Numerical study on the behavior of ground and structure in a geosynthetic-reinforced soil integral bridge

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ABSTRACT: In bridge structures, lateral squeeze due to lateral stress of embankment placement and thermal movement of the bridge structure leads to failure of approach slab, girder, and bridge bearing. Recently, GRS (Geosynthetic-Reinforced Soil) integral bridge has been proposed as a new countermeasure. The GRS integral bridge is a combining structure of a GRS retaining wall and an integral abutment bridge. In this study, a series of numerical analysis which considered construction sequences and earthquake loading conditions were performed to compare behavior of a GRS integral bridge structure and a conventional PSC (Pre-Stressed Concrete) girder bridge. The analysis results show that the GRS integral bridge is more stable than the PSC girder bridge in an aspect of stress concentration and deformation on foundation ground and bridge structures including seismic stability.

Keywords: GRS integral bridge, PSC girder bridge, numerical analysis, ground stability

1 INTRODUCTION

Problems with bridge approach are various and require investigations inclusive of the approach pavement system such as pavement layers, joints, backfill, drainage systems, etc. Better solutions to alleviate these problems are needed to reduce maintenance costs, improve riding quality, and eliminate hazards to drivers. Bridge approach settlement has been investigated previously by a number of researchers (Schaefer and Koch 1992, Briaud et al. 1997, Hoppe 1999, Abu-Hejleh et al. 2006), focusing on both superstructure and substructure components. The factors causing differential settlement of the bridge approaches are listed as: (1) Type and compressibility of the soil or backfill material used in the embankment and foundation; (2) Thickness of the compressible foundation soil layer; (3) Height of the backfill embankment; (4) Type of abutment; (5) Poor construction practices; (6) High traffic loads; (7) Poor drainage condition; (8) Poor fill material; (9) Loss of fill by erosion; (10) Poor joints; and (11) Temperature cycles. According to previous studies results, lateral movement of the bridge abutment and settlement of the embankment are considered amongst the primary reasons for the problem.

A new type bridge combining an integral bridge and a pair of geosynthetic-reinforced soil (GRS) retaining walls having full-height rigid (FHR) facings, called the GRS integral bridge, was developed to overcome several inherent problems with conventional type bridges typically comprising a simple-supported girders, RC abutments and approaches of unreinforced backfill: i.e. high construction/maintenance cost while bumps immediately behind the abutments; a low stability of the bearings and backfill against seismic loads; massive abutment structures; needs for piles etc (Tatsuoka et al. 1997, Tatsuoka et al. 2009, Tatsuoka et al. 2016). GRS integral bridges are basically much more cost-effective in construction and long-term maintenance while having a much higher seismic stability than conventional-type bridges having a girder via movable and fixed supports on a pair of cantilever abutments. GRS integral bridges are better than bridges consisting of GRS retaining walls as abutments and also conventional integral bridges with unreinforced backfill (Tatsuoka et al. 2016).

To validate the above, a series of numerical analysis which considered construction sequence were performed to compare ground and structure stability of GRS integral bridge structure and conventional PSC (Pre-Stressed Concrete) girder bridge in this study.

2 HISTORY OF GRS INTEGRAL BRIDGE

The GRS retaining wall (RW) with staged-constructed FHR facing was developed in the mid-1980s (Tatsuoka et al. 1997). GRS integral bridge, integrating without using bearings both ends of a continuous girder to the top of the FHR facings of a pair of GRS RW, was developed in 2000s (Tatsuoka et al. 2009). GRS integral bridge is now one of the standard bridge types for railways in Japan. Many of them were constructed in place of gentle-sloped embankment, cantilever RC (Reinforced Concrete) RWs, conventional type bridge abutments, RC viaducts and conventional type bridges, typically for Hokkaido Shinkansen (Tatsuoka et al. 2016).

Geosynthetic-reinforced soil technology is applied to bridges for which reinforced soil abutments made with cement-mixed gravel were developed to solve the problem of backfill settlement and low earthquake resistance as shown in Figure 1 (Shindo and Tatsuoka 2017). Integral bridges which do not have bearings are one of the standard type of bridge which could be found in America and Europe.

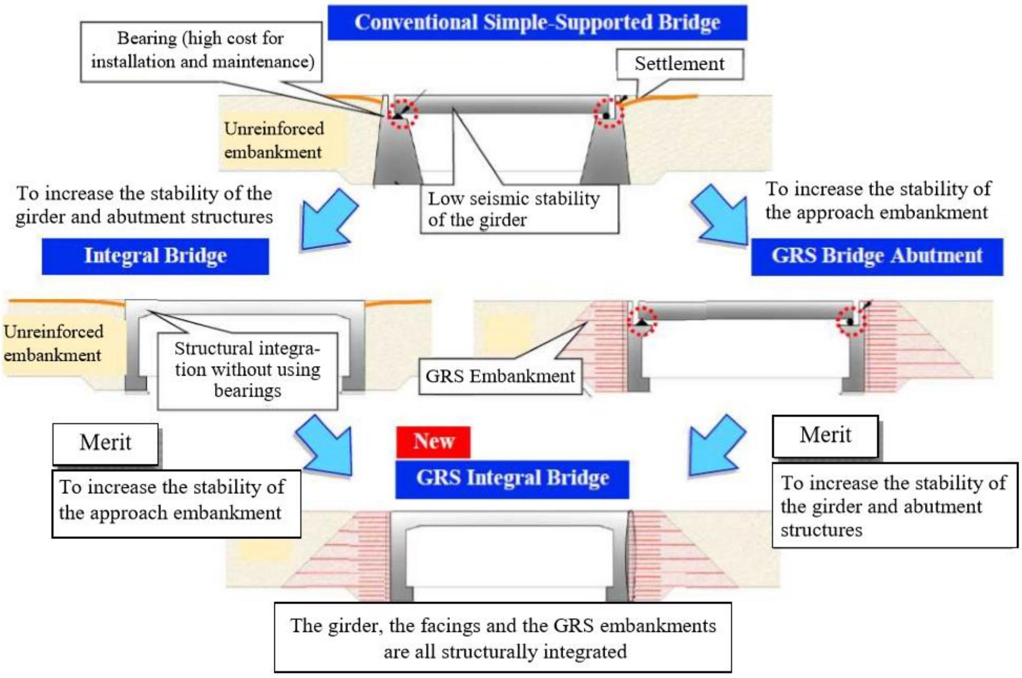


Figure 1. The concept of GRS integral bridge (after Shindo and Tatsuoka 2017)

3 NUMERICAL STUDIES OF GRS INTEGRAL BRIDGE

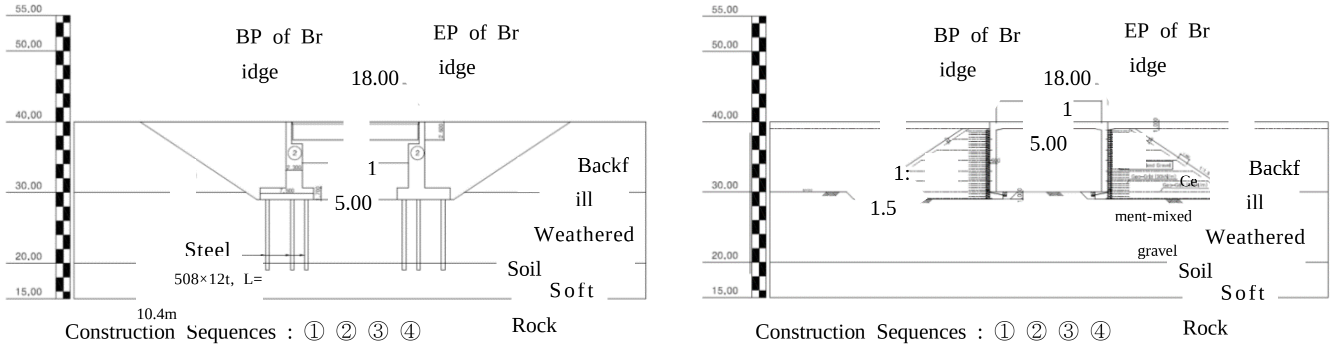
3.1 *Numerical Modeling*

3.1.1 *General*

The main purpose of this study is to analyze the stability of GRS integral bridges compared to traditional PSC girder bridge structures through numerical analysis. A two-dimensional finite element (FE) code, PLAXIS 2D (Brinkgreve 2002), was used to analyze the behavior of GRS integral bridge and traditional PSC girder bridge. The Plaxis domain was discretized by 15-node plane strain triangular elements. No water was considered in the model; all the analyses were performed under drained conditions.

Since the numerical analysis for stability review should consider the construction stage, the following four stages of construction were considered for traditional PSC girder bridge structures as: (1) In-situ stress modelling and initialization; (2) Setting-up of pile foundations; (3) Construction of bridge structures; and (4) Backfill and applying traffic load. In case of GRS integral bridge, the following construction stages were considered as: (1) In-situ stress modelling and initialization; (2) Construction of bridge abutment made of cement-mixed geogrid-reinforced gravel backfill; (3) Backfill behind the geogrid-reinforced backfill; and (4) Construction of bridge and applying traffic load as shown in Figure 2.

The PSC girder bridge was constructed by Korea Land and Housing Corporation in Se-Jong city Korea, and GRS integral bridge was designed with the same site condition by authors in this study.



(a) Traditional PSC girder bridge (b) GRS integral bridge

Figure 2. Construction Sequence

Mohr-Coulomb model was used in this study to simulate foundation soils and backfills, and the elastic model was introduced to simulate the bridge structures and geo-grid elements. The detailed material properties used in the analyses are given in Table 1.

Table 1. Foundation soils, backfills and geo-grid material properties for FE analysis

Types	Unit weight (kN/m^3)	Cohesion (kN/m^2)	Friction angle (degree)	Elastic modulus (kN/m^2)	Poisson ratio	Stiffness (kN/m)	Notes
Backfill	19.0	15.0	25.0	20,000	0.35	-	MC*
Weathered soil	18.0	5.0	30.0	30,000	0.35	-	MC
Soft rock	24.0	300.0	35.0	1,800,000	0.26	-	MC
Cement-mixed gravel	20.0	100.0	35.0	9,000,000	0.30	--	MC
Bridge structures	25.0	-	-	24,400,000	0.15		E*
Geo-grid (long)	-	-	-	-	-	60	E
Geo-grid (short)	-	-	-	-	-	30	E

* Notes : MC = Mohr-Coulomb material model, E = Elastic model.

3.1.2 *Seismic Analysis*

The numerical simulations consisted of a static analysis stage (including construction sequence), followed by a dynamic loading stage. Dynamic seismic analysis was performed for conditions starting at the end of static loading. The artificial time history of seismic acceleration is shown in Figure 3. The peak ground acceleration (PGA) was assumed 0.154g according to the Korean seismic design standard (ground conditions : S_c (stiff soil to soft rock), performance criteria : collapse prevention level, return period : 1,000 years) and was applied at the bottom boundary in the longitudinal direction. Free-field conditions were imposed at the lateral boundaries to absorb seismic waves and prevent them from reflecting back into the problem domain.

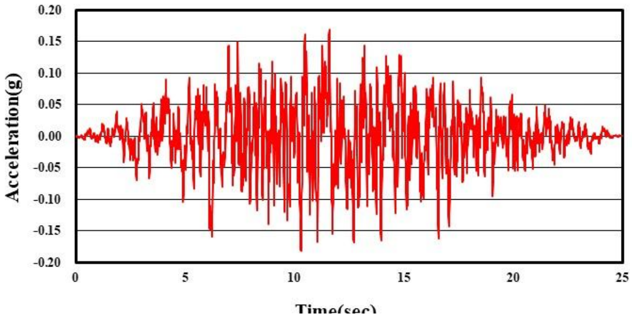


Figure 3. Artificial earthquake for the seismic analysis (PGA = 0.154g)

3.2 *FEM Simulation Cases*

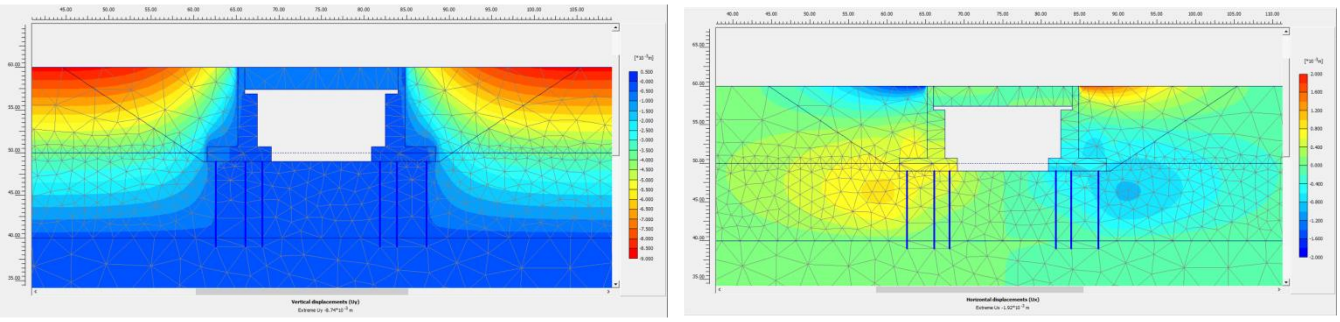
The FEM analyses details of the bridge structures and embankments including conventional bridge and GRS integral bridge cases are discussed in this section.

3.2.1 *Case 1: Conventional PSC girder Bridge on Weathered Soil Ground Condition*

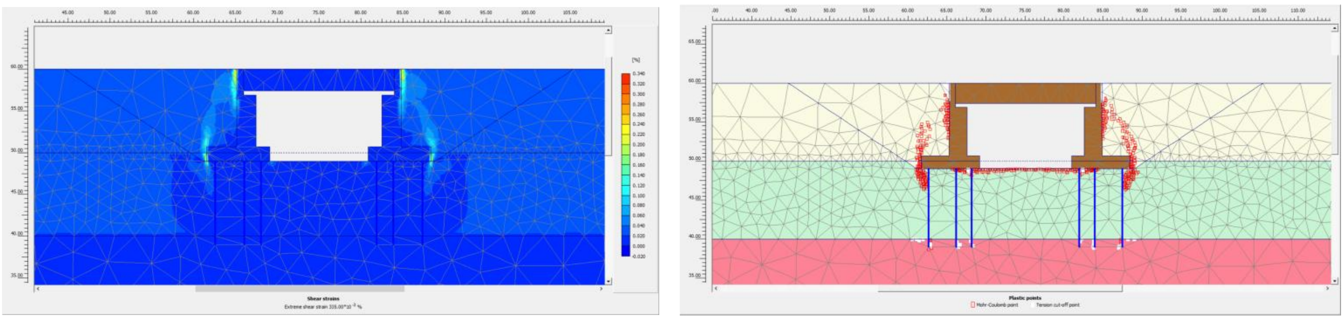
After the completion of the construction, the vertical abutment displacement appears to have little settlement, which is presumed to be the effect of the stiffness of pile foundation. However, the backfill layer behind the bridge abutment shows a maximum vertical settlement of about 8.7mm as shown in Figure 4(a). The differential settlement between the abutment and the backfill, which causes inconvenience to passengers and increases the cost of maintenance and repair of the distressed approach slabs of the bridge approaches, is about 7.9mm. The horizontal displacement as presented in Figure 4(b) represent the typical lateral movement behavior of bridge abutment embankment on top of the weathered soil. The maximum horizontal displacement of the bridge abutment is about 1.9 mm at the position of the backfill surface and the horizontal displacement of about 1.2 mm occurs in the middle of weathered soil layer.

As a result of investigation of vertical, horizontal and shear stress/strain distribution, stresses tend to be concentrated on the several locations (the girder at the upper part of the bridge abutment, the contact part between pile foundation and the bottom of bridge abutment structure, and the contact part between pile foundation and foundation ground). In case of horizontal stresses, it shows the largest value in the middle girder of the bridge, and it is considered to reflect the tendency of the largest compression and tensile stress to occur in the middle part of the simple beam. It shows the characteristics that the structure supports all major loads. However, the location where the highest stress is concentrated is the intersection parts between the abutment structure and the girder (bridge shoe/bearing locations), which can cause frequent defects during the maintenance periods.

According to the abutment rotation by the lateral earth pressure of backfill, plastic zones mainly appear at the abutment bottom plate and maximum shear strain locations as shown in Figures 4(c) and 4(d).



(a) Vertical displacements (b) Horizontal displacements



(c) Shear strain (d) Plastic points

Figure 4. FEM static analysis results of conventional PSC girder bridge on weathered soil

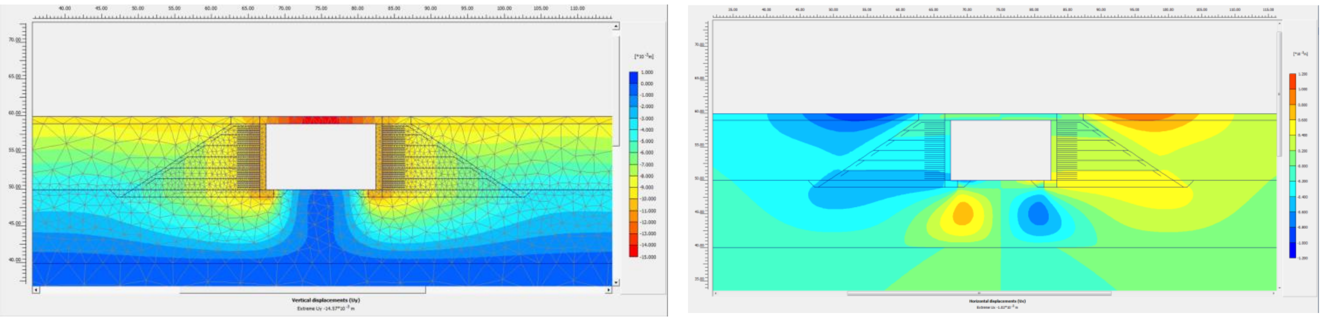
3.2.2 *Case 2: GRS Integral Bridge on Weathered Soil Ground Condition*

The trend of the settlement profile is totally different with previous conventional PSC girder bridge. After the completion of construction, a maximum settlement about 14.6mm occurred in the middle of the bridge due to the effect of self-weight and traffic load as shown in Figure 5(a). However, the differential settlement between the abutment and the backfill is about only 1.2mm. The main reason for this small value compared with the PSC girder bridge is most of the settlement occurred before the GRS integral bridge was built up considering the construction sequences.

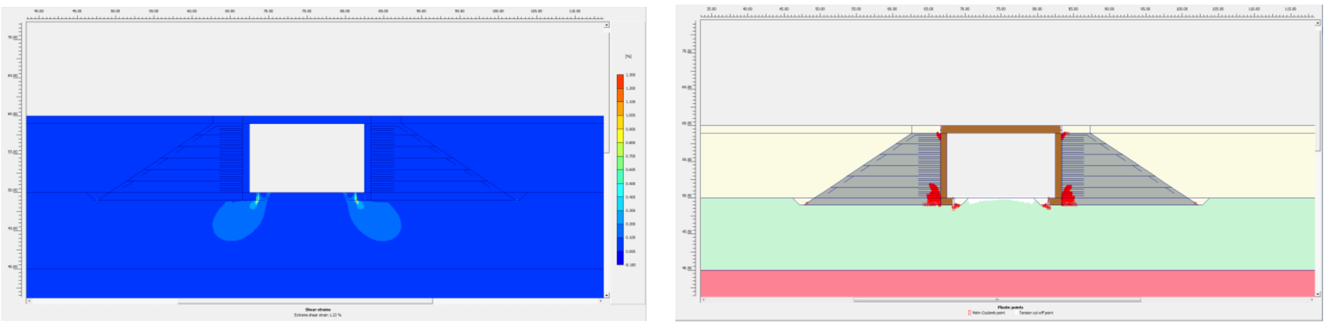
The maximum horizontal displacement occurred about 1.1 mm in the general backfill layer on the backside of the cement-mixed geogrid reinforced gravel layer and less than about 0.8 mm in the weathered soil layer as shown in Figure 5(b). The vertical/horizontal displacement of GRS integral bridge structure and backfill (including cement-mixed geogrid gravel layer) shows a homogeneous pattern compared with previous conventional PSC girder bridge.

The maximum shear strain occurred at the front of the foundation of the cement-mixed geogrid reinforced gravel layer as shown in Figure 5(c), and the axial force of geogrid reinforcement was sufficiently smaller than the allowable tensile strength.

The stress distribution was very homogeneous due to the load distribution effect of the cement-mixed geogrid reinforced gravel layer, and stress concentration phenomenon was only limited at the connection corner part of the bridge structure. The maximum vertical / horizontal / shear stress occurred at the interface of the structure where the stress concentration occurred. The plastic zone appeared mostly in the front of the cement-mixed geogrid reinforced gravel layer foundation and behind the abutment retaining wall as shown in Figure 5(d).



(a) Vertical displacements (b) Horizontal displacements



(c) Shear strain (d) Plastic points

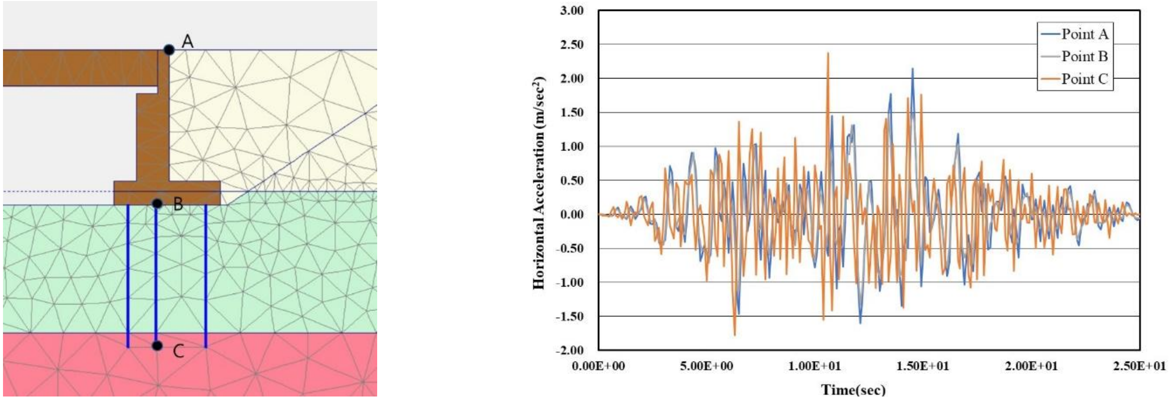
Figure 5. FEM static analysis results of GRS integral bridge on weathered soil

3.2.3 *Case 3: Seismic Analysis of Conventional PSC girder Bridge on Weathered Soil Ground Condition*

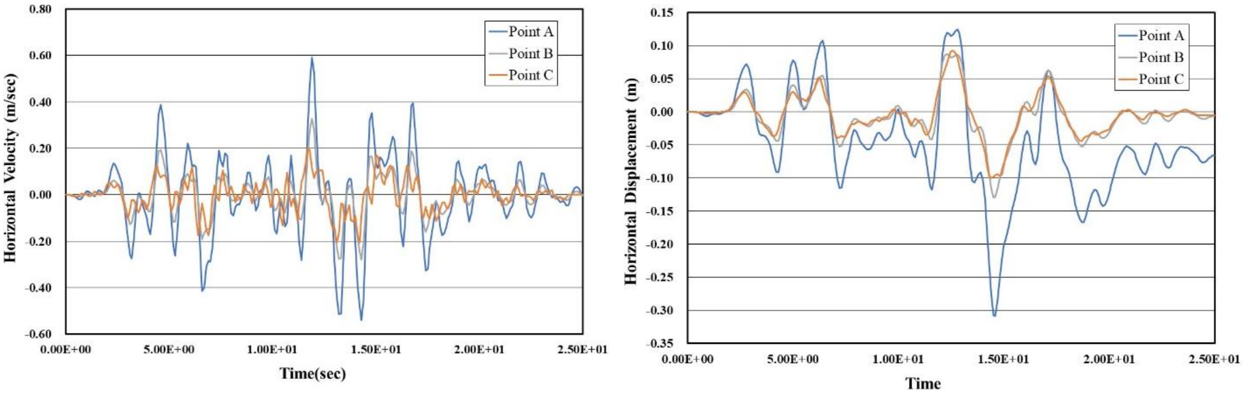
The performance characteristics of PSC girder bridge abutments subjected to earthquake loading were investigated to check the seismic stability of conventional PSC bridge. The dynamic responses including the horizontal accelerations / velocities / deformations at different locations (the top of the abutment – Point A, the bottom of the bridge foundation – Point B, and the end of pile foundation in soft rock layers – Point C) were measured and compared as shown in Figure 6.

Due to the impact of amplification/attenuation effects of seismic waves along the different soil layers, the shape of peak horizontal acceleration including the time to peak value were different depending on the locations of measurement points as shown in Figure 6(b). The peak ground horizontal acceleration at the top of the abutment (Point A) was 2.14 m/s^2 (0.218g), the maximum seismic-induced horizontal displacement was about 309 mm, and the peak horizontal velocity was about 0.59 m/s as shown in Figure 6. The seismic-induced residual settlements at the top of abutment was estimated about 27 mm (Figure 8(b)).

The abutment wall of conventional PSC girder bridge suffered not only base sliding, but also overturning. It should be also noted that multiple progressive failure planes were formed in the backfill due to the effects of strain localization and strain softening behavior.



(a) Locations of measurement points (b) Measured horizontal acceleration responses



(c) Measured horizontal velocity responses (d) Measured horizontal displacement responses

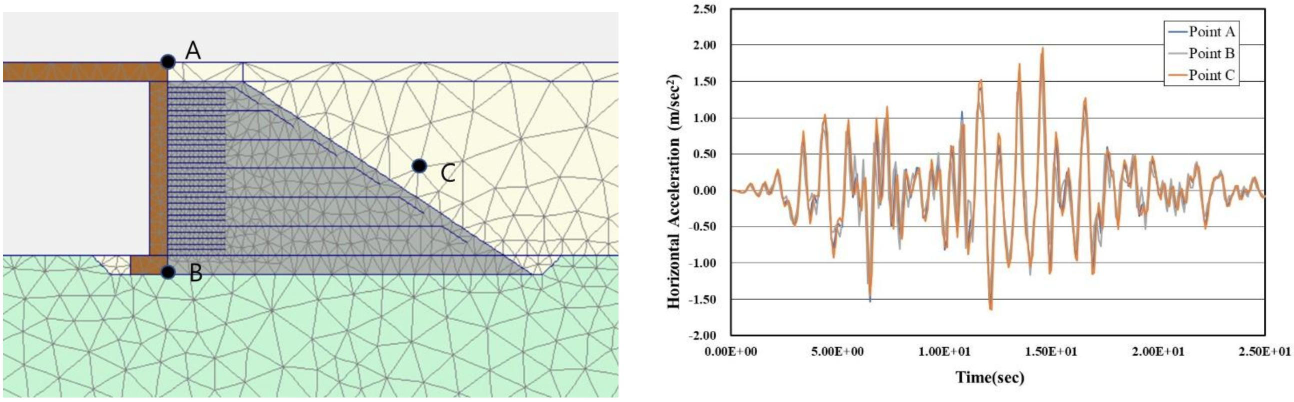
Figure 6. Seismic analysis results of conventional PSC girder bridge on weathered soil

3.2.4 *Case 4: Seismic Analysis of GRS Integral Bridge on Weathered Soil Ground Condition*

The dynamic responses of the abutment and backfill were measured at different locations (the top of the abutment – Point A, the bottom of cement-mixed geogrid reinforced gravel layer – Point B, and the middle backfill layer – Point C) and compared as shown in Figure 7.

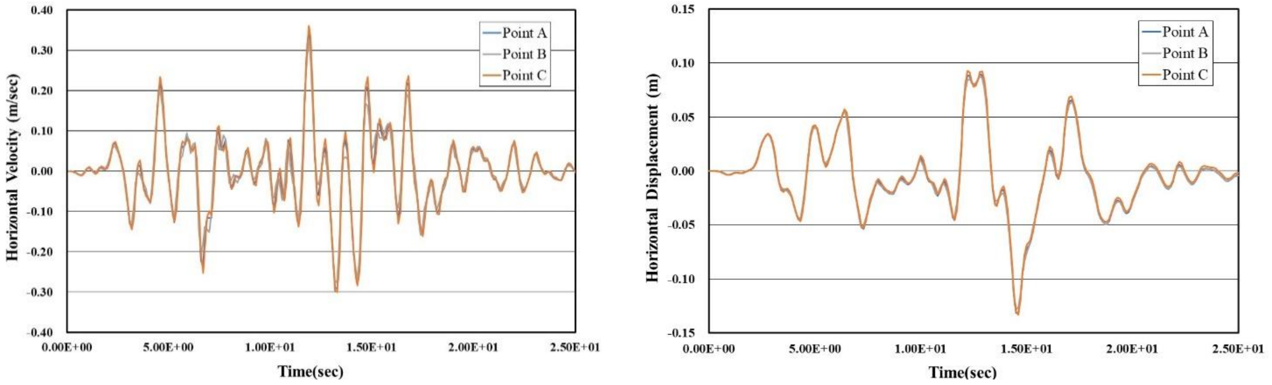
The peak ground horizontal acceleration at the top of the abutment (Point A) was estimated about 1.82 m/s^2 (0.186g) and the maximum horizontal acceleration was 1.96 m/s^2 (0.200g) in the middle backfill layer (Point C). This is because the stiffness of the general backfill layer is softer than cement-mixed gravel layer. The maximum seismic-induced horizontal displacement was about 132 mm, and the peak horizontal velocity was about 0.35 m/s as shown in Figure 7. Due to the increased stiffness of cement-mixed gravel layer, the seismic responses at different measurement locations did not show too much differences.

The seismic-induced residual settlements at the top of abutment was estimated about 16 mm as shown in Figure 8(b). By constructing the approach backfill using a stiffer material such as cement-mixed gravel soil, the backfill would exhibit substantially smaller settlements immediately behind the abutment.



(a) Locations of measurement points (b) Measured horizontal acceleration responses

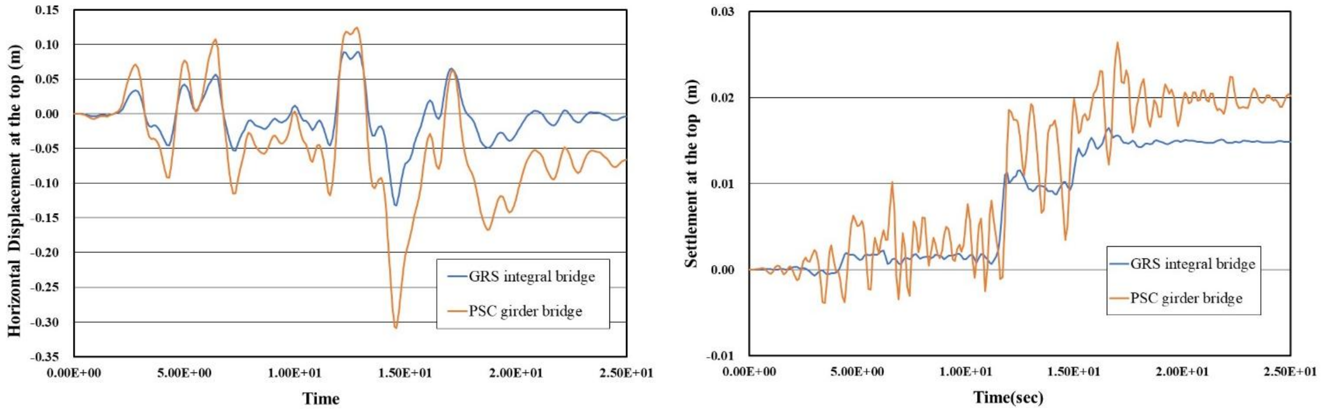
Figure 7. Seismic analysis results of GRS integral bridge on weathered soil (continued)



(c) Measured horizontal velocity responses (d) Measured horizontal displacement responses

Figure 7. Seismic analysis results of GRS integral bridge on weathered soil

The overturning mode was more predominant with the GRS structures compared with conventional PSC girder bridge. Figure 8 shows the comparisons of seismic-induced horizontal displacements and settlements of different types of bridges at the top of the abutment locations, and the seismic stability of cement-treated abutments was increased significantly, compared to conventional PSC girder bridge.



(a) Seismic-induced horizontal displacement (b) Seismic-induced settlements

Figure 8. Seismic responses for different types of bridges

4 CONCLUSIONS

For the understanding of the stability characteristics of traditional PSC girder bridge and GRS integral bridge, a series of numerical analysis which considered construction sequence were performed and analyzed. The performance characteristics subjected to earthquake loading were also investigated to check the seismic stability. The major conclusions from this study could be summarized as follows:

- The vertical displacement of the traditional PSC girder bridge abutment was very little due to the stiffness of pile foundation. However, the relatively large horizontal displacement which cause the lateral movement occurred in the backfill layer. However, the displacement of GRS integral bridge structure and backfill (including cement-mixed geogrid gravel layer) was smaller and showed a homogeneous pattern compared with previous conventional PSC girder bridge.
- Stresses concentration were occurred on the several locations (the girder at the upper part of the bridge abutment, the contact part between pile foundation and the bottom of bridge abutment structure, and the contact part between pile foundation and foundation ground) for traditional PSC girder bridge. It shows the characteristics that the structure supports all major loads. The location where the highest stress is concentrated is the intersection parts between the abutment structure and the girder (bridge shoe/bearing locations), which can cause frequent defects during the maintenance periods.

- In case of GRS integral bridge, the stress distribution was very homogeneous due to the load distribution effect of the cement-mixed geogrid reinforced gravel layer, and stress concentration phenomenon was only limited at the connection corner part of the bridge structure.
- It can be concluded that GRS integral bridge is more stable than the PSC girder bridge in an aspect of stress concentration and deformation on foundation ground and bridge structures.
- For the seismic stability, the GRS integral bridge shows less peak ground horizontal acceleration, seismic-induced horizontal displacement, and the peak horizontal velocity at the top of the abutment than conventional PSC girder bridge. Furthermore, the seismic-induced residual settlements at the top of abutment would exhibit substantially smaller settlements immediately behind the abutment.
- The abutment wall of conventional PSC girder bridge suffered not only base sliding, but also overturning. However, the overturning mode was more predominant with the GRS structures. The seismic stability of cement-mixed geogrid reinforced gravel layer was increased significantly, compared to conventional PSC girder bridge.

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