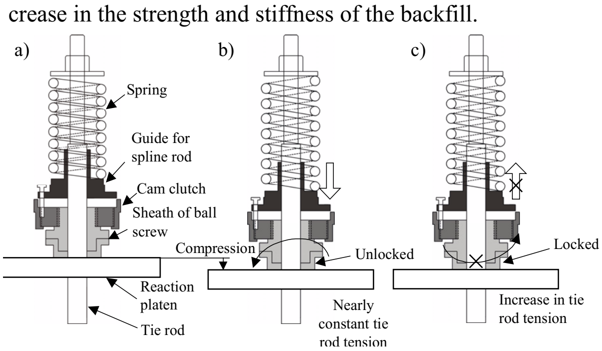

Figure 4. Ratchet connection system

2.3 *Test procedures*

In the tests on the plane strain and 3D models, a time history of acceleration with an adjusted predominant frequency of 5 Hz made from the time history of horizontal acceleration recorded on the ground at the Kobe Marine Meteorological Observation Station during the 1995 Hyogo-ken Nambu Earthquake was used as the input acceleration at the shaking table. The maximum amplitude of the input acceleration a_{max} was increased stepwise from 100 gals to 1,000 gals with an increment of 100 gals. Subsequently, sinusoidal uniform inputs with a frequency of 5 Hz was applied for a duration of 10 seconds with a_{max} = 300 gals and 700 gals.

Two plane strain tests were performed. In test 1, function 2 properly worked, while function 1 did not due to improper setting of the load cells along the tie rods inside the backfill zone (i.e., the load cells could not move freely relatively to the backfill, which prevented the free contraction of the backfill). For this reason, the prestress decreased largely temporarily in each cycle of shaking and gradually with time. In test 2, both of the functions worked properly keeping the prestress always higher than the initial value, while preventing the temporary expansion of the backfill in each cycle of shaking.

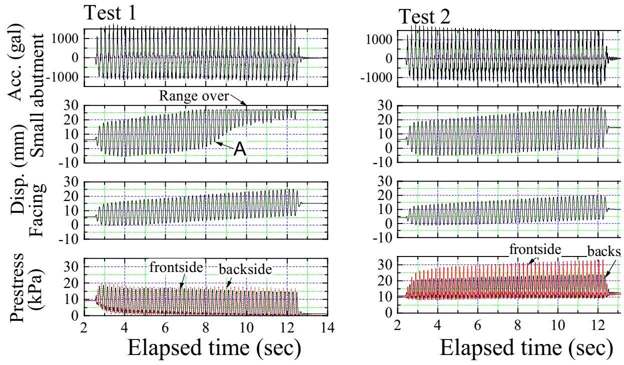

Figure 5. Behaviours of plane strain models

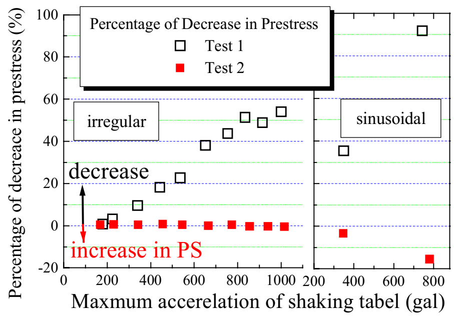

Figure 6. Decrease in the prestress at the end of shaking stage

3 BEHAVIOUR OF PLANE STRAIN MODELS

3.1 *Effect of the ratchet system*

Figure 5 shows the behaviour of the two plane strain models during shaking using sinusoidal waves with a_{max}= 700 gals. Hollow arrows in Figure 2 show the definition of the displacements. Figure 6 shows the relationships between a_{max} and the ratio of the decrease in the prestress (i.e. total tension in the four tie rods) observed at the end of each shaking stage divided by the initial prestress at the start of shaking. If the prestress became less than a certain value, 80% of initial value, the prestress was re-introduced to returned to the initial value equal to 20 kPa before the next shaking stage. In test 1 (with improper function of the ratchet system), the initial prestress was re-introduced after every shaking stage with a_{max} more than 400 gals. In test 2, the initial prestress was re-introduced only before starting the first test using sinusoidal waves. The following can be noted:

1) In test 1, the prestress at the end of each shaking stage became smaller than the initial value except in the first shaking stage and the amount of decrease increased with the increase in a_{max}. In particular, in the shaking stage using sinusoidal waves with a_{max}= 700 gals, most of the prestress disappeared before the end of shaking due to a large compression of the backfill.
2) The residual compression of the backfill in test 2 was similar to that in test 1. With model 2, however, the prestress at the end of each shaking stage was nearly the same as the initial

value. Further, the residual prestress noticeably increased during the shaking stage using sinusoidal waves with a_{max}= 700 gals, due to some residual expansion of the PLPS gravel backfill zone supporting the top reaction block.

These results show that the prestress does not decrease during strong shaking if function 1 properly works and detrimental deformation of the PLPS GRS bridge abutment can be restrained by function 1, with help of function 2 as shown below.

3.2 *Displacements of small abutment and facing structure*

Figure 7 shows the residual settlement of the top reaction block at the end of each shaking stage and a_{max}, while Figure 8 shows the relationships between the residual lateral outward displacements of the top reaction block and the facing (measured at a height of 485 mm from the bottom of the facing) and a_{max} from the two plane strain tests. The following can be noted:

1) Despite that the residual deformation of the models increased with a_{max}, the deformation was particularly small when the a_{max} was lower than 500 gals, showing a high seismic stability of the PLPS GRS structures.
2) The residual deformation of model was generally larger in test 1 than in test 2, while the difference increased with a_{max}. The displacement at the small abutment was particularly large at the shaking stage using sinusoidal waves with a_{max}= 700 gals in test 1, which took place when the prestress was temporarily nearly zero (Figure 5). This behaviour is analyzed below.

3.3 *Seismic stability of small abutment*

Figures 9 shows the relationships between the lateral displacement at the small abutment and the one near the top of the facing observed at the shaking stage using sinusoidal waves with a_{max}= 700 gals in tests 1 and 2. The following may be seen:

1) In test 2, in which functions 1 & 2 worked properly, the lateral displacements measured at these two places were nearly the same throughout the shaking stage, showing that the top reaction block did not slide along the crest of the backfill at any moment during the high-level shaking.
2) In test 1, the displacement at the top reaction block gradually became larger than that at the top of the facing after a certain time. As shown below, the relative displacement between the top reaction block and the top of the facing became particularly large when the prestress became very small.

Figures 10 shows the relationships between the acceleration at the top reaction block and the average prestress, which represents the relationships between the shear stress and the normal stress at the bottom of the top reaction block, for elapsed time 8.0 - 8.2 seconds. Figures 11 shows the corresponding relationships between the acceleration at the bottom of the top reaction block and the relative lateral displacement between the top reaction block and the shaking table. These results suggest that slipping of the top reaction block along the backfill took place only in test 1 and it was when the prestress became nearly zero while the acting acceleration was very small, close to zero (i.e., at moments denoted as (2) & (4) in Figures 10 and 11). These results indicate the following:

1) It is essential to prevent the prestress become nearly zero at any moment during shaking to maintain a high integrity of PLPS GRS structure.
2) As far as the prestress does not become lower than a certain limit, which is rather small, say 5 kPa, and the increase in the height of backfill is not allowed, the integrity of PLPS GRS structure can be maintained.

The second fact implies that the initial prestress is not necessary to be very high as far as the backfill expansion is prevented during shaking (i.e., as far as function 2 works). If a low initial prestress is allowed, a lower-cost ratchet connection system can be used, which makes the construction of PLPS GRS bridge structures more feasible.

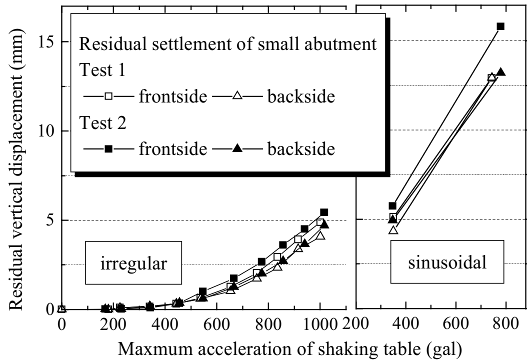

Figure 7. Residual settlement of small abutment.

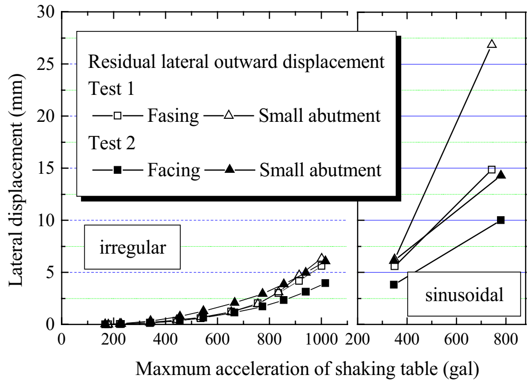

Figure 8. Residual lateral outward displacement.

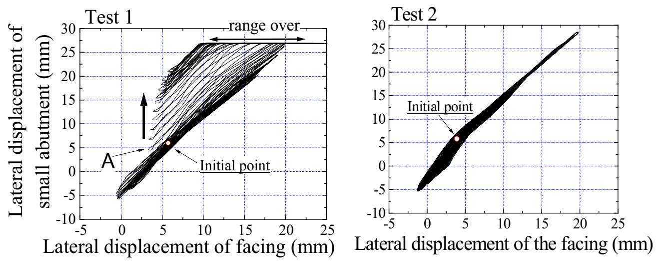

Figure 9. Relationships between displacement of top reaction block and facing.

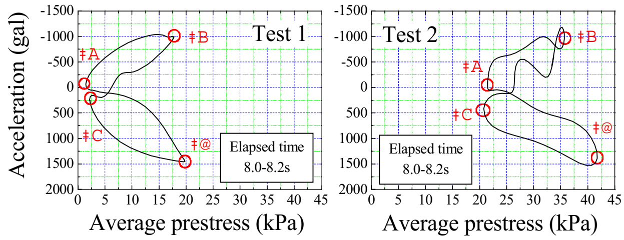

Figure 10. Relationships between acceleration at top reaction block and average prestress

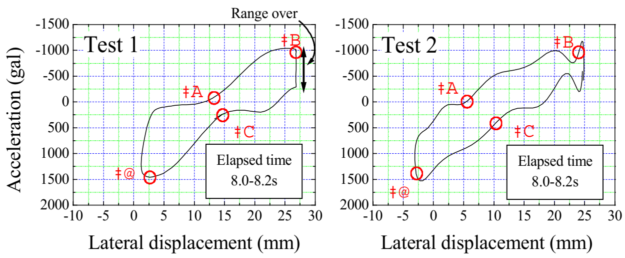

Figure 11. Relationships between acceleration and relative displacement of the top reaction block.

3.4 *Phase difference*

One may consider that a PLPS GRS bridge abutment is less stable than a PLPS GRS bridge pier under otherwise the same conditions because of dynamic earth pressure acting on the back of the abutment of PLPS backfill. However, the above is not true as shown below.

Figure 12 shows the time histories of the maximum phase difference in each cycle between the shaking table and points A09 & A10 (in the PLPS gravel zone) and A11 & A12 (in the Toyoura sand zone) at the stage using sinusoidal waves with a_{max}= 700 gals in test 2 (see Figure 13). The maximum response ratios in each cycle are also shown. Figure 14 shows the time histories of the acceleration and the tensile force of the reinforcement for a period representative of this behaviour. The following may be noted:

1) The phase difference and response ratio is very similar at points A09 & A10 (and the facing), indicating that the PLPS gravel zone (with the facing) behaved like a monolith.
2) The phase difference between the PLPS gravel zone and the backside backfill zone (consisting of a reinforced gravel zone where PLPS was not effective and the unreinforced Toyoura sand zone) is quite large.

The second fact indicates that the backside zone restrained the dynamic response of the PLPS gravel zone. That is, when the PLPS gravel zone was under the passive condition, the earth pressure acting on the back of this zone increased, showing that the PLPS gravel zone was supported by the backside backfill zone. On the other hand, under the active condition, the reinforcement tensile force increased preventing the separation of the PLPS gravel zone from the backside backfill zone.

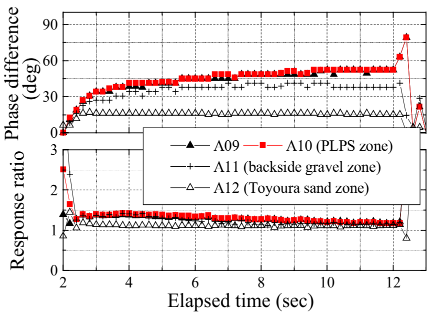

Figure 12. Time histories of phase difference and response ratio.

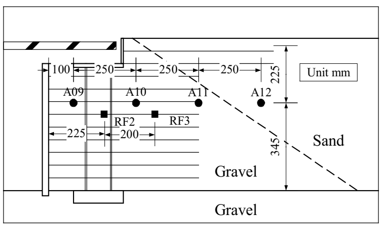

Figure 13. Arrangements of pickups.

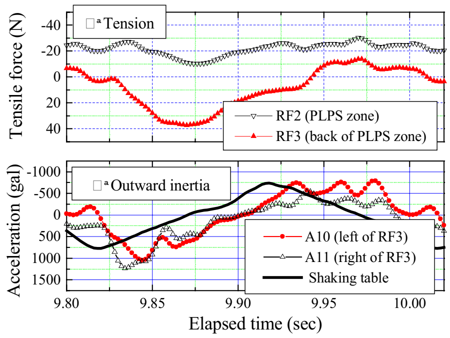

Figure 14. Time histories of acceleration and tensile force.

4 THREE-DIMENSIONAL MODEL

Figure 15 compares the residual lateral displacements at the top reaction block and the top of the facing in plane strain and 3D tests performed under otherwise the same conditions. It may be seen that the displacements were only slightly larger with the 3D model than with the plane strain model, showing that the behaviour of the plane strain model is representative of the 3D model when allowing this small difference.

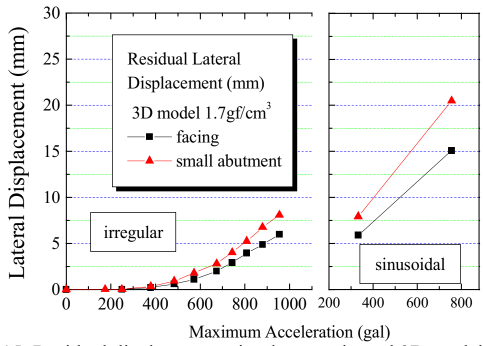

Figure 15. Residual displacements in plane strain and 3D models.

5 CONCLUSIONS

The following conclusions can be derived from the test results:

1) The use of ratchet system is very effective to prevent a large drop in the prestress and an increase in the height of backfill during strong shaking. These two functions are essential to decrease the residual displacement of the PLPS GRS bridge abutment.
2) Due to different dynamic characteristics, the backside backfill zone could restrain the dynamic response of the PLPS GRS zone with a decrease in the earth pressure under the active condition and development in the tensile stress in the reinforcement extending in both PLPS GRS zone and backside backfill zone.

6 ACNOWLEDGEMENTS

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