Design and construction of various type GRS structures for a new high-speed railway

Diasuke Soga, Yusuke Takano & Toyoji Yonezawa
Japan Railway Construction Transport and Technology Agency (JRTT), Japan)

Masaru, Tateyama
Railway Technical Research Institute (RTRI), Japan

Fumio Tatsuoka*
Tokyo University of Science, Japan (tatsuoka@rs.noda.tus.ac.jp)

ABSTRACT: Due to high-cost effectiveness resulting from low construction cost and high-performance in long-term maintenance and against heavy rains, floods and severe earthquakes, various type Geosynthetic-Reinforced Soil Structures (i.e., GRS Retaining Walls etc.) have been constructed for high-speed railways (HSRs), as well as ordinary railways, as standard structures in place of conventional type structures. An about 66 km-long new HSR (i.e., Kyushu ShinKanSen Nagasaki Route) is now under construction to be completed in 2022. To protect the aquatic environment in the adjacent mountain areas, the tunnel level was raised to relatively high elevations, which resulted in an increased number of shorter tunnels, therefore an increased number of elevated structures between adjacent tunnel entrances. To meet this and other design conditions, GRS RWs with a total length of 5 km, 80 GRS bridge abutments, 55 GRS tunnel entrance protections and 7 GRS integral bridges, which is densest ever for railways, were adopted. This paper summarizes lessons from their planning, design and construction.

Keywords: GRS bridge abutment, GRS integral bridge, GRS retaining wall, high-speed railways

1 INTRODUCTION

Fig. 1 shows the current network of High Speed Railways (HSRs) (ShinKanSen, SKS, in Japanese). For these HSRs, as well as ordinary railways and highways, GRS retaining walls with staged-constructed full-height rigid (FHR) facing (Fig. 2) together with 36 GRS bridge abutments and 6 GRS integral bridges have been constructed at 1,178 sites (Fig. 3a) with a total wall length more than 170 km (Fig. 3b) as of June 2017. The first GRS RW for HSR was constructed in 1991 for Hokuriku SKS. This type of GRS RW is staged-constructed (Fig. 2). First, the fill soil is compacted with a help of gravel gabions (or their equivalent) placed at the shoulder of each soil layer. After completed full-height wall and supporting ground has sufficiently deformed, a FHR facing is constructed by casting-in-place fresh concrete directly on the wall face wrapped around with geogrid reinforcement. In this way, the fill behind the wall face is effectively compacted without interactions with rigid facing, while the facing/reinforcement connection is not damaged by differential settlement between the facing and the reinforcement during and after construction. Moreover, construction using compressive soil on a compressive subsoil becomes possible. During casting-in-place, fresh concrete enters the gravel bags through the aperture of the geogrid bags. Geogrid of PVA having a bi-axial structure is usually used because of high resistance against high PH environment by concrete, high adhesiveness with concrete and good anchorage in the facing concrete and the fill. The vertical spacing between the geogrid layers is 30 cm to ensure good compaction of the fill in a lift of 15 cm and strong integration of the FHR facing to the reinforced fill. The use of FHR facing ensures not only high durability of the wall face but also high wall stability by: 1) developing high earth pressure on the back of the facing, which results in high confining pressure thereby high stiffness and strength of the fill back of the facing; and 2) making the behaviour of reinforced zone monolithic by preventing the development of local excessive deformation and failure planes crossing the facing. Besides, unlike discrete panel facings for GRS RWs and conventional type cantilever RWs, the FHR facing behaves as a continuous beam laterally supported by a number of geogrid layers. Therefore, large shear forces and moments are not activated in the facing, which results in a light facing structure, and large overturning moment and lateral thrust forces are not activated at the facing bottom, which makes it unnecessary to use a pile foundation for the facing in ordinary cases. Moreover, the FHR facing can support several railway facilities, such as noise barrier walls and electric poles. Fully taking advantage of this feature, GRS bridge abutment and GRS integral bridge, with which the FHR facing directly supports a bridge girder, were developed, as described below.

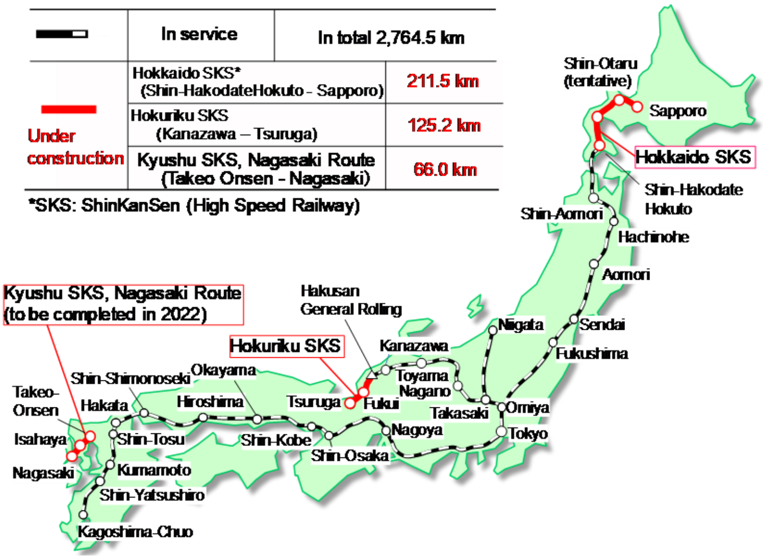


Figure 1. Network of High Speed Railway (ShinKanSen), as of June, 2017.

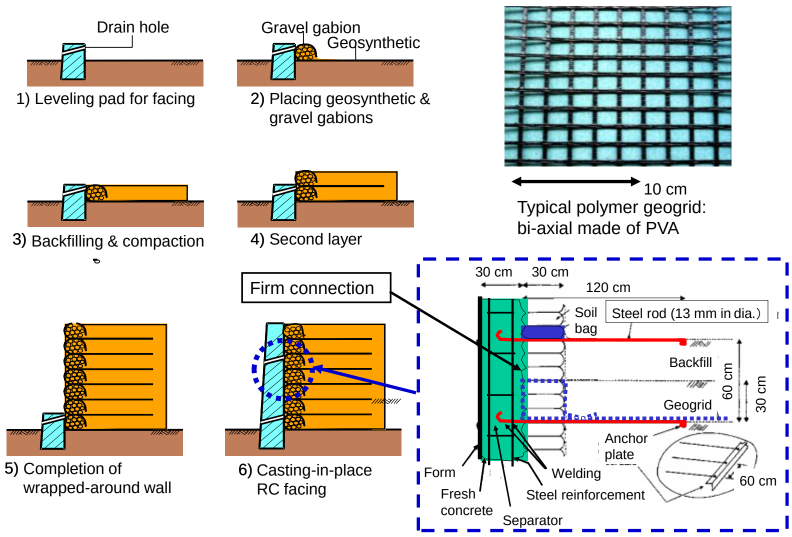
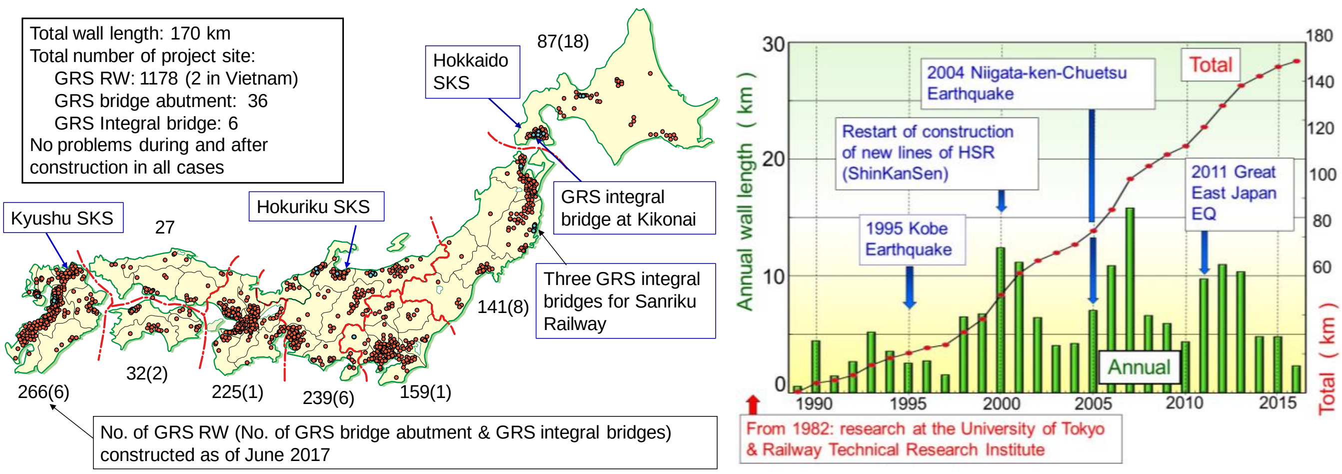


Figure 2. Staged-construction and structure of GRS RW with FHR facing (Tatsuoka et al., 1997, 2014a).



a) b)

Figure 3. a) Locations; and b) statistics of GRS structures constructed as of June, 2017

A high seismic stability of this type of GRS RW was validated by its good performance during the 1995 Great Kobe Earthquake (Tatsuoka et al., 1997, 1998). Based on this lesson and results of a comprehensive series of research, the seismic design of GRS structures was developed to have a similar stability as other type structures (i.e., bridges, viaducts, box culverts and tunnels) against such high seismic loads as experienced during the 1995 Great Kobe Earthquake (Tatsuoka et al., 2010, 2014b; Koseki et al., 2007). This seismic design was validated by satisfactory performance of many GRS RWs designed following this method during the 2011 Great East Japan Earthquake and the 2016 Kumamoto Earthquake in Kyushu. Moreover, a number of GRS RW of this type were constructed replacing conventional type RWs that collapsed by not only seismic forces but also scouring during flooding. Besides, continuous RC roadbed is more advantageous than conventional ballasted roadbed due to low life cycle cost resulting from very low maintenance cost despite relatively high construction cost. With HSRs in Japan, continuous RC roadbed was employed first only on viaducts and bridges, but not on ordinary embankments. In the meantime, it was confirmed that GRS RWs (Fig. 2) exhibit very small residual settlement and GRS RWs approaching bridge abutments, box culverts and viaducts can alleviate the problem of bump in conventional type approach fills. Now, the construction of continuous RC roadbed on GRS RWs of this type is the standard practice for HSRs in Japan. As a result, this type of GRS RW (Fig. 2) is now the standard RW type for railways basically replacing conventional type cantilever RC RWs (Tatsuoka et al., 2014a). In October 2017, three HSRs are under construction (Fig. 1). This paper reports the planning, design and construction of a number of GRS structures that were constructed or under construction or will be constructed, most densely ever for railways, for Kyushu SKS Nagasaki Route (about 66 km long; Fig. 4a).

a)

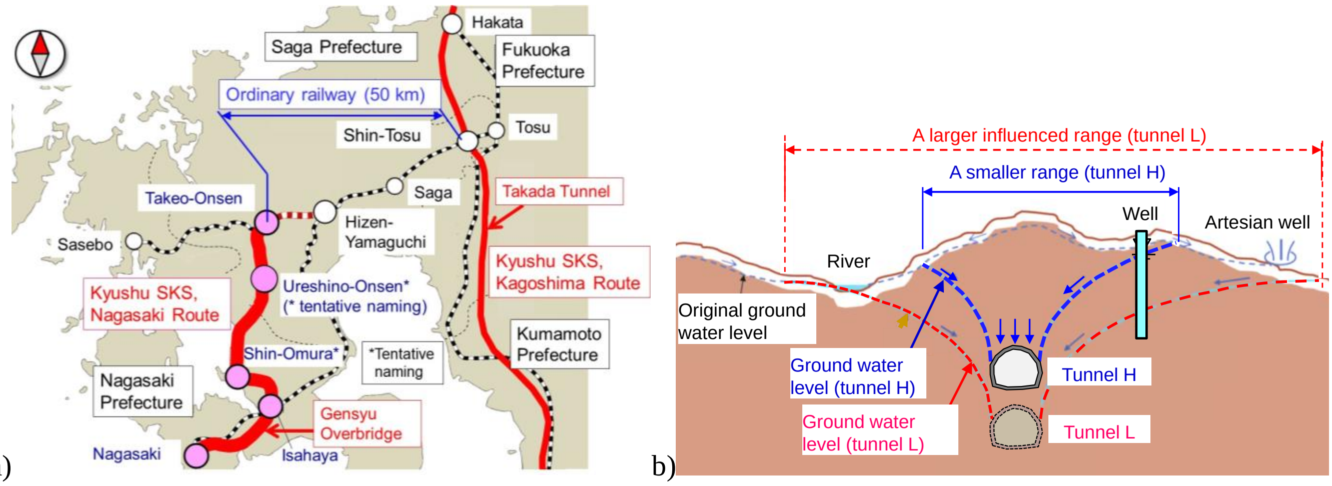


Figure 4. a) Kyushu ShinKanSen, Kagoshima & Nagasaki Routes; and b) rising of tunnel level.

2 GRS STRUCTURES FOR KYUSHU SHINKANSEN NAGASAKI ROUTE

2.1 *General*

As this route runs mainly in mountainous areas (Fig. 5), the ratio of the total tunnel length to the total route length is very high, about 61 % (Table 1b). Besides, to reduce as much as possible the impact by tunnel construction to the aquatic environment in these areas, the elevation of the tunnels was raised as much as high (Fig. 4b), which reduced the total tunnel length but increased the total number of tunnel, resulting in the highest tunnel number per length, about 0.46/km, among the recent three HSR projets (Table 1a). Then, the total number of tunnel entrances, bridges, viaducts and embankments in valleys between adjacent tunnel entrances became very large, which resulted in a large number of GRS structures (Table 1c) basically in place of conventional type structures.

2.2 *GRS RWs*

Of a total length of about 5 km for Nagasaki Route, GRS RWs with FHR facing (Fig. 2) will be constructed for a length of about 1.7 km to retain the embankment for Omura general rolling stock center. GRS RWs of this type will be also constructed on both sides of the embankments approaching tunnel entrances at many other sites.

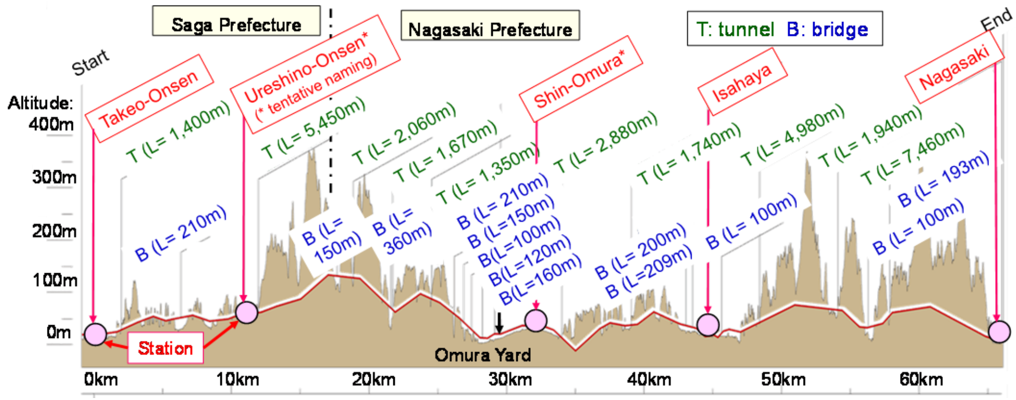


Figure 5. Stations, bridges and tunnels along Kyushu SKS Nagasaki Route.

Table 1. Comparison among the latest three HSR projects in Japan: a) the total number and the number per length of tunnel; and b) length ratios of different structure types; and c) GRS structures for Kyushu SKS Nagasaki Route.

a)

	Length	Total No. of tunnel	No. per length
Hokkaido SKS (Shin-Hakodate Hokuto- Sapporo)	211.5 km	19	0.09 /km
Hokuriku SKS (Kanazawa – Tsuruga)	125.2 km	20	0.18 /km
Kyushu SKS, Nagawaki Route (Takeo-Onsen - Nagasaki)	66.0 km	31	0.46 /km

b)

	Tunnel	Bridge	Viaduct	Soil structure
Hokkaido SKS	80.0%	2.0%	13.0%	5.0%
Hokuriku SKS	32.0%	15.0%	50.0%	3.0%
Kyushu SKS Nagasaki Route	60.7%	8.6%	22.1%	8.6%

0% 50% 100%

c)

	Saga Pref.	Nagasaki Pref.	Total
① GRS RW with FHR facing	1,009 m	3,979 m	4,988 m
② GRS tunnel entrance protection	15	40	55*
③ GRS bridge abutment	34	46	80
④ GRS integral bridge	2	5	7

* 89 % of the total tunnel entrance protections (62)

2.3 *GRS bridge abutments*

GRS bridge abutment (Fig. 6a) was developed to alleviate the following several problems with conventional simple girder bridges (Tatsuoka et al., 2004, 2005): i.e., 1) needs for a massive abutment as a cantilever structure resisting earth pressure from the unreinforced fill often supported by a pile foundation; and 2) a low stability of the approach fill, in particular against seismic loads, developing a bump immediately behind the abutment. To ensure a high seismic stability and to make the thickness of unbound fill behind increases continuously from zero to the full-height to prevent the development of bump, GRS bridge abutment (Fig. 6a) comprises an approach block of well-compacted lightly cement-mixed gravelly soil reinforced with geogrid layers connected to the back of the facing that is trapezoidal with the base wider than the crest.

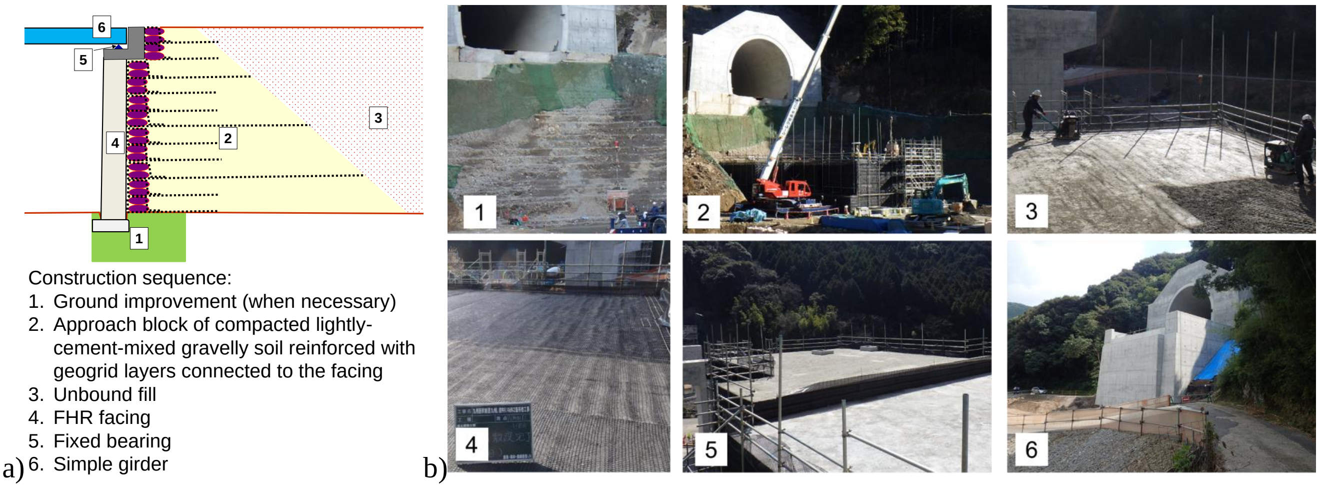


Figure 6. GRS bridge abutment: a) structure; and b) construction on a slope at Sugamuta viaduct.

After the first prototype was constructed in 2002 at Takada along Kysuhu SKS Kagoshima Route (Fig. 4a) (Aoki et al., 2005), 36 have been constructed (Fig. 3a). For Nagasaki Route, in total 80 GRS bridge abutments were adopted in place of conventional type bridge abutments (Table 1b), many at tunnel entrances. The tallest one is 13.5 m-high. Fig. 6b shows a typical construction procedure: i.e., 1) the natural slope is bench-cut; 2) & 3) an approach block is constructed by compaction lightly cement-mixed gravelly soil in a lift of 15 cm confirming the compacted dry density being at least 95 % of the maximum dry density by Modified Proctor; 4) geogrid layers are arranged in the approach block; and 5) & 6) the GRS abutment is completed by constructing FHR facings on the three lateral sides of approach block.

2.4 *GRS integral bridges*

GRS bridge abutment still uses bearings to support a simple girder. However, bearings are costly for installing and long-term maintenance while vulnerable to seismic loads often inducing dislodging of the girder. To alleviate these problems, GRS integral bridge (Fig. 7a) was developed (Tatsuoka et al., 2009, 2016; Koda et al., 2013, 2018). By integrating both ends of a simple girder to the top ends of a pair of FHR facing, the girder and facings become more slender while more stable than a simple-girder bridge comprising GRS bridge abutments. As listed in Table 2a, the first prototype was constructed in 2012 for Hokkaido SKS, followed by three for Sanriku Railway constructed in 2014 replacing three simple girder bridges that totally collapsed by tsunami of the 2011 Great East Japan Earthquake (Fig. 7b).

a)  b)

Figure 7. GRS integral bridge: a) structure & construction; and b) Haipe-sawa bridge, 60 m-long, Sanriku Railway.

Table 2. GRS integral bridges; a) previous major projects (see Fig. 3a); and b) projects for Nagasaki Route

Railway	Bridge name	Span	Girder structure	Note
Hokkaido SKS, between Shin-Aomori & Shin-HakodateHokuto stations	Tyugakkousen Overbridge (at Kikonai)	12.00m	RC slab	First prototype
Sanriku Railway (local & ordinary) between Shimanokoshi & Tanohata stations	Matsumaegawa Bridge	27.40m (13.7m+13.7m)	RC slab	Continuous girder with two spans
	Koikorobesawa Bridge	39.86m (19.93m+19.93m)	RC slab	
	Haipesawa Bridge	60.00m (32.16m+27.84m)	SRC* through girder	

a) * Steel-framed steel-reinforced concrete

Location	Bridge name	Span	Girder structure
Between Takeo-Onsen & Ureshino-Onsen stations	Momoki No.1 O.B.+	12.00 m	RC slab
	Tsubakihara O.B.	10.00 m	
Between Ureshino-Onsen & Shin-Omura stations.	Onibashi No.1 O.B. (for a line to Omura General Rolling)	10.10 m	
Between Isahaya & Nagasaki stations	Genshu O.B.*	30.00 m	Pretentioned PC T-shaped main girders
	Genshu Bridge	20.00 m	RC slab
	Kaizu Bridge	15.00 m	
	Funaishi No.4 O.B.	15.00 m	

b) +: ober-bridge; * explained in details in this paper.

For Nagasaki Route, in total seven were adopted (Table 2b), most for spanning over a valley between adjacent tunnel entrances. The over bridge at Genshu (Fig. 8) has the longest span, 30 m, among these seven. The bridge comprises four pre-stressed concrete (PC) girders produced, post-tensioned on site and placed on the top ends of the two FHR facings by means a crane. A pair of trapezoidal approach blocks of geogrid-reinforced lightly cement-mixed gravelly soil were designed to be symmetric for simple analysis of in-deterministic forces induced by residual deformation of the girder. The span of Genshu over-bridge, 30 m, exceeds the cost-effectively applicable limit of steel-reinforced-concrete (RC) girders for GRS integral bridges. Among relevant structure types for Genshu Bridge, PC girders are less costly than steel-framed steel-reinforced concrete (SRC) girders (used for Haipesawa bridge, Fig. 7b), therefore it is expected that PC girders are frequently used for GRS integral bridges in the future. However, unlike RC or SRC girders, changes in the steel reinforcement forces (i.e., prestress) in the PC girder due to seasonal thermal expansion and contraction, drying shrinkage and creep deformation by prestress of the concrete of the girder (Fig. 9). In this respect, contraction of the girder concrete after girder/facing integration should be minimized to restrain the development of tension cracks in the bottom side of the girders. These factors were carefully taken into account in design so that they do not become significant with this relatively long-span bridge. In addition, to minimize the compressive creep deformation that would take place after the girder/facing integration, concrete was made strong enough and initial creep deformation by prestress was allowed to take place sufficiently by curing for a period of 1 month after their production on site until the integration.[下線の部分を正確に書くために、①コンクリートの打ち込み（この日時が知りたい）、②Prestressの導入(11/18), ③桁設置(12/14)、④桁と壁面工の構造的接合(2/6)、のそれぞれ工程の間の経過時間を教えて頂けませんか？] On the other hand, it was not necessary to take into account the effects of residual displacement of the approach blocks on the prestress in the girders (i.e., factor 1 in Fig. 9), as they are constructed on rock foundation.

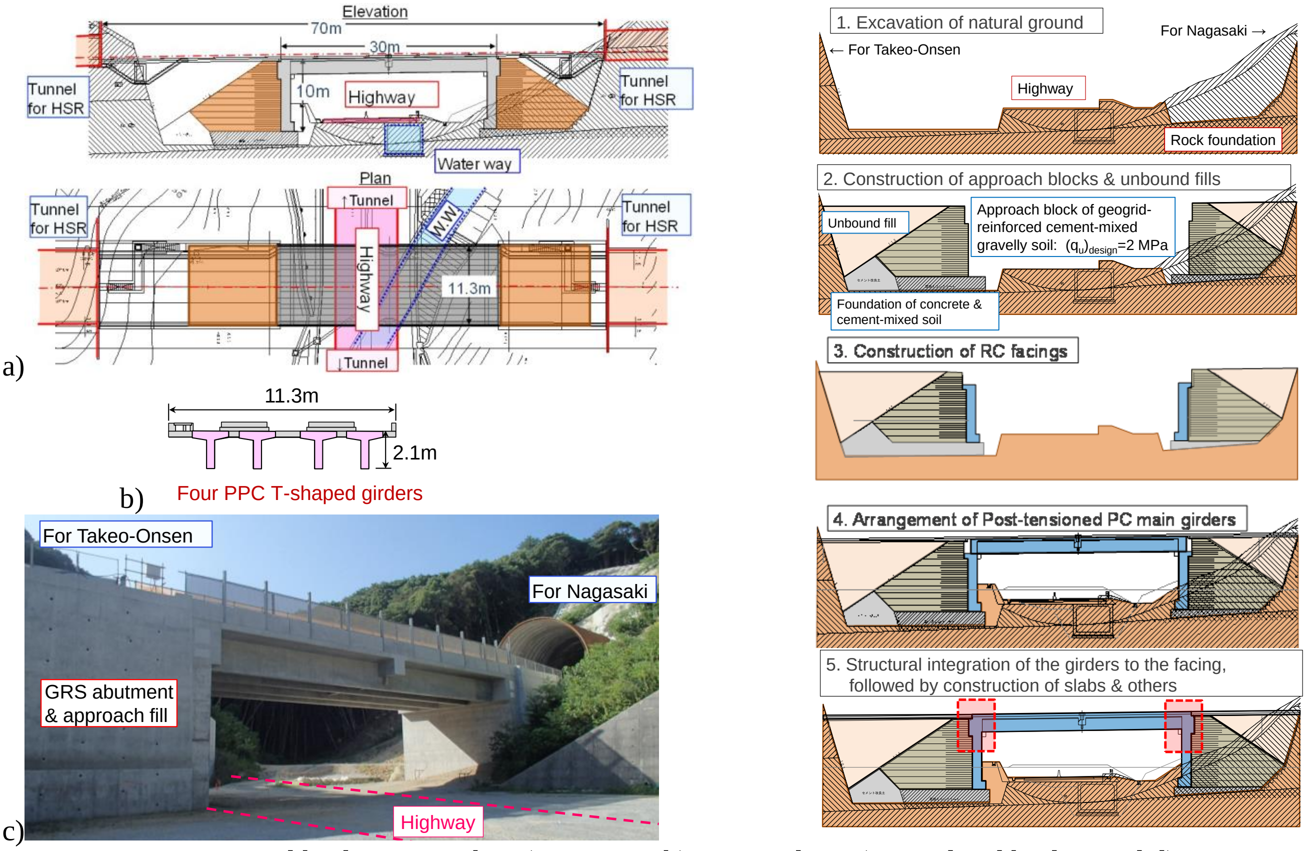


Figure 8. GRS integral bridge at Genshu: a) structure; b) PPC girders; c) completed bridge; and d) construction.

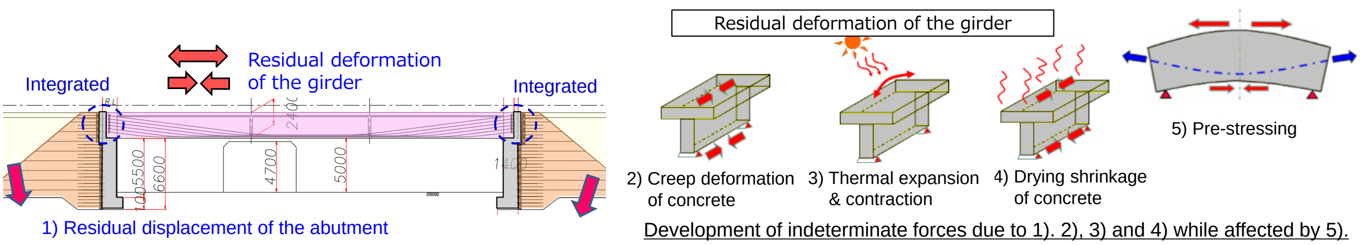


Figure 9. Several potential problems with long span GRS integral bridges.

Referring to Fig. 2, gravel bags are arranged at the shoulder of each soil layer of GRS RW: 1) to keep the wall stable during fill compaction and a subsequent period until the construction of FHR facing; 2) to function as a drain for a completed wall in service; and 3) to act as a buffer that absorbs relative displacements between the facing and the backfill, particularly during earthquakes. With GRS integral bridges, this buffer zone comprising unbound gravel should absorb frequent relative displacements between the FHR facing and the approach blocks comprising cement-mixed gravelly soil caused by seasonal thermal girder deformation (factor 3 in Fig. 9) in addition to large ones by severe seismic loads. These factors becomes more significant as the span increases. With long GRS integral bridges at Koikorobe-sawa and Haipe-sawa (40 m and 60 m, Table 2a), this buffer zone was made 1.0 m-wide (Fig. 10), wider than 30 cm-wide unbound gravel-filled bags for ordinary GRS RWs and 40 cm-wide buffers for shorter GRS integral bridges. As seen from Fig. 10, the buffer zone comprises 70 cm-wide welded metal wire mesh boxes, used in place of geogrid bags to reduce construction time, and a 30 cm-wide free zone of unbound gravelly soil. The acceptable performance of this buffer zone against frequent or large relative displacements was confirmed by performing full-scale cyclic loading tests (Tatsuoka et al., 2016; Koda et al., 2017, 2018). This buffer zone (Fig. 10) was also adopted for Genshu Bridge with a relatively long span, 30 m. The performance of Genshu Bridge has been monitored since the start of construction to confirm the relevance of the design and construction procedures employed.

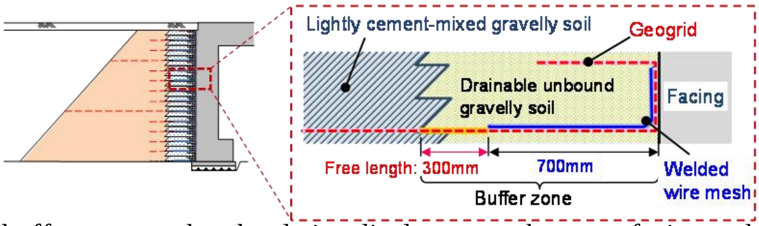


Figure 10. A wide buffer zone to absorb relative displacements between facing and approach block.

2.5 *GRS tunnel entrance protections*

At a tunnel entrance for a railway, particularly for a HSR, a relevant structure is necessary: 1) to protect the end section of the tunnel lining; 2) to stabilize the natural slope immediate above the tunnel entrance; and 3) to protect trains against falling rocks and sliding soil masses, in particular against those by severe seismic loads and heavy rains. For Nagasaki Route, this type of structure became necessary at many sites, 62 in total. With the conventional type, however, as shown in Fig. 11, the front RC facing is a complicated cantilever structure integrated to the end of tunnel lining while supporting unbound fill covering the end tunnel section extruded from the slope. Moreover, the soil filling work in narrow zones surrounded by the curved tunnel lining, the facing and the slopes is difficult. Besides, a number of this conventional type structure were damaged by previous earthquakes.

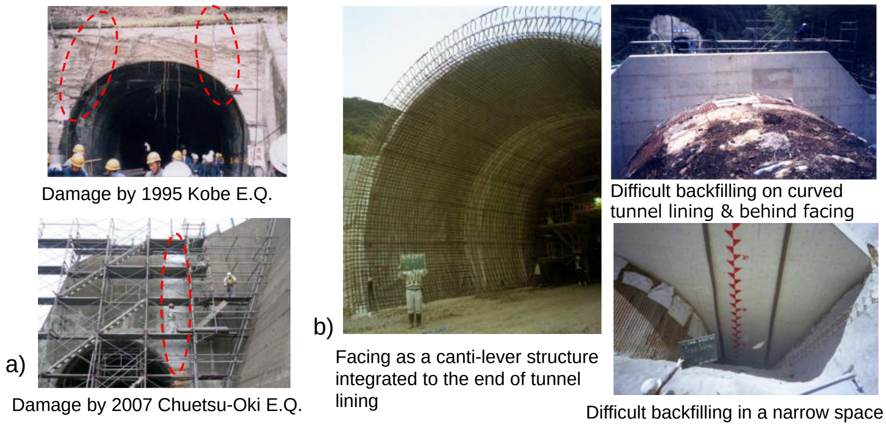
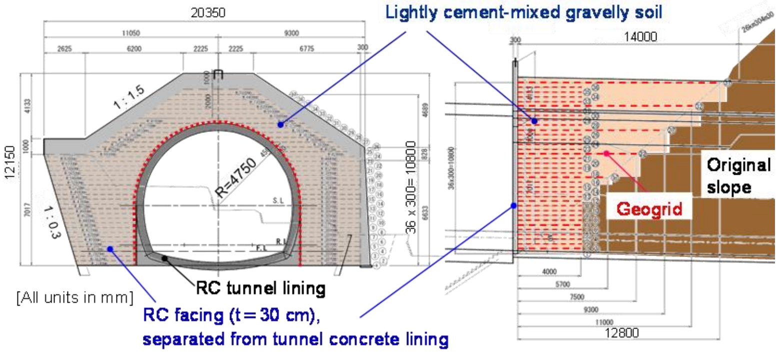


Figure 11. Conventional type tunnel entrance protection: a) seismic damage; and b) technical problems

To alleviate these problems with the conventional type, GRS tunnel entrance protection has been developed (Fig. 12a) and adopted at 55 sites (i.e., 90 % of all the sites) of Nagasaki Route (Table 1b). As shown in Fig. 12b, after the natural slope at the tunnel entrance is bench-cut from the top, the tunnel lining section extruded from the slope is constructed in open-air, which is then covered by geogrid-reinforced compacted lightly cement-mixed soil. The stiffness of the fill soil is designed to be slightly lower than the natural slope in such that the lateral earth pressure acting on the tunnel becomes about 10 % of the final over-burden pressure {OK?}. Fig. 12b-3 shows the front view during construction. The structure is completed by constructing a front FHR facing by casting-in-place fresh concrete in such that the facing is structurally integrated to the geogrid-reinforced fill while structurally separated from the tunnel lining so that the tunnel lining is not damaged by interactions with the side GRS walls. Fig. 13 shows a special case where a GRS tunnel entrance protection and a GRS bridge abutment constructed consecutively were designed to function as counter weight to prevent slide in the nearby slope.

3 SUMMARY

High cost-effectiveness and high performance of various type GRS structures (i.e., retaining wall, bridge abutment, integral bridge and tunnel entrance protection) compared with conventional type structures has been validated by their high performance. These GRS structures are now the standard soil structures for high speed railways (HSRs), as well as ordinary railways, constructed basically in place of conventional type soil structures. A large number of these GRS structures were adopted for a new HSR, Kyushu SKS Nagasaki Route, most densely ever for railways. Many of them are constructed at entrances of many short tunnels constructed at raised elevations to protect the aquatic environment in the adjacent mountain areas. One of the challenging GRS structures is a GRS integral bridge comprising 30 m-long PC girders.



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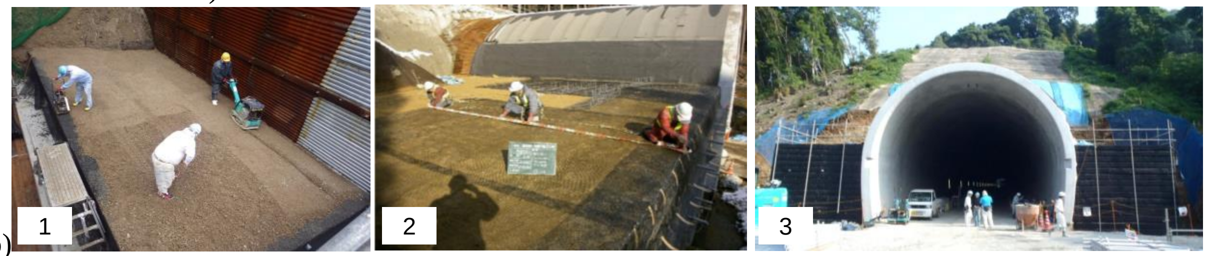

b)

Figure 12. GRS tunnel entrance protection: a) structure: b) construction, Shiozuru tunnel, Nagasaki Pref.

Figure 13. GRS tunnel entrance protection and GRS bridge abutment, Tawarazaka, Nagasaki Pref. side.

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