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Effects of the tensile resistance of reinforcement in the backfill on the seismic stability of GRS integral bridge

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ABSTRACT: A new bridge system comprising of a pair of geosynthetic-reinforced soil (GRS) retaining walls having full-height rigid facings unified with a girder is proposed. Shaking table tests were performed on five GRS integral bridge models to evaluate the effect of the tensile resistance of reinforcement layers on the seismic stability of the bridge. The dynamic stability of integral bridge increases by reinforcing the backfill and by increasing the tensile resistance of reinforcement layers, which increases with an increase in the number of reinforcement layer as well as an increase in the connection strength between the facing and the reinforcement layer for give pull-out strength and tensile rupture strength of reinforcement.

1 INTRODUCTION

A great number of conventional-type bridges with a girder supported by gravity or cantilever-type reinforced concrete (RC) abutments via fixed and moveable supports were seriously damaged or totally collapsed during previous major earthquakes, including the 1995 Hyogoken-Nambu (Kobe) earthquake and the 2003 Niigataken-Chuetu earthquake in Japan. The structural drawbacks of the conventional-type bridges include not only a relatively low seismic stability, but also a relatively high construction cost due to the use of girder-supports (and piles in many cases) but also long-term maintenance works for girder-supports. A bump between the backfill and the abutment that may be formed due to residual settlement of the backfill by long-term dead and live loads as well as seismic loads is another serious potential problem. Therefore, the development of a new cost-effective bridge structure having a high seismic stability against so-called Level 2 design seismic loads with a low cost for construction and maintenance has been required.

The integral bridge system (with unreinforced backfill) is now becoming popular in the UK and the USA due mainly to a low construction cost due to its simple structure. However, it has one inherent serious structural drawback even under static loading conditions. That is, by cyclic lateral displacements at the top of the abutment due to seasonal cyclic thermal expansion and contraction of the girder, the backfill gradually exhibits significant residual settlement and the earth pressure activated on the back of the abutment over years increases significantly (e.g., England, 2000). Hirakawa et al. (2006) showed that the above-mentioned detrimental effects are caused by "a ratcheting phenomenon" in the earth pressure and deformation behaviour of the backfill. They also showed that this problem can be effectively alleviated by reinforcing the backfill with geosynthetic layers with the ends connected to the back of the facing.

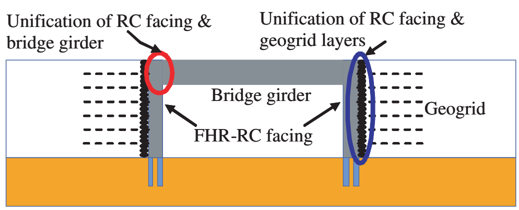

Figure 1. GRS integral bridge.

Based on the experiences described above, a new type bridge system consisting of a pair of geosynthetic-reinforced soil (GRS) retaining walls having full-height rigid (FHR) facings (i.e., GRS integral bridge; Fig. 1) was proposed (Tatsuoka et al., 2007; Aizawa et al., 2007). The proposed bridge system does not use girder supports but the girder is integrated with the FHR facings. Aizawa et al. (2007) performed a series of model shaking table tests and showed that the dynamic stability of the GRS integral bridge with a sufficiently high connection strength between the

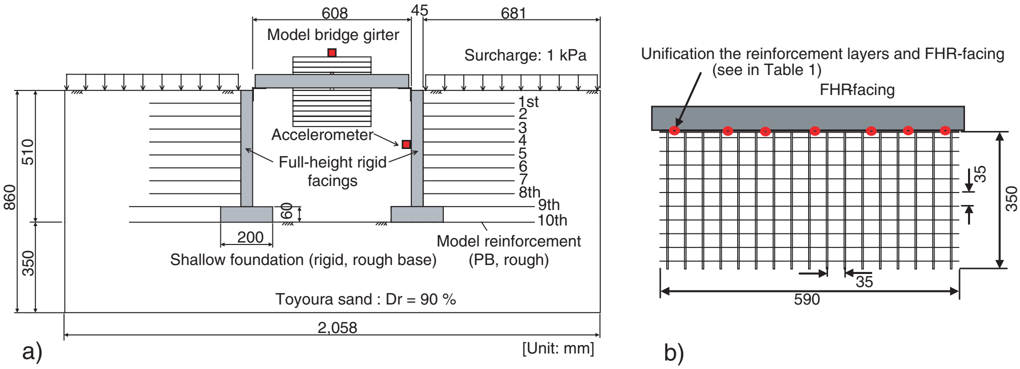

Figure 2. a) Cross-section of GRS-integral bridge model (Test 3 & 4), and b) plan of model reinforcement layer.

reinforcement layers and the facing was much more higher than conventional bridge types consisting of gravity type and GRS abutments as well as the integral bridge (with unreinforced backfill). They also showed that the center of the gravity of the non-soil structural part of the GRS integral bridge is located much higher than that of conventional-type bridge abutments, because:

1) the facings are integrated with a girder; and
2) the facings are much thinner and lighter than the conventional type abutment structures, as the facings act as a continuous beam with a number of supports (i.e., the geosynthetic reinforcement layers) with a small span between vertically adjacent supports (typically 30 cm).

They also showed that the collapse of the integral bride was associated with a large rotation of the facing with the bottom being pushed out and therefore large tensile force was activated in the reinforcement via the connection at the back of the facing in the lower part of the structure. That is, sufficiently high connection strength and pull-out strength of the reinforcement layers as well as high rupture strength of reinforcement are essential for high seismic stability of integral bridge.

In the present study, the effects of the tensile resistance of the reinforcement layers, in particular the number of reinforcement layer and the connection strength between the reinforcement and the facing, on the seismic stability of the proposed GRS integral bridge were investigated by performing a series of shaking table tests.

2 MODEL AND TESTING PROCEDURES

The GRS integral bridge model is described in Fig. 2. The model girder was unified with the model FHR facings that were placed on a subsoil layer while supporting the backfill. The subsoil and backfill were dense dry Toyoura sand at a relative density equal to 90% produced by pluviating air-dried sand particles through air via multiple sieves. Shallow foundations were arranged at the bottom of the FHR facings (Fig. 2a). No pile foundation was employed to observe the basic failure mode of integral bridge.

The model size was assumed to be 1/10 of a typical prototype bridge. A dead weight of 180 kg was attached to the center of the girder to make the girder length equivalent to 2 m (i.e., 20 m with the assumed prototype). The girder was integrated with the FHR facings via L-shape metal fixtures (3 mm-thick, 50 mm-wide and 200 mm-long). The fixtures were designed to start yielding when the facing rotates with the bottom being pushed out 6.5 mm, before the ultimate collapse of the model bridge system. It was actually the case in the model tests as shown by Aizawa et al. (2007) and later in this paper. It was considered that this collapse mode be likely with the prototype. The back face of the FHR facings and the bottom face of their foundations were made rough by gluing sandpaper #150 so that high shear stresses can be mobilized on these faces.

The reinforcement was a grid consisting of strands made of phosphor-bronze (PB) strips (0.3 mm-thick, 3 mm-wide and 350 mm-long) and ribs for transversal members made of PB (0.5 mm in diameter) (Figure 2b). Sand particles were glued on their surface. The reinforcement layers were arranged at a vertical spacing of 50 mm in the backfill.

Five model shaking tests were performed on integral bridge models (Fig. 3). With one model, the backfill was not reinforced, while, with four models, the backfill was reinforced changing the tensile resistance of reinforcement layers to evaluate its effects on the dynamic stability of GRS integral bridge. To this end, the number of reinforcement layers and the connection strength between the reinforcement and the facing were changed in these model tests, as listed in Table 1. In tests 3 and 4, ten reinforcement layers

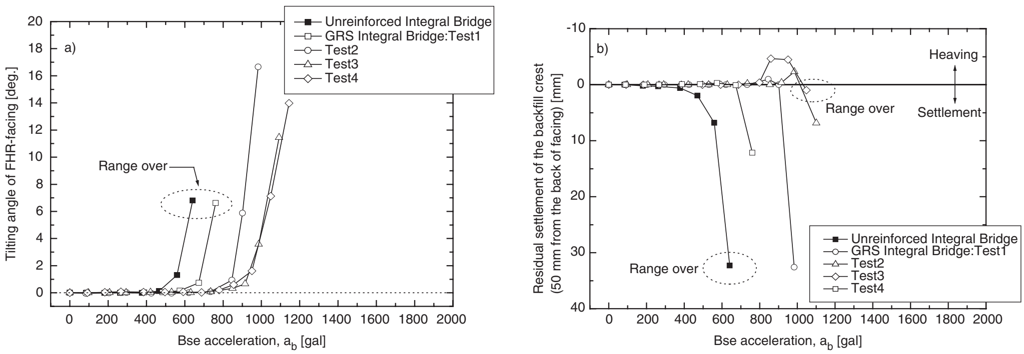

Figure 3. Relationships between base acceleration and a) residual tilting angle of the facing, and b) residual settlement of the backfill crest (50 mm from the back of facing).

Table 1. Summary of reinforcement properties.

Test name	Num. of reinforcement layers	Conection condition Conection strength [N/layer]	connection	Strand Rupture strength [N]	Num. of strand	Covering ratio, CR [%]	Friction angle at CR = 100% [deg.]
Test1	8	400	Melting, 4 points	207	17	10.1	35.0
Test2	9	520	Bolt(M3), 4 points	207	17	10.1	35.0
Test3	10	520	Bolt(M3), 4 points	207	17	10.1	35.0
Test4	10	1,070	Bolt(M3), 6 points	207	17	10.1	35.0

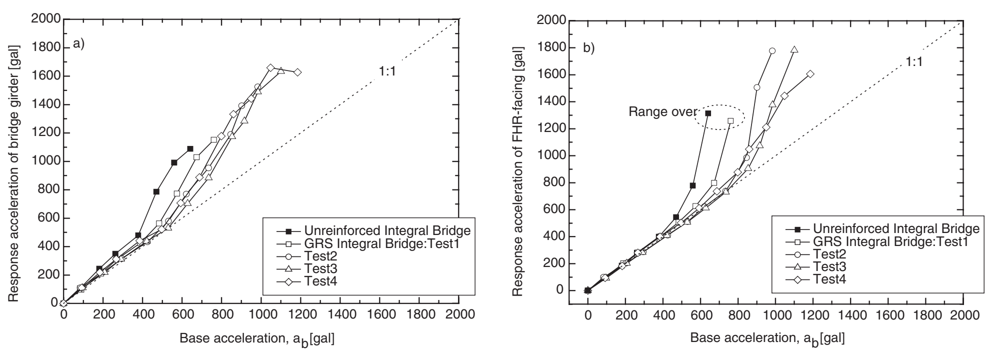

Figure 4. The relationships between base acceleration and a) response acceleration of the bridge girder, and b) response acceleration of the facing.

were arranged with 9th and 10th layers connected to the foundation of the respective facings (as shown in Fig. 2a). On the other hand, in tests 1 and 2, respectively eight and nine layers were arranged. As seen from Table 1, the connection strengths were different by a factor up to about 2.5 times among tests 1–4.

The input motion at the shaking table was 20 cycles of horizontal sinusoidal wave at a frequency of 5 Hz at each loading stage. The amplitude of acceleration at the table (α_b) was increased step by step from 100 gal with an increment of 100 gal.

3 TEST RESULTS AND DISCUSSIONS

Effects of backfill-reinforcing and connection strength: Fig. 3a presents the relationships between the residual tilting angle of the facing and the amplitude of base acceleration, a_b, while Fig. 3b shows the relationship between the residual settlement at the backfill crest at 50 mm back from the back face of the facing and a_b. Fig. 4 presents the relationships between the response acceleration of the bridge girder and FHR facing and a_b. The locations of the accelerometers are shown in

Fig. 2. The results from a shaking table test on the integral bridge with unreinforced backfill are also shown in Figs. 3 and 4. Fig. 5 compares the failure modes of these five models. The locations where the connection between the reinforcement and the facing failed are also indicated in Fig. 5. The following trends of behaviour may be seen from these figures:

1) In all the tests, the collapse of the integral bridge system was associated with a large rotation of the facing relatively to the girder about its top with the lower part being pushed out (Fig. 5).
2) The dynamic stability of the GRS integral bridge models (tests 1–4) was generally higher than the conventional integral bridge model with unreinforced backfill. The stability increasesd with an increase in the tensile resistance of reinforcement layers, which was achieved by increasing the number of reinforcement layer and the connection strength between the reinforcement and the facing (Figs. 3a & b). In particular, the tensile resistance of the reinforcement layers arranged at the lower level of the facing effectively resisted against the outward displacement of the facing, thereby increased the stability of the GRS integral bridge.
3) In all the tests, the residual deformation of the integral bridges (i.e., the tilting of the facing and the settlement of the backfill; Fig. 3) started increasing after the response ratio of acceleration at the girder and FHR facing to the input at the table (α_b) started increasing (Fig. 4). The increase in the response at the girder was caused by the passive yielding at the upper and lower levels in the backfill as well as the yielding of the fixtures between the girder and the facings.
4) The differences in the increasing rate of the residual deformation among the different tests (Fig. 3) were noticeably larger than those of the response ratio of acceleration (Fig. 4). This result indicates that the restraining effects of the reinforcing of the backfill and the increase in the tensile resistance of the reinforcement layers on the residual deformation of the integral bridge were more significant than those on the dynamic stiffness of the integral bridge.
5) The number of the connections between the reinforcement and the facing that failed decreased with an increase in the number of reinforcement layer or/and the connection strength among tests 1–4, which resulted in an increase in the stability of the bridge system. The failed connections were located more densely at lower places in accordance with the failure mode of the bridge systems (Fig. 5).
6) Despite that the connection strength in test 4 was significantly higher, by a factor of nearly two, than the one in test 3 for the same and largest number of reinforcement layer, the base acceleration,

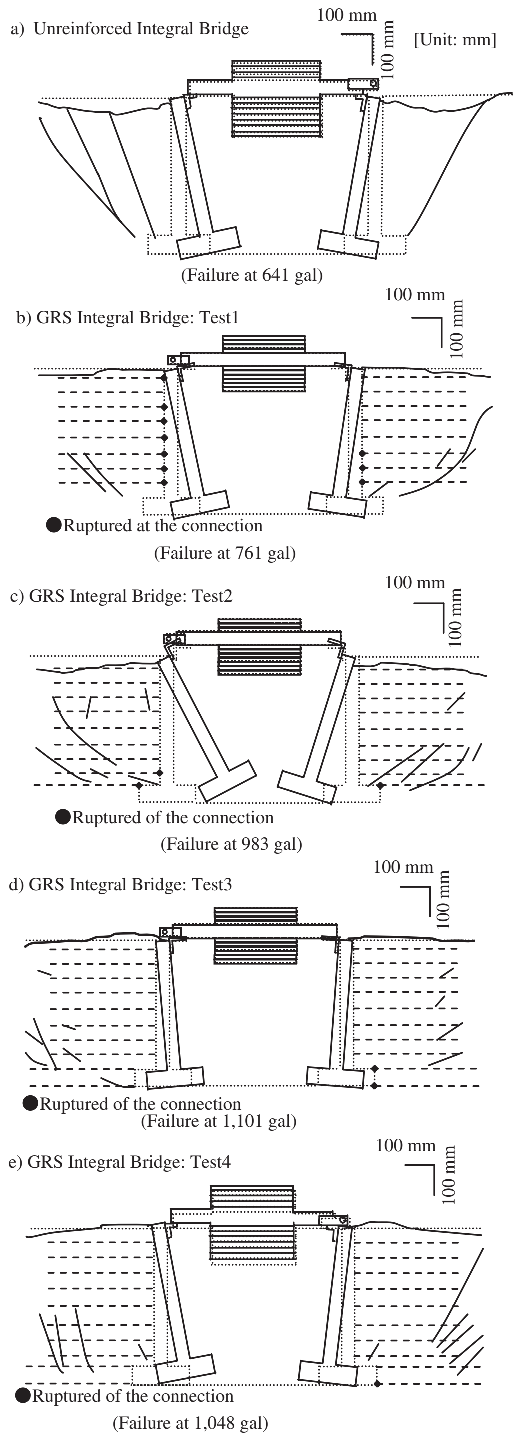

Figure 5. Failure modes of a) unreinforced integral bridge and b)-e) GRS integral bridges.

a_b, when the bridge collapsed was similar. Furthermore, the connection failure took place only at limited locations at the foundations of the facings. These results indicate that the collapse of the bridge system in tests 3 and 4 was associated with pull-out failure of the reinforcement layers at the lower level of the facing.

These results indicate that the seismic stability of GRS integral bridge is controlled in particular by the tensile resistance of the reinforcement layers at the lower level of the facing.

Failure mode: The following structural features control the dynamic failure mode of GRS integral bridge. The advantageous features are: 1) a girder and facings are integrated and the girder functions as a strut against the earth pressure acting on the facings; 2) the facing is laterally supported by a number of tensile reinforcement layers; and 3) the backfill is reinforced. An independent single bridge abutment of GRS retaining wall supporting a girder via a fixed support lacks the features 1) & 2), which results in a lower seismic stability with a less ductile failure compared with the GRS integral bridge (i.e., Koseki et al., 2006). On the other hand, the disadvantageous feature is that 4) the girder/facing system is relatively top-heavy while large lateral inertia force of the girder is activated to the top of the facing.

To develop a relevant seismic design procedure of GRS integral bridge taking into the above-mentioned features, the deformation and failure modes of the bridge observed in the five tests are analyzed more in detail below. Figs. 6a, 6b and 6c show the basic deformation modes as the input motion increased based on load and resistance components described in Fig. 7 that control the major failure mode of the bridge system.

Load components:

L1: Inertia force of the girder and the facings: In particular, large inertia force of the girder is activated on the top of relatively light facings, which results in large over-turning moment activated on the facings. The overturning moment increases with an increase in the weight of the girder (usually by an increase in the bridge length).

L2: Active earth pressure on the upper level of the facing on the right: This earth pressure is relatively small due to shallow concerned depths.

L3: Active earth pressure on the lower level of the facing on the left: This becomes more important when the forced rotation of the facing becomes larger after the passive yielding in the backfill has become large.

Resistance components:

R1: Passive earth pressure on the upper level of the facing on the left: This component cannot become large because of shallow concerned depths. The tensile reinforcement cannot help in increasing the passive earth pressure.

R2: Passive earth pressure on the lower level of the facing on the right: Full mobilization of this component needs relatively large pushing-in displacements of the facing into the backfill. Therefore, it is not relevant to expect full mobilization of this component in the design.

R3: Tensile force of the reinforcement layers at the upper level of the facing on the right: This cannot become very large because of low pull-out strength due to low confining pressure.

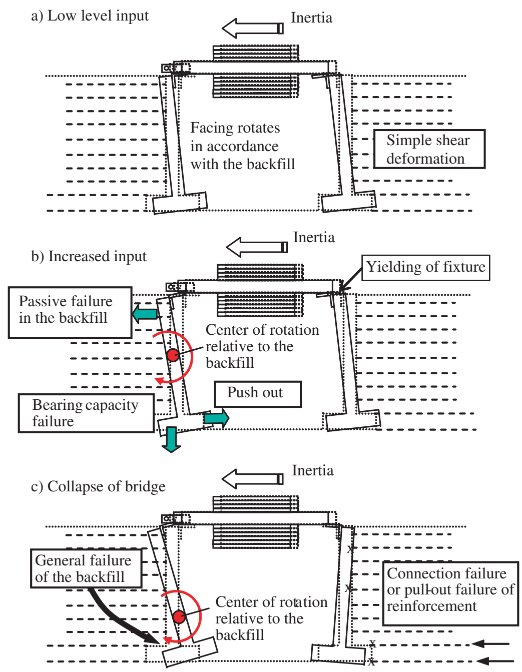

Figure 6. Failure mechanisms at different load levels.

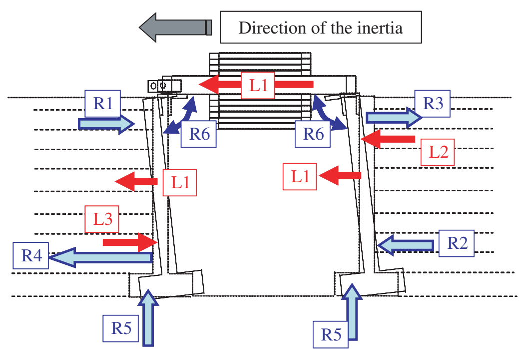

Figure 7. Load and resistance components when the inertia force of the structure is acting toward the left.

R4: Tensile force of the reinforcement layers at the lower level of the facing on the left: This is the most important resistance component, and analyzed in detail below.
R5: Bearing capacity of the subsoil at the bottom of foundations of the facings: This component becomes smaller at a fast rate as the eccentricity and inclination in the applied load becomes larger by an increase in the rotation of the facing.
R6: Bending strength of the fixtures between the girder and the facings: This component is activated by a small rotation of the facing and can effectively restrain the facing rotation when the input motion is relatively low. After the fixtures start yielding as the input motion increases, its importance becomes relatively small.

When the input load level is low and the dynamic behaviour of the bridge system is stable (Fig. 6a), the major deformation mode of the bridge system is in accordance with the basic deformation mode (i.e., simple shear) of the backfill. So the response ratio of acceleration at the girder is similarly very low (Fig. 5a) whether the backfill is reinforced and whether the tensile resistance of the reinforcement layers (i.e., R4) is different. At this stage, R6 is the most important resistance component while the other resistance components are not very active.

As the input load increases, the fixtures start yielding and the passive failure starts taking place in the upper level of the backfill on the left and in the lower level in the backfill on the right (Fig. 6b). Then, the response ratio of acceleration at the girder starts increasing associated with an increase in the tilting of the facing. As the passive failure is more significant in the upper part of the backfill on the left, the center of rotation of the facing on the left is then shifted downward, which increases the rotation moment acting on the facing for given load L1. Larger rotation of the facing relative to the backfill activates resistance components R1–R5. Then, if the connection strength is not sufficient, the connection failure may start taking place at all levels of the facing, as typically seen from Fig. 3b.

Fig. 6c illustrates the stage when the collapse becomes imminent. The push-out displacement at the lower part of the facing on the left becomes very large by a large rotation of the facing relative to the backfill. This is associated with a general rotational failure taking place in the backfill. Then, R4 becomes essential to prevent the ultimate collapse of the bridge, which may result into connection failure and/or pull-out failure of selected reinforcement layers at the lower part of the facing.

The tensile resistance of the reinforcement layers increases with an increase in: 1) the number of reinforcement layer, in particular at the lower level of the facing; and 2) the tensile resistance of the respective reinforcement layers. Factor 2) is equal to the minimum of: a) the strength at the connection between the reinforcement layer and the rigid facing; b) the pull-out strength of reinforcement; and c) the rupture strength of reinforcement (Tamura, 2006). The material properties (strength, stiffness, surface roughness ….), shape (strip or grid or sheet), length, arrangement in the backfill (vertical spacing ….) and so on of reinforcement layers should be determined by taking into account the above factors in the design of GRS integral bridge. In particular, if either the connection strength or the pull-out resistance is lower than the tensile rupture strength, the full capability of reinforcement cannot be activated in achieving high seismic performance of GRS integral bridge. Large connection force corresponds to large earth pressure activated on the back of the facing. This does not result into any serious structural damage of facing, because the facing is supported with the reinforcement layers at a small span (i.e., a small vertical spacing). A high connection strength also result in an increase in the tensile force that can be activated along the whole length of the reinforcement, which results in better reinforcing effects for the backfill (i.e., more stable behaviour of the backfill). To achieve high pull-out strength of the reinforcement, it is important to select an appropriate reinforcement type (e.g., a grid having stiff and strong enough not only longitudinal but also transversal members; a high friction angle between the surface of the reinforcement and the backfill material, a sufficient length and son on). Strip type reinforcement without any relevant anchorage system is not relevant.

4 SUMMARY

The following conclusions can be derived from the results from model shaking tests presented above:

1) The seismic stability of integral bridge increases substantially by reinforcing the backfill and connecting the reinforcement to the back of full-height rigid facings that are integrated with a girder. This type of integral bridge can also alleviate problems by cyclic displacements at the top of the facing due to seasonal thermal expansion and contraction of the girder as well as those by residual settlement of the backfill back of the facing by dead and live loads.
2) The stability increases with an increase in the tensile resistance of reinforcement layers, which increases with an increase in the number of reinforcement layer as well as an increase in the connection strength for given pull-out strength and rupture strength of reinforcement. The pull-out failure may take place when the connection strength became sufficiently large.

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