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Performance of PLPS, geosynthetic-reinforced soil structure against working and seismic loads

Performance de structures en terre renforcée par PLPS géosynthétique face aux charges mobiles et sismiques

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ABSTRACT: A preloaded and prestressed (PLPS) reinforced soil method, developed aiming at making reinforced backfill very stiff against external loading, is described. According to this method, vertical compressive load is applied to the backfill during construction (preloading) and also in service (prestressing). The long-term behaviour of a prototype PLPS geogrid-reinforced soil bridge pier supporting railway steel girders has proven the effectiveness of this method. Results from model shaking table tests of PLPS pier showed that the use of a ratchet system to fix tie rods to the backfill could substantially increase the seismic stability of the structure.

RÉSUMÉ: Les PLPS méthodes de renforcement des sols par préchargement et par précontrainte ont pour but de rendre les remblais plus rigides en les comprimant verticalement pendant la construction (préchargement) et en service (précontrainte). Une culée de pont en sol renforcé par un système de géotextile PLPS a été construite pour supporter les poutres en acier d'une voire ferrée et l'efficacité de cette méthode a été prouvée. Les résultats d'essais sur table vibrante sur des modèles réduits de pile PLPS ont montré plusieurs points importants pour la conception de structures stables sous sollicitations sismiques.

1 INTRODUCTION

A new construction method has been developed to construct geosynthetic-reinforced soil structures as important permanent structures supporting highly concentrated load, replacing conventional reinforced concrete (RC) structures, such as bridge abutments and piers. According to this method, reinforced backfill is made very stiff against vertical loading by applying vertical compressive load during construction (preloading, PL) and also during service (prestressing, PS). This method was developed aiming at a high cost-effectiveness and high seismic performance of structure, taking advantages of such features as that the deformation of soil becomes smaller and more recoverable by preloading and the soil becomes stronger at higher prestress.

The behaviour of a preloaded and prestressed (PLPS) geogrid-reinforced soil bridge pier, constructed as the first prototype to support two temporary railway steel girders, will be described. Results from model shaking table tests performed to examine the seismic stability of this type of structure will also be described.

2 LONG-TERM PERFORMANCE OF THE PLPS PIER

2.1 *Construction and preloading*

The PLPS geogrid-reinforced soil bridge pier (P1 in Fig. 1) was constructed in Fukuoka City, Japan, in 1996. The pier is 6.4 m x 4.4 m in cross-section, and 2.7 m in height. The design dead load by the girder weight and the design live load by train including impact load are 196 kN and 1,280 kN, respectively. Before constructing the pier, an about 9 m-thick very soft clay layer was improved by constructing in-situ a set of 0.8 m in-diameter cement-mixed soil columns. The whole cross-section of a 1 m-thick surface clay layer immediately below the pier was improved by cement-mixing to form a reaction layer for applying vertical compressive load to the backfill. The lower ends of four steel tie rods were anchored into the cement-mixed soil columns for a length of 4 m (Fig. 1b). The nominal yield tensile strength of the tie rod is 1,034 kN. A well-graded gravel of crushed sandstone (D_{max} = 30 mm; D_{50} = 0.9 mm; U_c = 16.5; and ϕ = 60° at σ'_3 = 50 kPa by triaxial compression tests) was used for

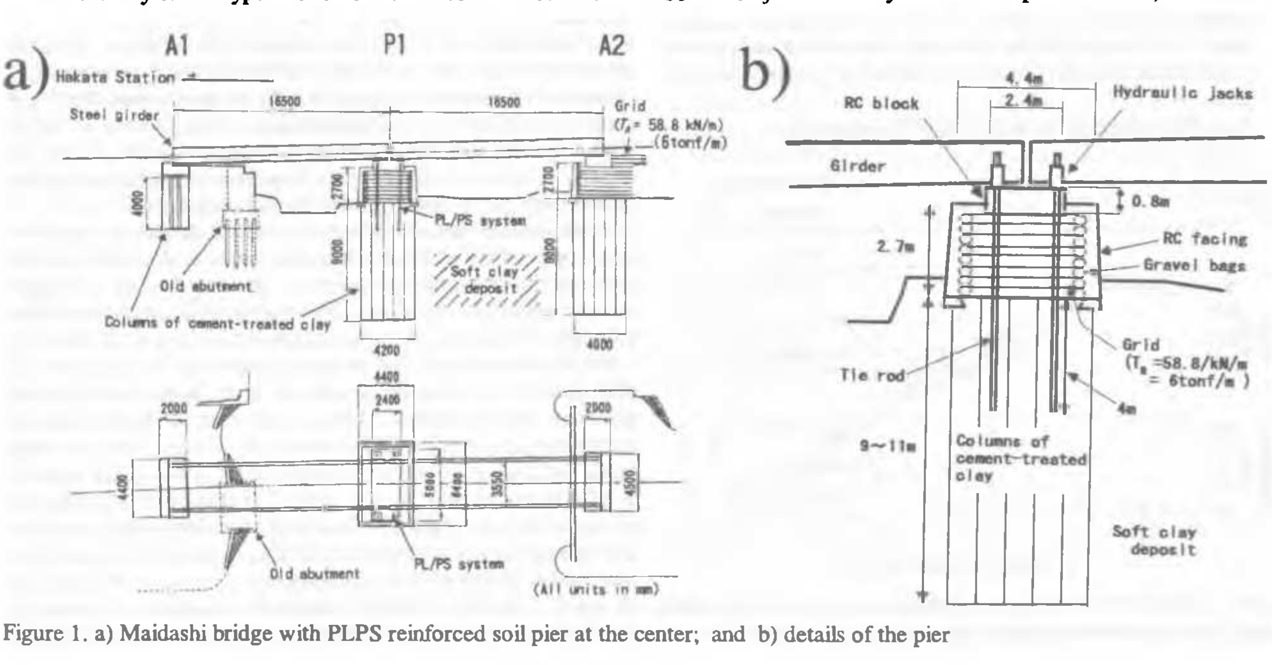

Figure 1. a) Maidashi bridge with PLPS reinforced soil pier at the center; and b) details of the pier

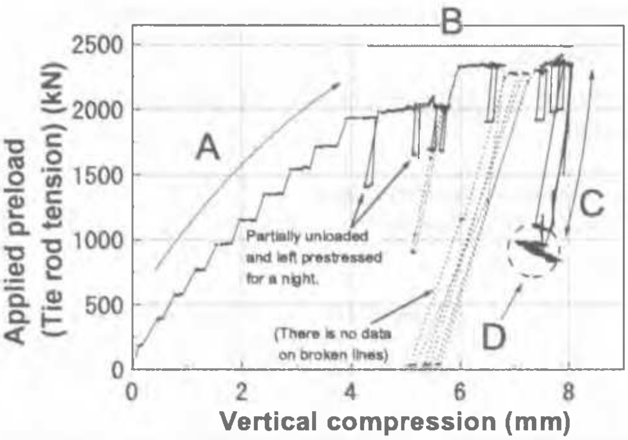

Figure 2. Compression of the pier by preloading.

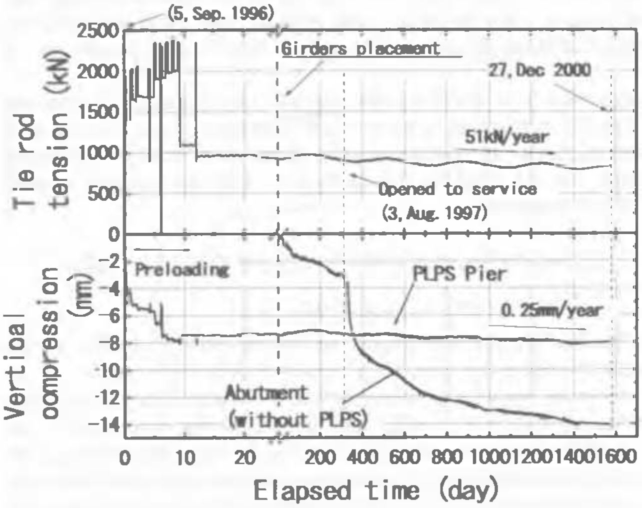

Figure 3. Long-term time histories of tie rod tension and vertical compression of the pier and abutment.

the backfill. The backfill was constructed with a help of gravel-filled bags stacked along the periphery of each gravel layer, wrapping-around the bags with reinforcement. The construction of the backfill took five days by a team of five workers.

A geogrid reinforcement was polyvinyl alcohol coated with polyvinyl chloride (PVC). The nominal rupture strength is 73.5 kN/m and the nominal stiffness is 1,050 kN/m at tensile strains less than 1 %. In each of the horizontal two orthogonal axes of the pier, the reinforcement layers were arranged in the same way

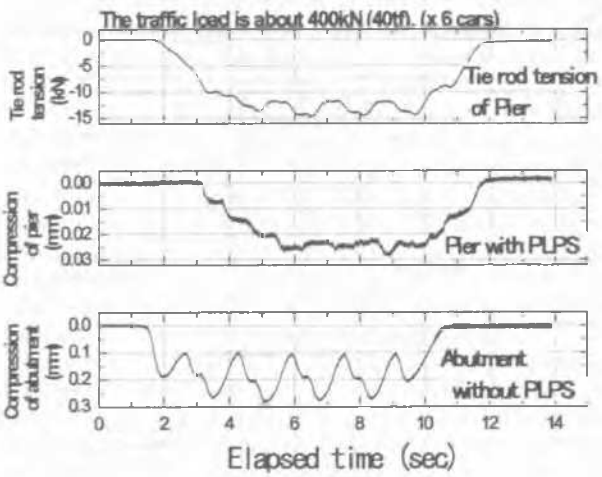

Figure 4. Time histories of tie rod tension and vertical compression of the pier and abutment during a train passing (July 16,1999).

as usual geosynthetic-reinforced soil retaining walls with a full-height rigid facing having the same height as the pier, constructed under plane strain conditions. The vertical spacing of reinforcement layers was 30 cm. As each cross-section having one pair of wall faces of the pier was designed independently, by overlapping the two cross-sections, the actual average vertical spacing of reinforcement layers became as small as 15 cm.

Preloading started ten days after constructing the top reaction RC block (5 m-long, 2.4 m-wide and 0.8 m-high). A vertical preload of 2,400 kN, equivalent to an average vertical pressure of 200 kPa, was applied to the backfill through the top reaction block by using four hydraulic jacks installed at the top of the tie rods (A in Fig. 2). After compressing the backfill by 8 mm by preloading (B in Fig. 2), the load was reduced to 970 kN (C in Fig. 2). Then, the top ends of the tie rods were fixed to the top RC block, applying the compressive stress as the initial prestress for the backfill. Finally, full-height rigid facings were cast-in-place around the backfill. The pier was opened to service about one year later (D in Fig. 2). The total construction period was about 1.5 months, and the total construction cost for the pier was estimated to be about a half of that for an equivalent conventional RC pier supported by piles foundation. Another benefit was that the pier was constructed without using large machines that would have required a much wider working area around the site, which was located in a residential area.

The abutment A2 was constructed following essentially the same construction procedure and using the same materials as the pier. However, the abutment was constructed as a single GRS retaining wall having a full-height rigid facing with reinforcement layers with a vertical spacing of 30 cm, without using the preloading and prestressing procedure, and the both sides are exposed slopes (1.5:1.0 in H:V) without facings.

2.2 *Behaviour during service*

The time histories of the vertical compression and the tie rod tension of the PLPS pier (P1 in Fig. 1) and the compression of the abutment (A2 in Fig. 1) for about four years after construction are presented in Fig. 3. The pier contracted by about 8 mm by the preload applied for the first 10 days, while its compression under the prestressed condition during the subsequent period was nearly zero. Even after having been opened to service, the compression rate of the pier remained to a very small value. Corresponding to the above, the tie rod tension decreased only very gradually. These rates of change are small enough for the planned temporary use of the pier for about five years.

On the other hand, the compression of the abutment A2 for the first ten months after construction was about 3 mm, which was due to its own weight and the weight of the girder. The compression rate became much larger after opening to service. The compression continued more than three years since then. A sharp contrast between the behaviours of the pier and abutment shows that the preloading and prestressing procedure is very effective to substantially decrease long-term vertical compression of the reinforced backfill caused by traffic cyclic load.

Figure 4 shows the time histories of the tie rod tension and vertical compression of the pier when a train passed over the bridge two years after opening to service. The train had six carriages, each weighing about 500 kN. The pier backfill contracted elastically by 0.025 mm, which corresponded to a soil strain of 0.001 %, while the tie rod tension temporarily decreased by 15 kN. Nearly the same elastic behaviour of the pier backfill was observed in the same kind of measurement made immediately after opening to service (Uchimura et. al. 1998). On the other hand, the abutment backfill contracted by 0.3 mm (equivalent to a soil strain of about 0.01 %), which was about ten times as large as that of the pier backfill. This large transient strain made the deformation of the abutment backfill less recoverable, resulting into much larger residual compression (Fig. 3). In fact, the abutment backfill exhibited noticeable irrecoverable compression in the measurement made immediately after opening to service. Yet, the other properties of the pier and abutments did not changed during those two years in service.

3 SEISMIC STABILITY OF PLPS SOIL STRUCTURE

PLPS reinforced soil structures as important structures, such the pier described above, have to be stable enough against strong seismic force, such as Level 2 design seismic intensity specified in the Japanese codes. A series of model shaking table tests of PLPS piers were performed (Fig. 5a). The models had a rectangular prismatic shape with 30 cm x 30 cm in cross-section and 60 cm in height. The backfill material was an air-dried well-graded gravel (D_{50}= 2.52 mm; U_c= 5.4; D_r= 90 %; and γ_d= 1.79 gf/cm^3). The model backfill was made by tamping to the prescribed density. Phosphor bronze strips with 3.5 mm in width and 0.2 mm in thickness were arranged to form a grid reinforcement with an aperture of 35 mm. The periphery of each backfill layer was confined laterally by using soft vinyl tubes filled with the backfill material. A steel reaction platen was placed on the top of the backfill. Four steel wires were used as vertical tie rods.

Results from two typical tests will herein be reported. In the first test, the tie rods were rigidly fixed to the top reaction block by using nuts (Fig. 5b). In this case, vertical compression of the backfill directly results in a reduction in the prestress. To avoid such behaviour, a ratchet system, which was newly developed in the present study, was used to fix the tie rods (Fig. 5c) in the second test. The ratchet system has a locking system, placed between a spring and the reaction platen. When the backfill tends to contract, the locking system does not work, allowing the length of the spring, having a low stiffness, to increase so that the vertical stress (i.e., the prestress) decreases at a very small rate. On the other hand, bending deformation of the backfill by shaking increases the height at either side of the backfill alternatively in each cycle of cyclic loading. In addition, the dense backfill exhibits positive dilatancy due to shear deformation. In those cases, the locking system works, not allowing the spring to extend and keeping the height of the backfill constant. The ratchet system can therefore prevent large bending and shear deformation of the backfill during strong shaking.

The two models were preloaded to 30 kPa and the initial prestress was set at 15 kPa at the start of shaking. The prestress values shown herein are the average vertical stress at the top of the backfill, resulting from the total tension working in the four tie rods and the weight of the top reaction platen. A sinusoidal input motion with a frequency of 5 Hz and a single amplitude acceleration of 700 gals was used. The peak motion lasted for about 16 seconds. The behaviours of the two models are summarized in Figures 6, 7, 8 and 9. The vertical compression of the backfill (Figs. 6, 7a & 8a), the average shear strain of the backfill (Figs. 7b & 8b) and the rotation angle of the top reaction platen (Figs. 7c & 8c) were much larger with the model using a rigid connection than with the model using a ratchet system.

These differences in the dynamic behaviour and the residual deformation between the two model tests can be attributed to different patterns in the time history of prestress. With the model having a rigid connection, most of the prestress disappeared within a very short period after the start of shaking (Fig. 7d), due to rapid shaking-induced compression of the backfill (Fig. 7a). A reduction of prestress resulted in softening of the backfill, making the shearing and bending deformation of the backfill larger, which caused more compression of the backfill, resulting in a more reduction in the prestress. In order to prevent such a chain reaction, it is essential to keep the prestress at a high value throughout during shaking.

On the other hand, with the model having a ratchet system, the prestress never became lower than the initial value, while it increased cyclically up to almost twice the initial value (Fig. 8d), indicating that the ratchet system functioned properly. Figure 9 shows the relationships between the horizontal acceleration at

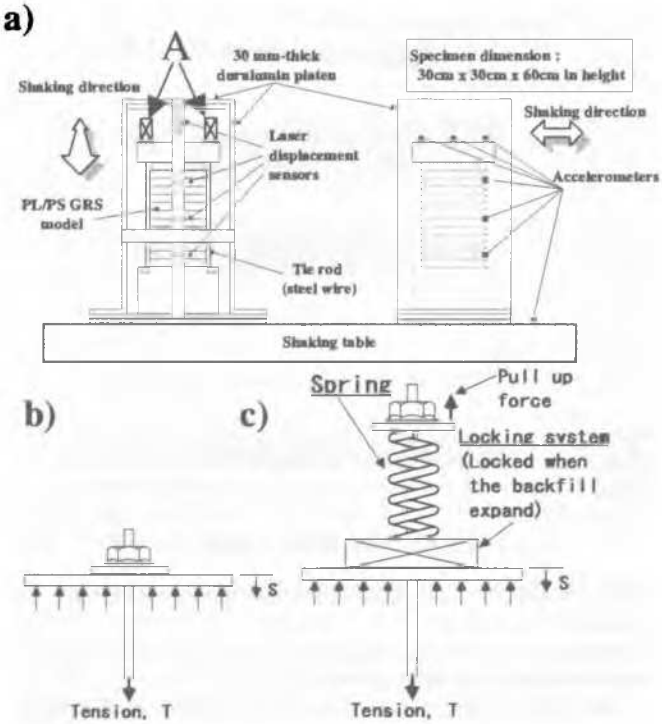

Figure 5. Shaking table tests on scaled models of PLPS pier:
a) model and measurement system;
b) a rigid connection with a nut; and
c) a connection using a ratchet system (parts A in **a)**).

the top reaction platen, which is proportional to the average shear stress at the top of the backfill, and the instantaneous average prestress during shaking (i.e. the average vertical stress at the top of the backfill). These relationships resemble the stress paths at the top of the backfill. With the model using a rigid connection, despite some dilative behaviour in each cycle, the prestress rapidly decreased to a very small value with cyclic loading. On the other hand, with the model using a ratchet system, the stress path exhibited dilative behaviour in each cycle, while not showing any drop in the prestress during the whole period of shaking. This behaviour is due to the following two mechanisms activated during cyclic loading: a) the locked ratchet system did not allow either side of the backfill to expand when the backfill at that side tended to expand due to bending deformation or positive dilatancy, or both, of the backfill, increasing the prestress on that side of the backfill; and b) the unlocked ratchet system allowed the backfill to contract at a nearly constant vertical stress when either side of the backfill tended to contract due to bending deformation or negative dilatancy, or both, of the backfill. Note that the constant volume condition in

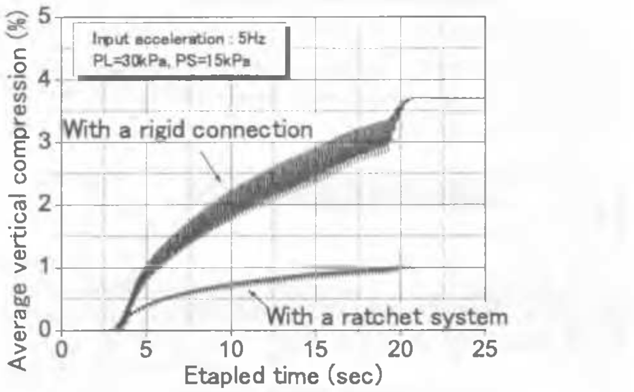

Figure 6. Comparison of vertical compression between the models with a rigid connection and a ratchet system.

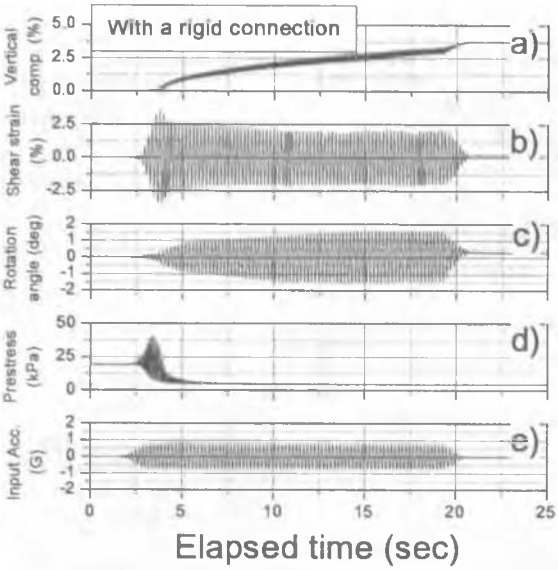

Figure 7. Behaviour of the model with a rigid connection.

the mechanism "a)" was achieved by means of both horizontal reinforcement layers and a tie rod system.

The other important role of the ratchet system is to avoid a resonance of PLPS reinforced soil structures. Due to the initial high prestress, the natural frequency of the model at the start of shaking was about 10 Hz, which was higher than the frequency of the input motion (5 Hz). The initial natural frequency of full-scale PLPS reinforced soil structures would also be much higher than the predominant frequency of usual strong seismic load. With the model using a rigid connection, as the prestress decreased by shaking, the natural frequency decreased and became similar to 5 Hz, which resulted in a transient resonance of the model. By a further decrease in the prestress, the natural frequency decreased further, becoming much lower than 5 Hz, which resulted into large deformation of the backfill. With full-scale PLPS reinforced soil structures using a rigid connection, the natural frequency may approach the transient predominant frequency of major motions of seismic load, resulting into a transient resonance, which may result into the failure of the structure. Such a resonance of the structure as described above did not occur with the model using a ratchet system, as the prestress was kept equal to, or higher than, the initial value, maintaining the natural frequency much higher than 5 Hz throughout shaking.

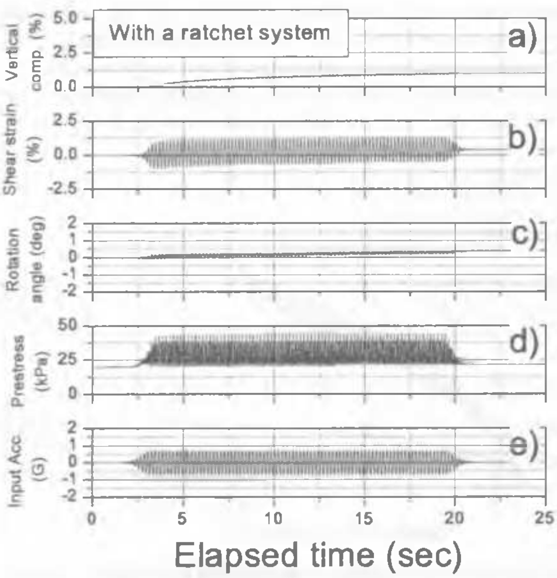

Figure 8. Behaviour of the model with a ratchet system.

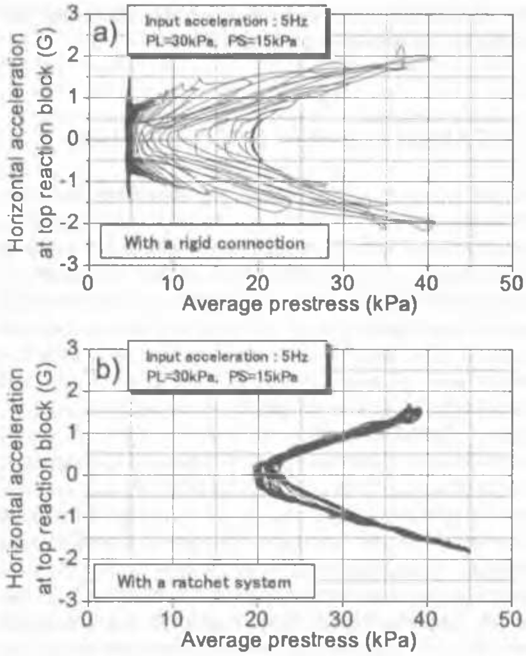

Figure 9. Relationships between the average compressive prestress and the average shear the horizontal acceleration of the top reaction block :
a) with a rigid connection and b) with a ratchet system.

4 CONCLUSIONS

The behaviour of a prototype PLPS reinforced soil bridge pier has shown that the proposed construction method using the preloading and prestressing technology is very effective to restrain vertical compression of the backfill against a very long-term cyclic loading by traffic. To avoid a serious softening of the backfill and a resonance of the structure during seismic loading, it is essential to prevent the reduction in the prestress when the backfill tends to contract and to keep the height of the backfill constant when the backfill tends to expand. Results from model tests showed that these apparently contradicting requirements can be satisfied by using fixing tie rods with a newly developed system, called the ratchet system.

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