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RRR Construction Technology Lecture
24 May 2023

Geosynthetic-Reinforced Soil Structures - Developments from Walls to Bridges -

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Abstract:

The developments of various types of geosynthetic-reinforced soil (GRS) structure with **full-height rigid (FHR) facing**, including those for High-Speed Railways, for the last about forty years are reported. Their total wall length has exceeded 200 km.

In the 1980's, GRS Retaining Wall (RW) was developed, for which, after the deformation of the backfill and subsoil by the construction of reinforced backfill has taken place, the FHR facing is constructed firmly connected to geogrid layers by casting-in-place fresh concrete directly on the geogrid-wrapped-around wall face. In the early 1990's, **GRS Bridge Abutment** was developed, for which a simple girder is supported by fixed & movable bearings at the top of FHR facing. In total 185 have been constructed. Then, **GRS Integral Bridge** was developed, for which both ends of a continuous girder are integrated to the top of FHR facing. 14 have been constructed. A number of embankments and conventional type RWs & bridges that collapsed by severe earthquakes, floods, tsunamis etc. were restored to these GRS structures with FHR facing.

All these GRS structures have been performing very well without exhibiting any problem during and after construction, while a very high cost-effectiveness has been validated.

Acknowledgements

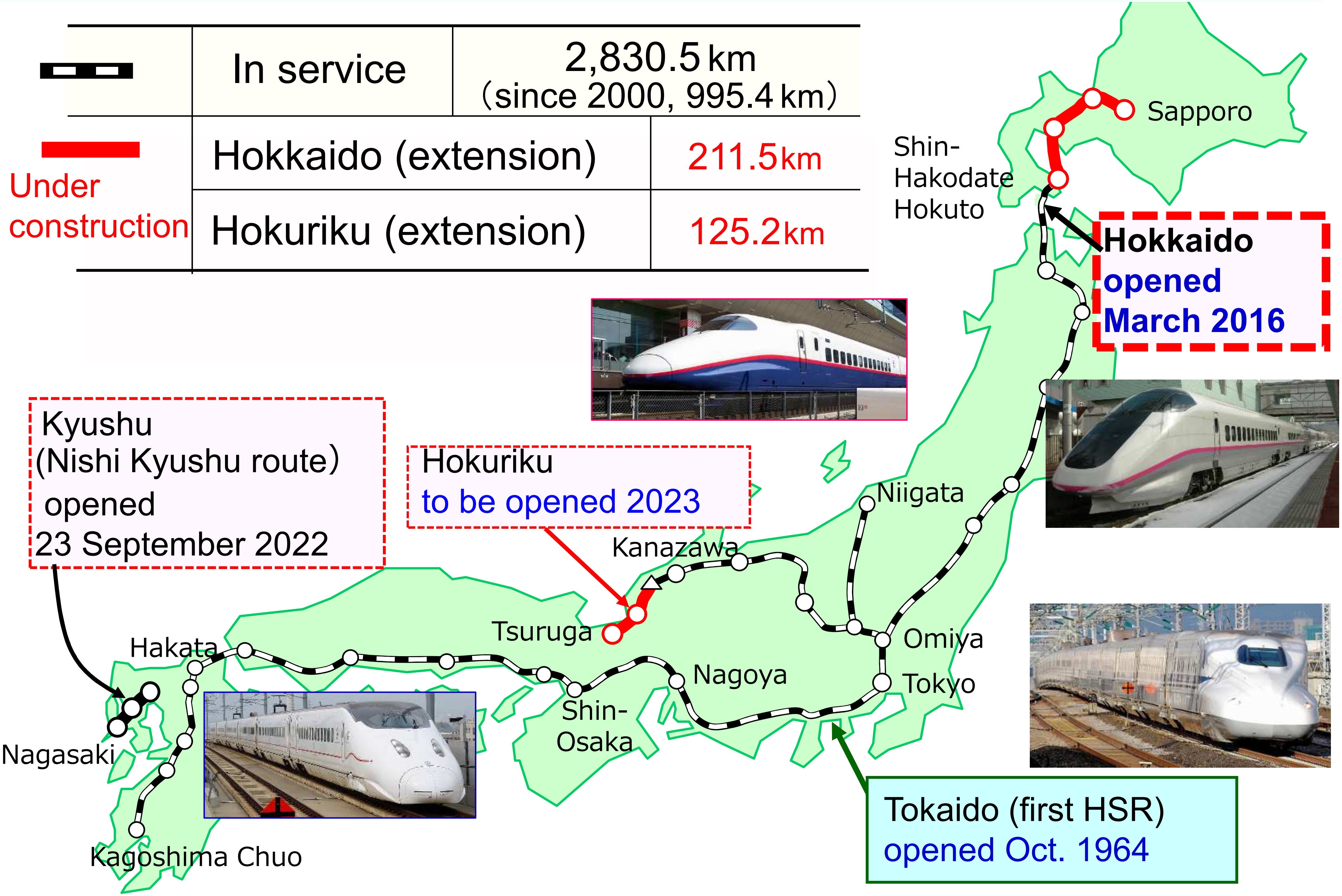
Sincere appreciation for great contributions of many colleagues, students, researchers and engineers who jointed this very long-term research project at:

University of Tokyo,
Tokyo University of Science,
Railway Technical Research Institute, Japan,
Japan Railway Construction, Transport and Technology Agency,
a number of railway companies,
Integrated Geotechnology Institute Ltd.,
RRR Construction Technology Association, and
many other consulting and construction companies.

Contents

High-Speed Railways (Shinkansen), 2022

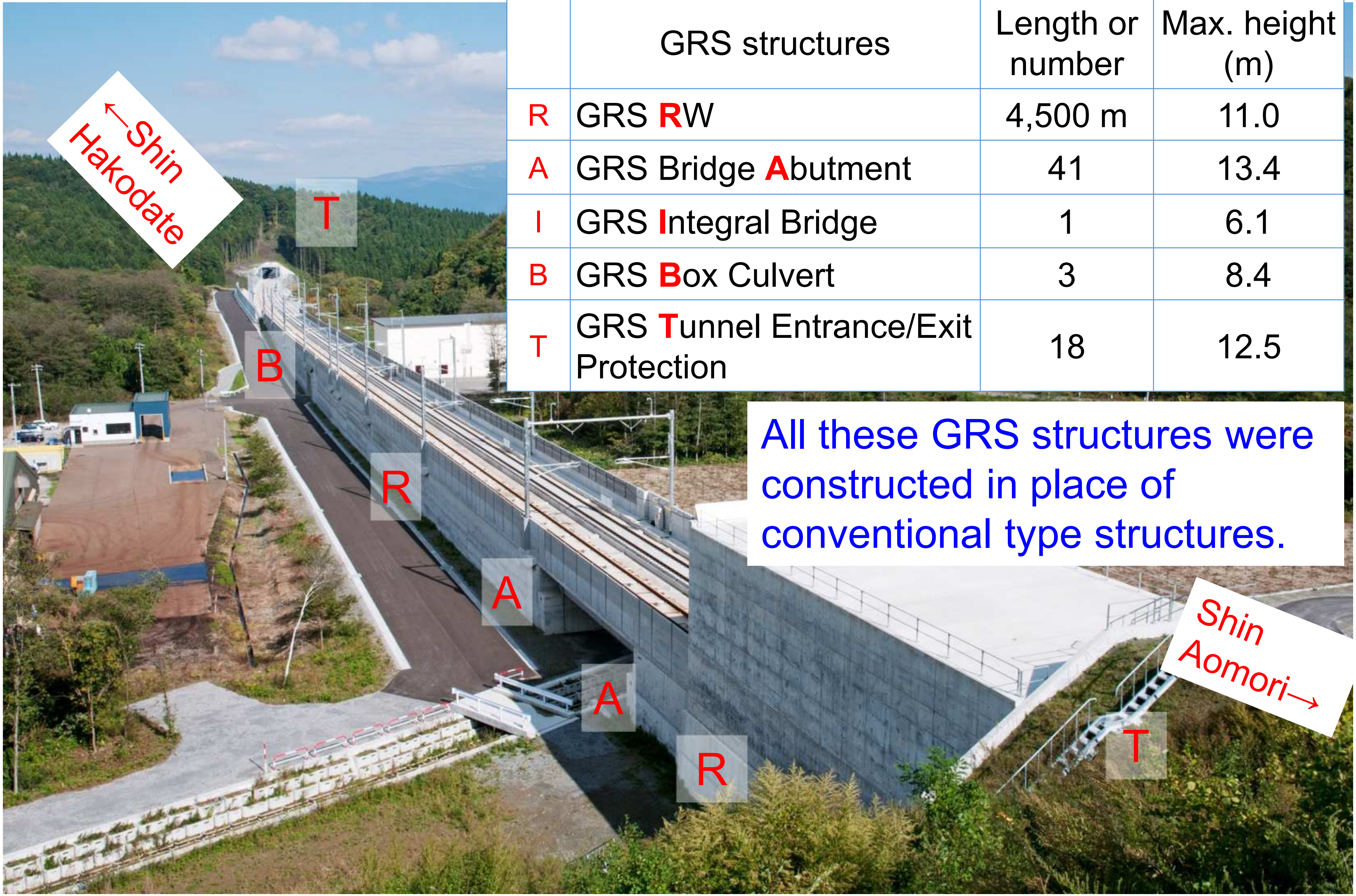
	In service	2,830.5 km (since 2000, 995.4 km)
Under construction	Hokkaido (extension)	211.5km
	Hokuriku (extension)	125.2km



Mantaro site

Hokkaido Shinkansen (High Speed Railway)

	GRS structures	Length or number	Max. height (m)
R	GRS **R**W	4,500 m	11.0
A	GRS Bridge **A**butment	41	13.4
I	GRS **I**ntegral Bridge	1	6.1
B	GRS **B**ox Culvert	3	8.4
T	GRS **T**unnel Entrance/Exit Protection	18	12.5

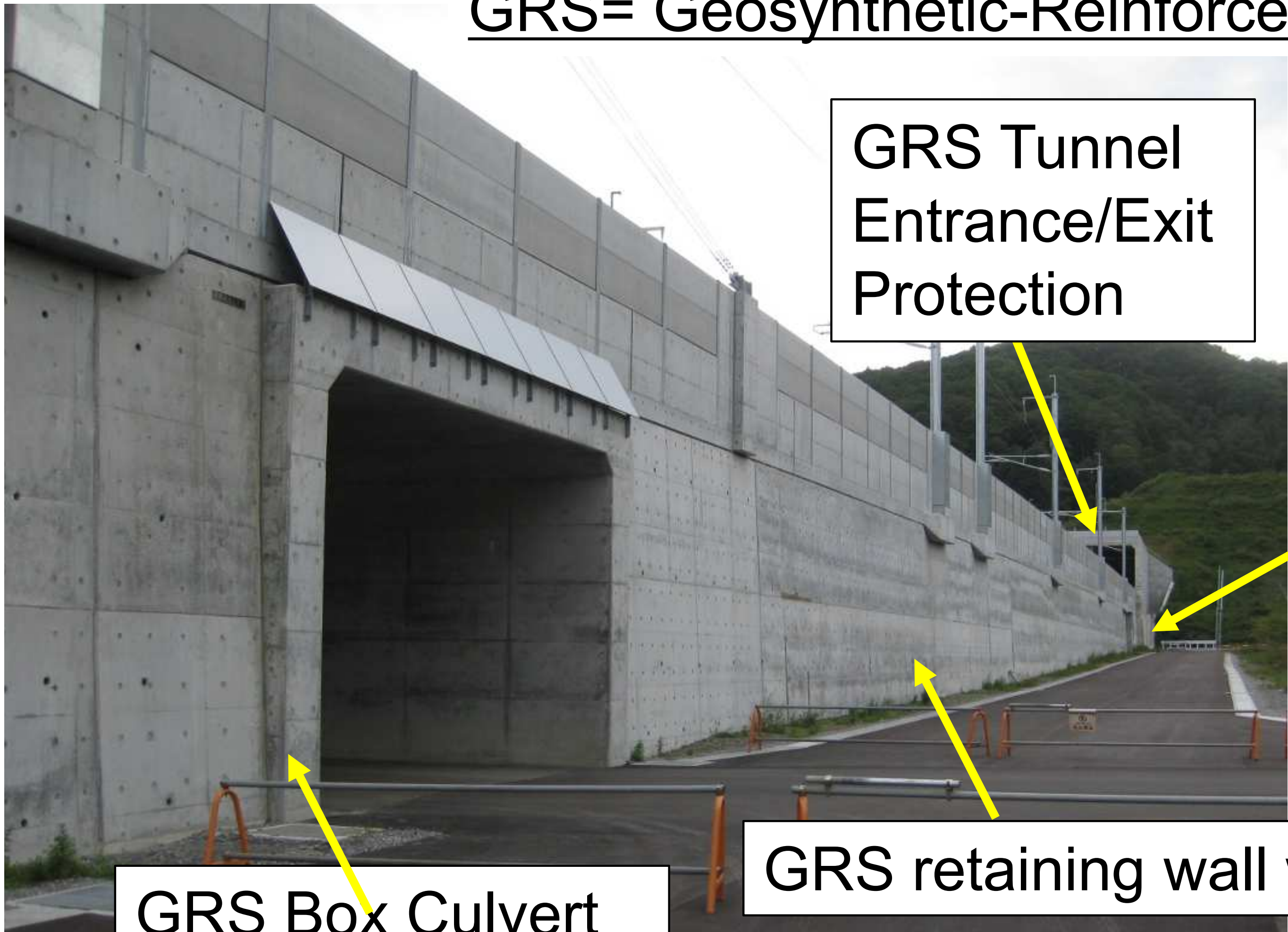


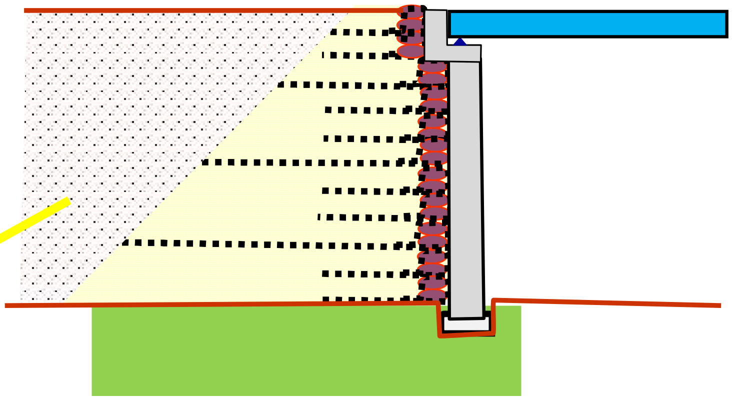
All these GRS structures were constructed in place of conventional type structures.

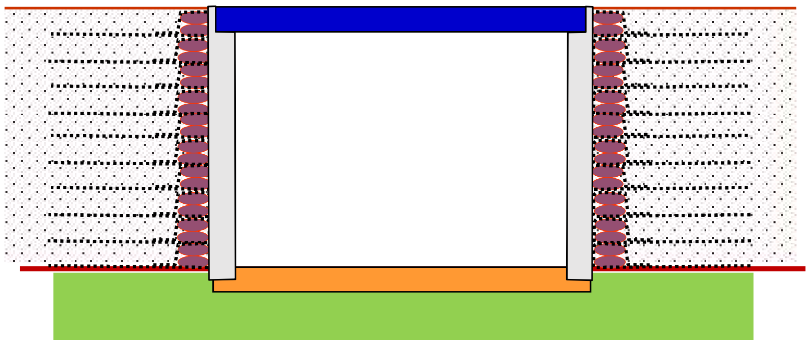
Yonezawa et al. (2014): JRTT

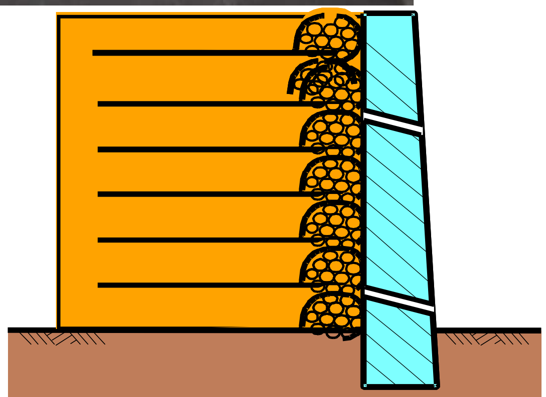
Mantaro site, Hokkaido Shinkansen

GRS= Geosynthetic-Reinforced Soil

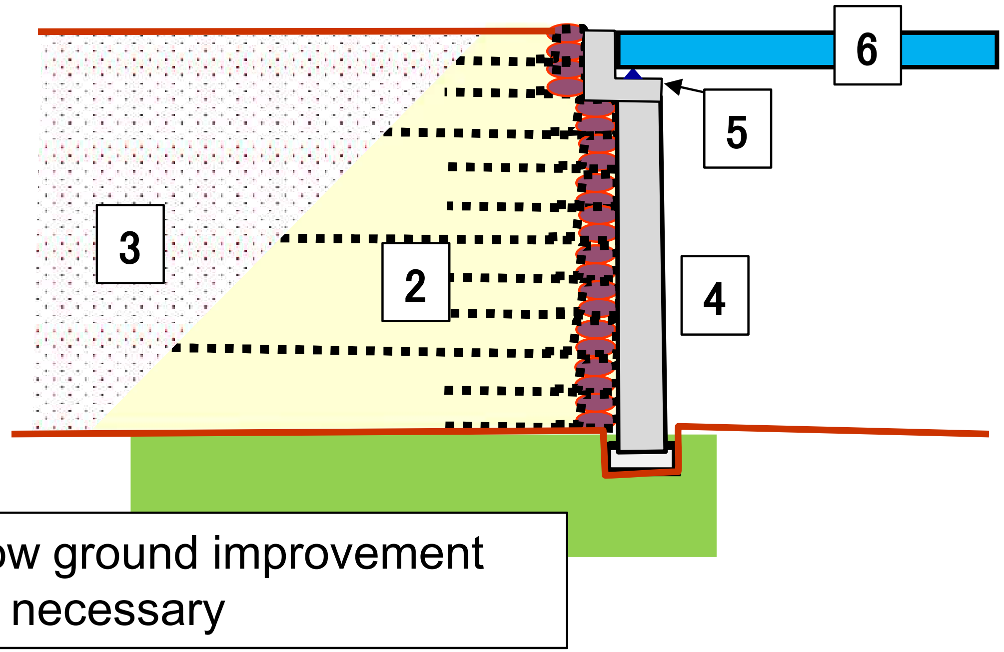








GRS Bridge Abutment



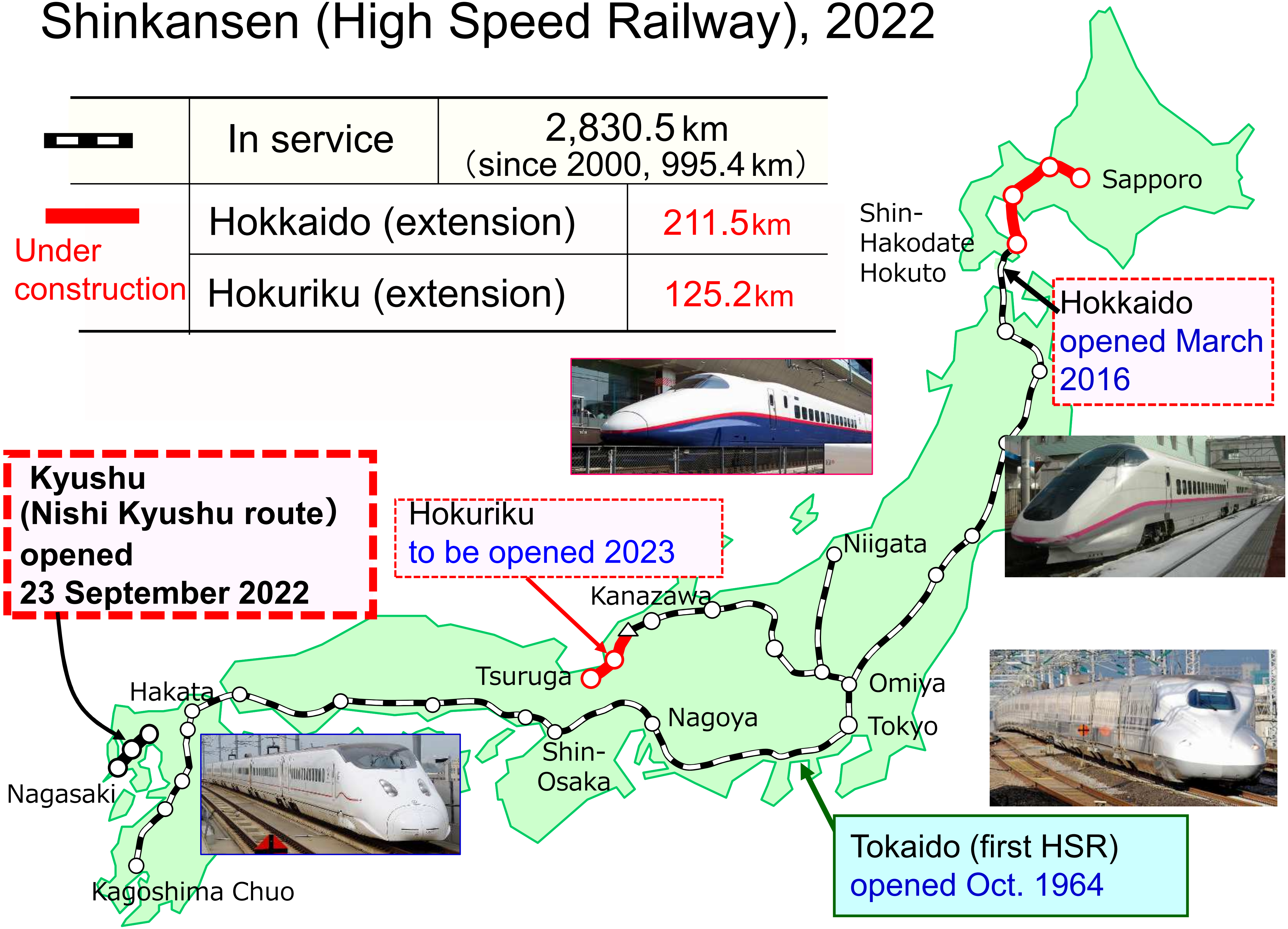
13.4 m-high, Mantaro site

Under construction
Oct. 2011

Completed
Aug. 2012

Shinkansen (High Speed Railway), 2022

	In service	2,830.5 km (since 2000, 995.4 km)
Under construction	Hokkaido (extension)	211.5km
	Hokuriku (extension)	125.2km



Kyushu Shinkansen, Nishi-Kyushu Route

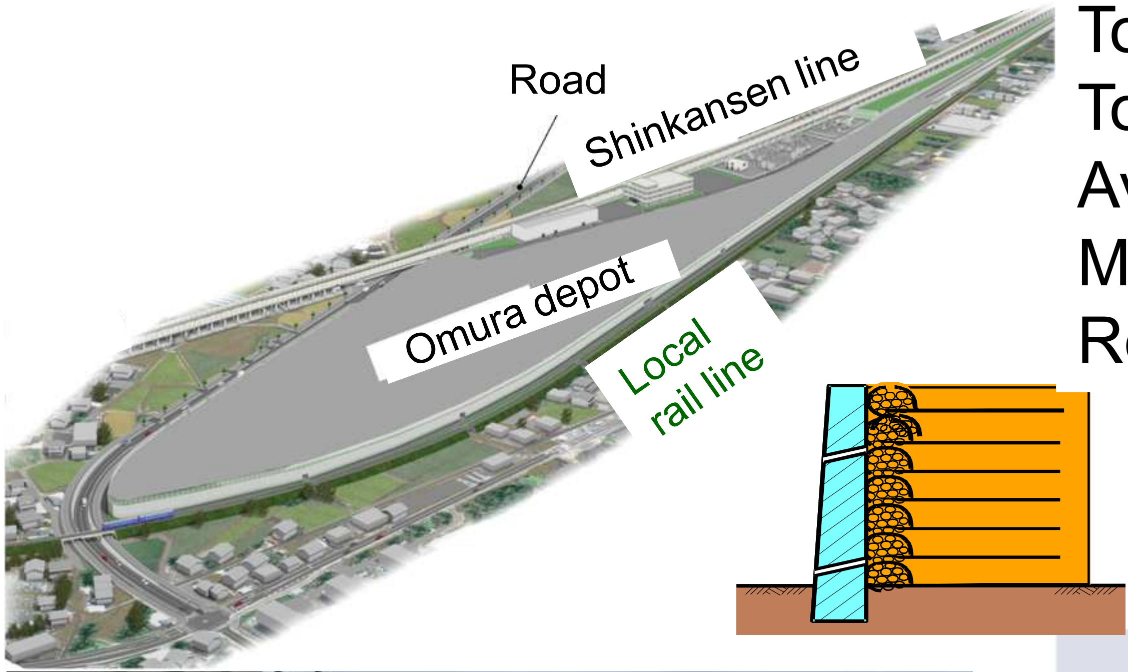
- Very dense construction of GRS structures

GRS structures	Length or number	Ratio of GRS structures to the total
GRS RW	5.1 km	
GRS Tunnel Entrance/Exit Protection	57	57/62= 92 %
GRS Bridge Abutment	**78**	**78/88= 89 %***
GRS Integral Bridge	7	

* 89 % of all the bridge abutments

Sakata (2021): JRTT

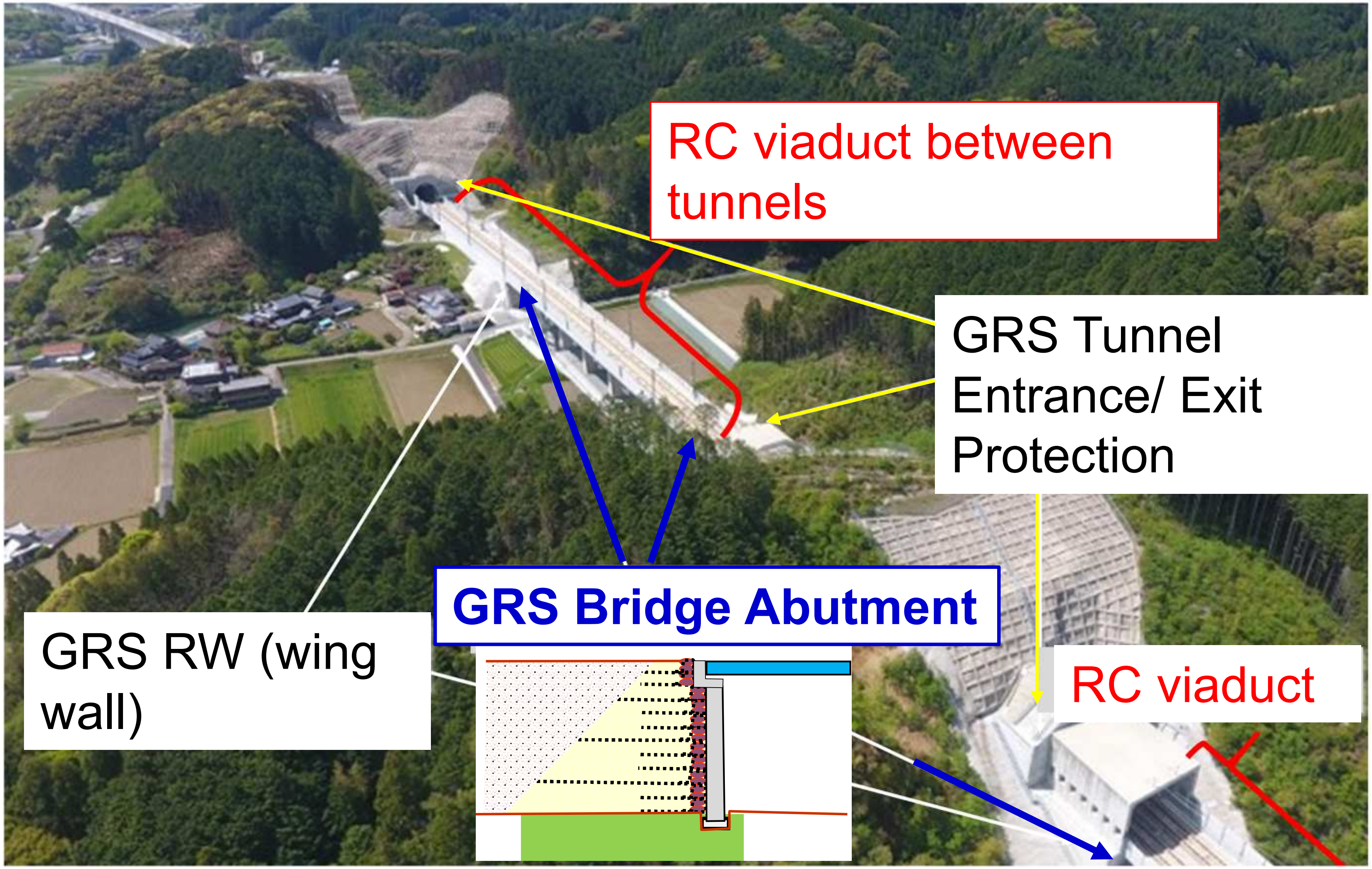
GRS RWs at Omura Depot



Total wall length: 1.7 km
Total wall area: 17,200 m^2
Average wall height: 9 m
Maximum wall height: 12.4 m
Reinforcement area: 240,000 m^2

In this route of High-Speed Railway, 88 bridge abutments were constructed at the tunnel exits.

Among them, 78 (i.e., 89 %) are GRS Bridge Abutments !



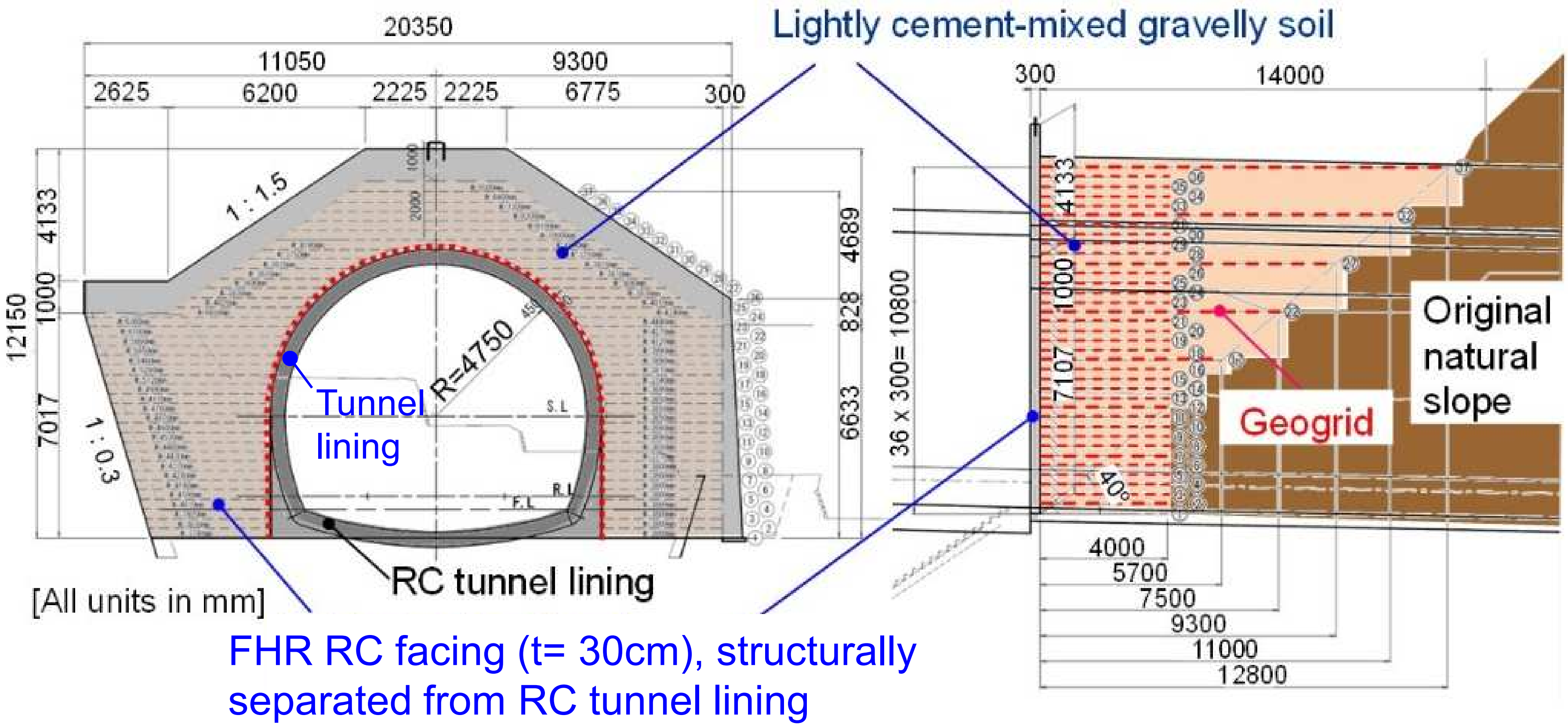
(By the courtesy of JRTT)

GRS Bridge Abutment for Sugamuta viaduct

1. Bench-cutting of stable natural slope
2. Construction of approach fill (i.e., geogrid-reinforced well-compacted lightly cement-mixed gravelly soil)
3. Compaction of the backfill (at least 95 % of $(\rho_d)_{max}$ at w_{opt} by Modified Proctor)
4. Arrangement of geogrid layer
5. Completed approach fill
6. Completed GRS Bridge Abutment after the construction of FHR facing

Soga, et al. (2018)

GRS Tunnel Entrance/Exit Protection



Compaction of the backfill

Arrangement of geogrid layer

Construction of GRS walls on both sides of a tunnel

Soga et al. (2018) & JRTT

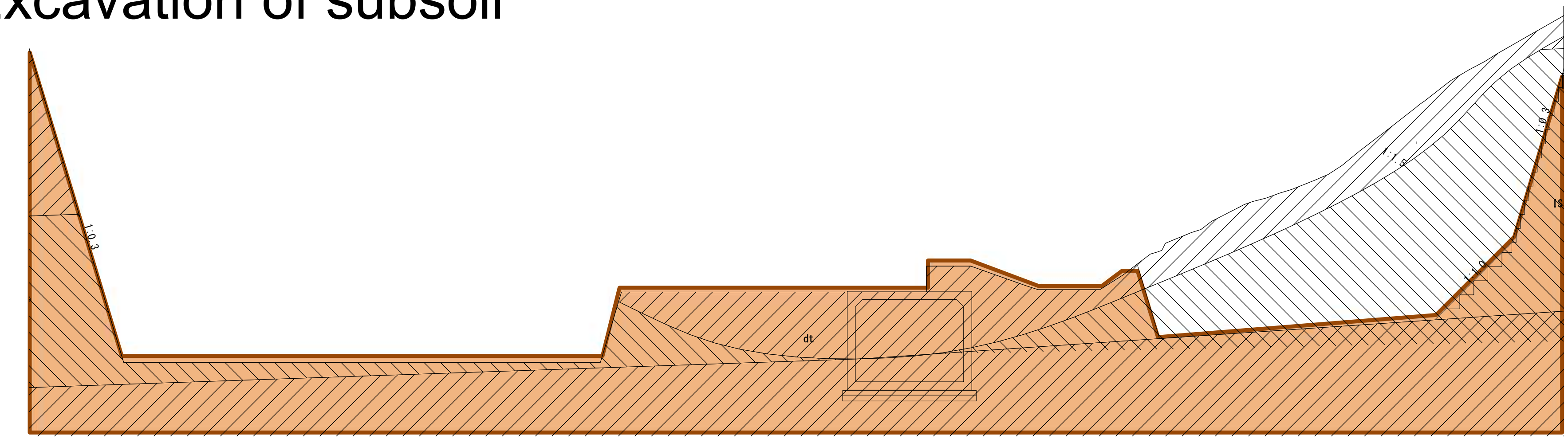
Kyushu Shinkansen, Nishi-Nihon Route, San-nose Tunnel

27 Oct. 2022


GRS Bridge
Abutment

GRS Integral Bridge at Genshu

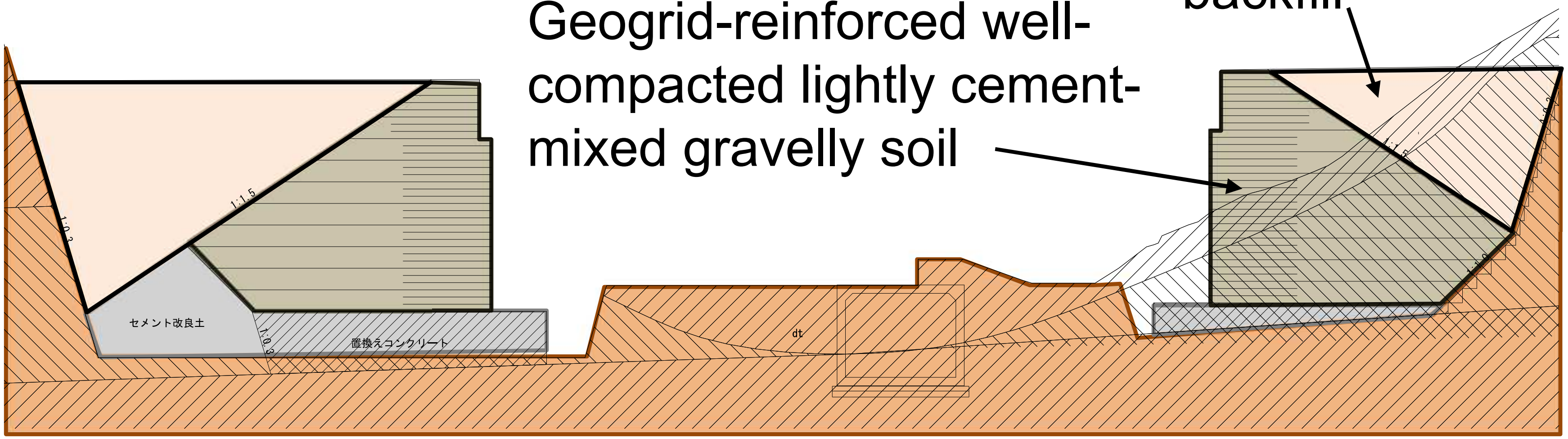
1. Excavation of subsoil



2. Construction of approach fills

Unreinforced backfill

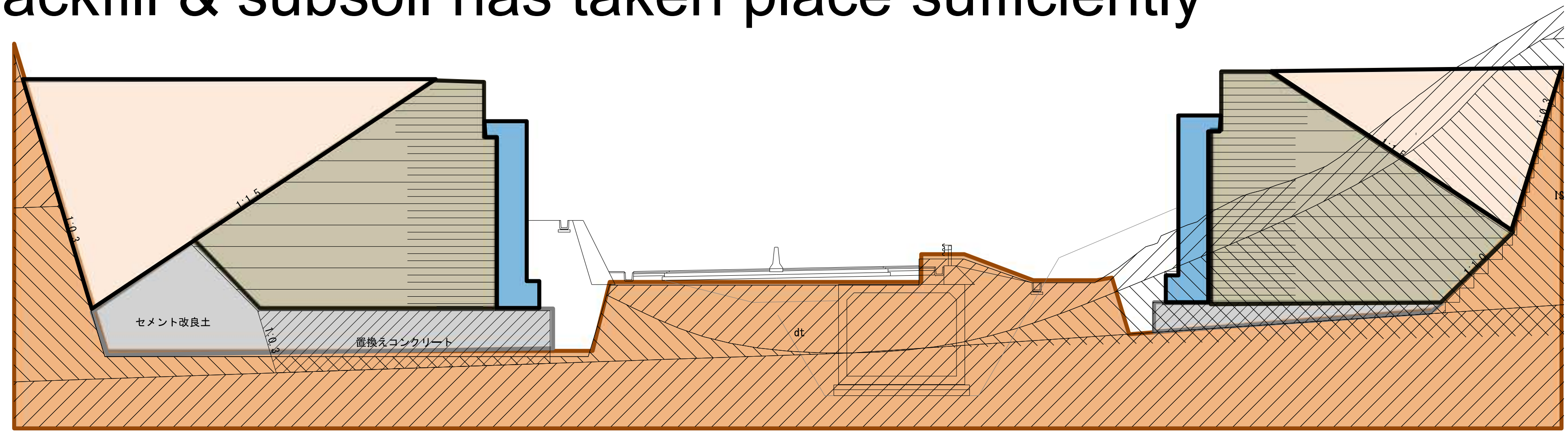
Geogrid-reinforced well-compacted lightly cement-mixed gravelly soil



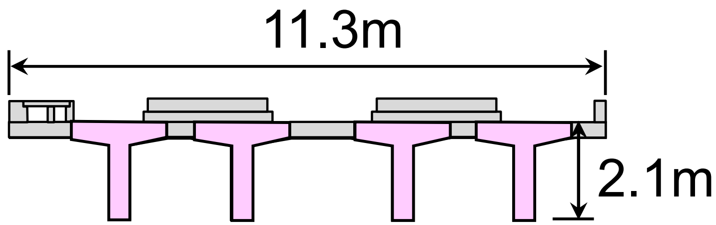
Soga et al. (2018) & JRTT

GRS Integral Bridge at Genshu

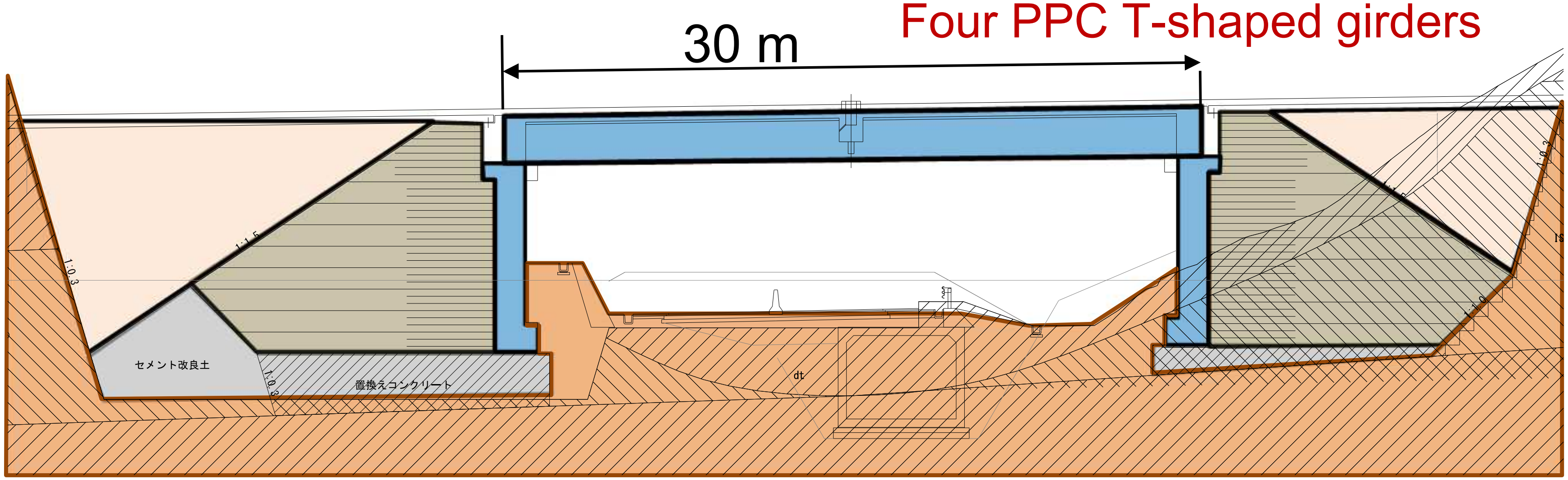
3. Construction of FHR RC facings after the deformation of the backfill & subsoil has taken place sufficiently



4. Arrangement of PC girders



Four PPC T-shaped girders

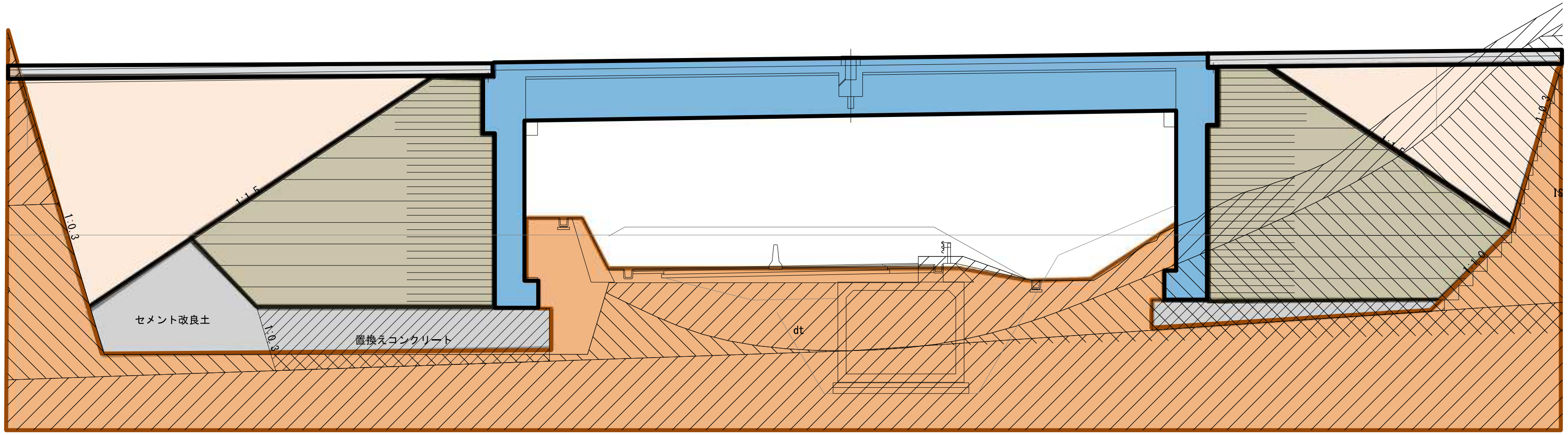


Arrangement of a 30 m-long PC girder

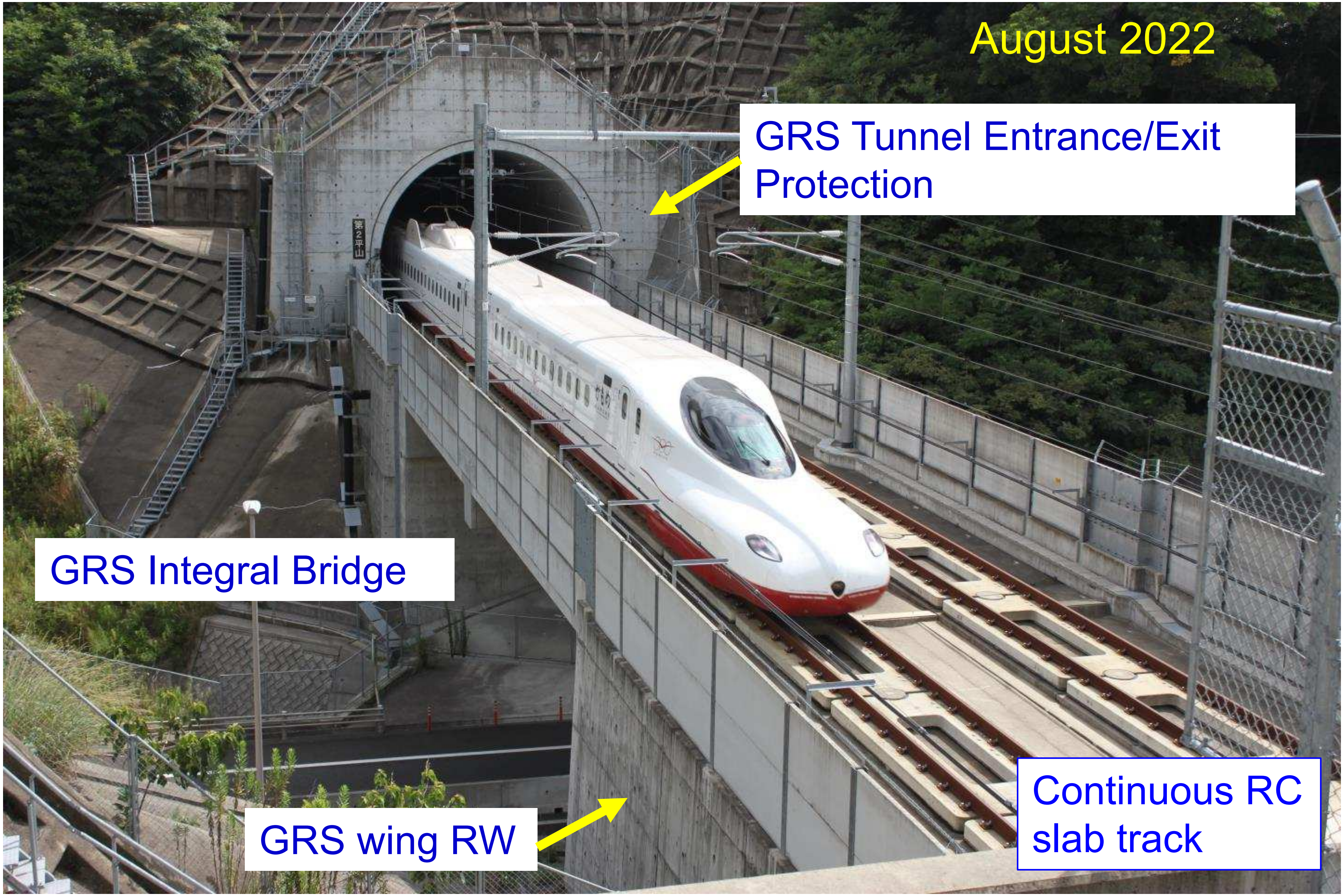
(By the courtesy of JRTT)

GRS Integral Bridge at Genshu

5. Structural integration of both ends of the girders to the FHR facings, then construction of slab & others to complete the bridge

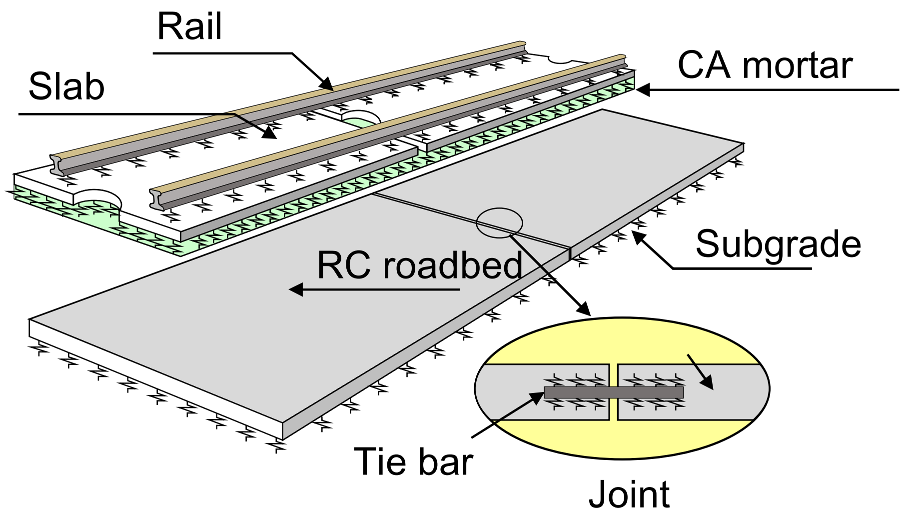


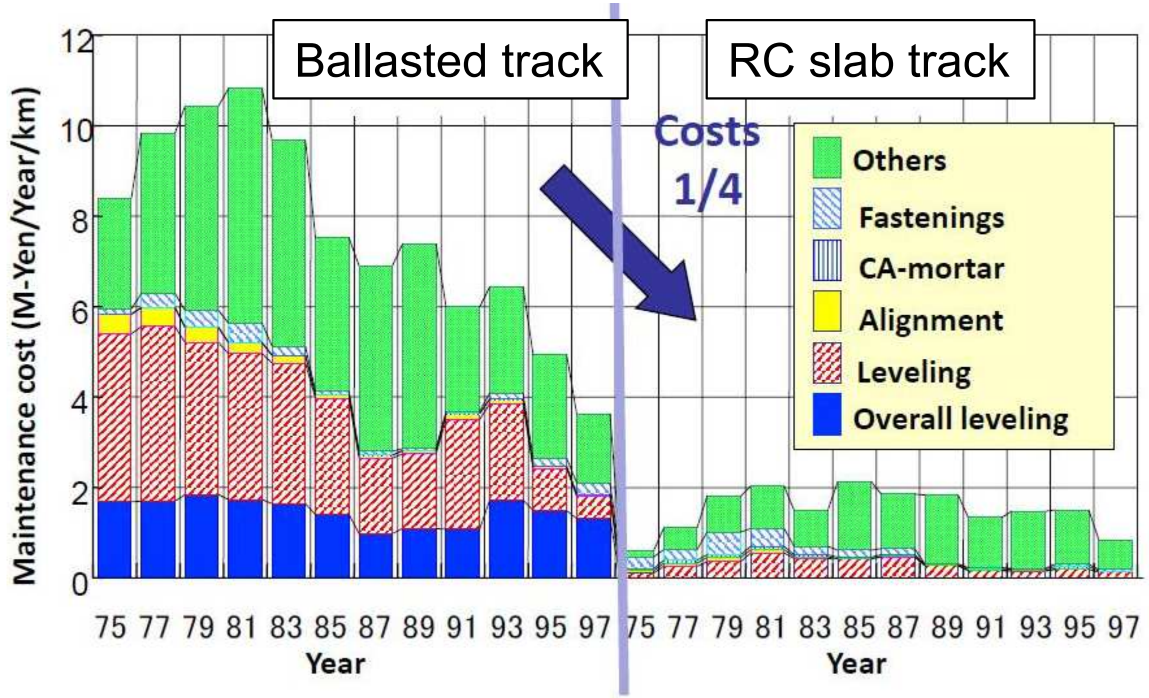
Completed GRS Integral Bridge at Genshu



By the courtesy of JRTT

Continuous RC slab track



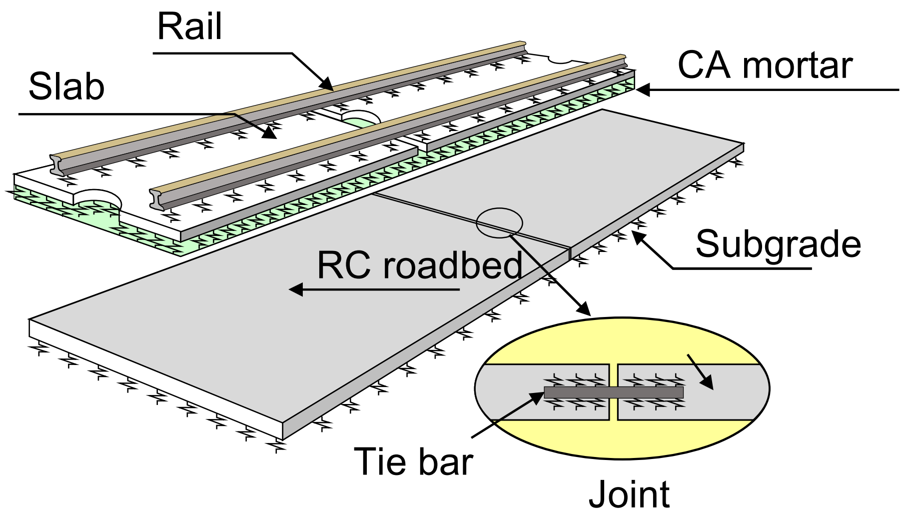


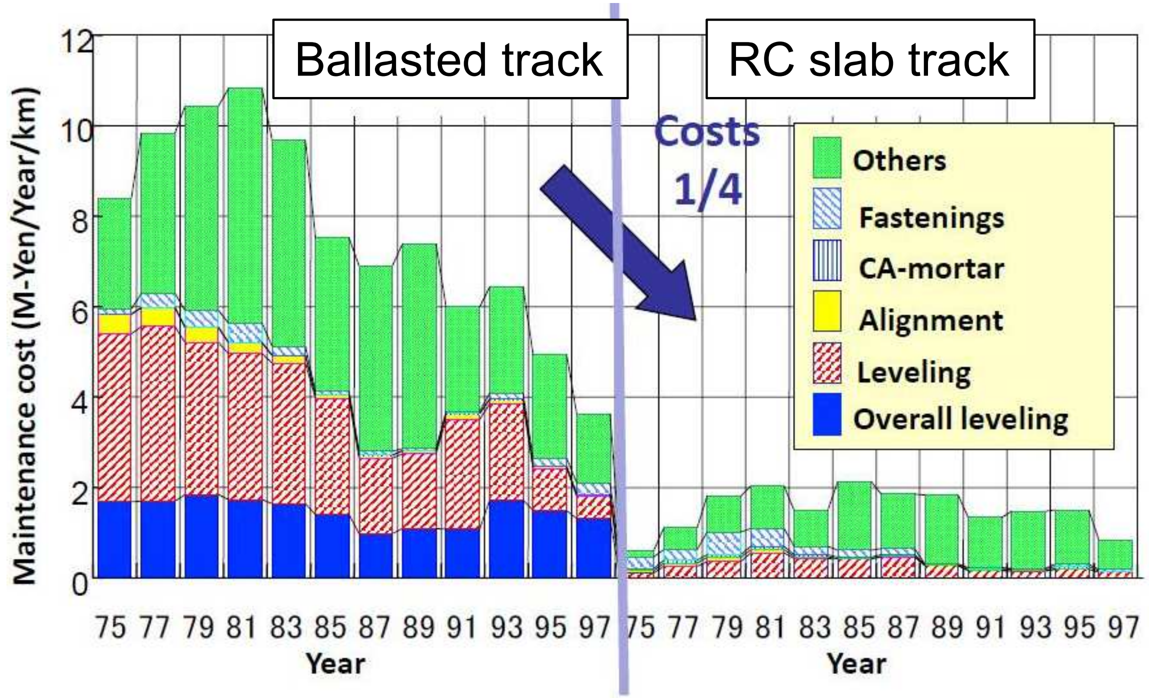
- Relatively high initial construction cost
- But, a very large reduction of maintenance cost
- And, very small allowable settlement of subsoil

10 mm/10 years (for required serviceability)
Less than 15 cm (for required restorability after a severe E.Q.)

By the courtesy of Japan Railway Construction, Transport and Technology Agency and Watanabe, K. (Univ. of Tokyo)

Continuous RC slab track

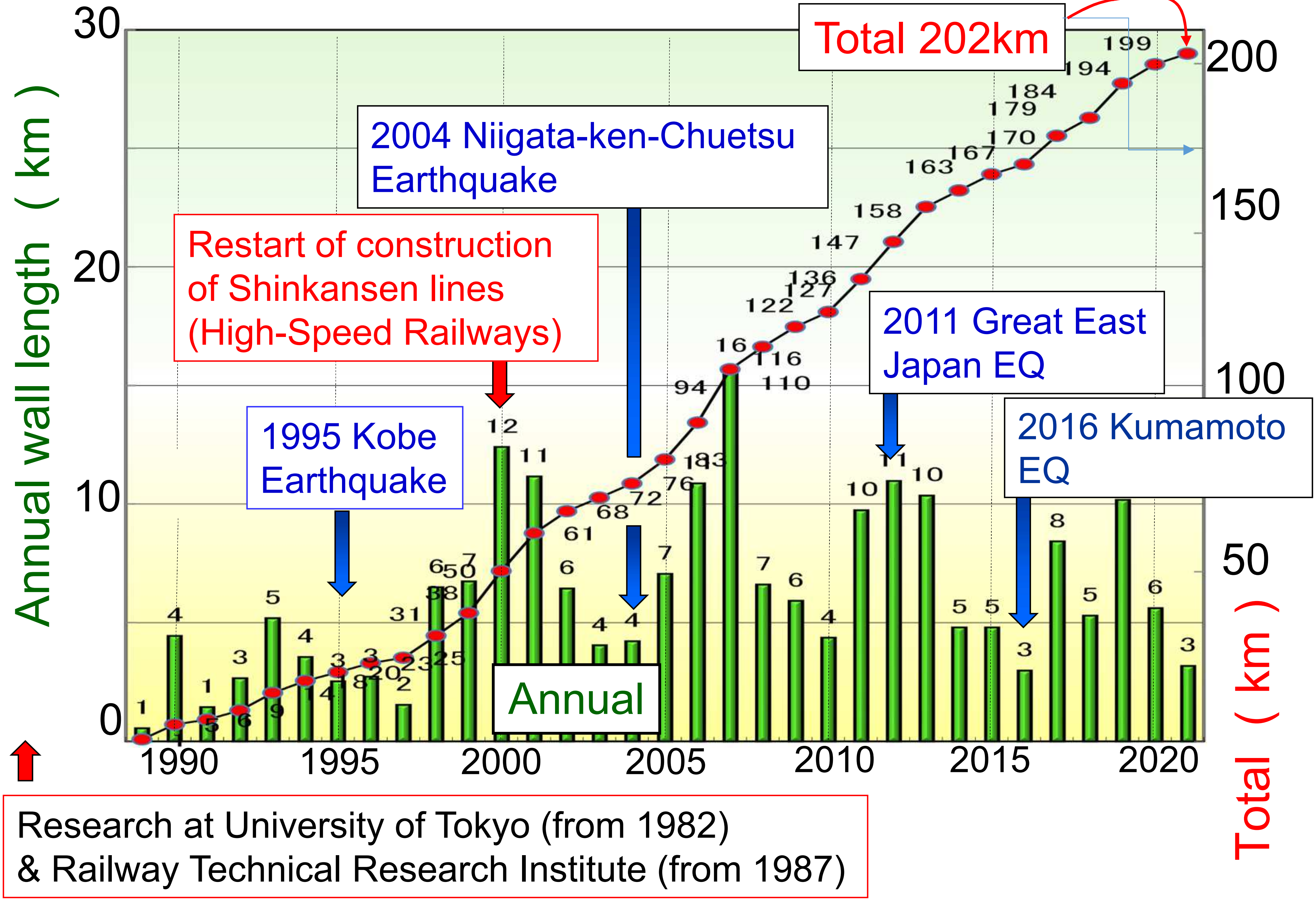




1) Not constructed on ordinary embankments & the backfill retained by conventional type RWs, because small settlement cannot be ensured.
2) Constructed on the reinforced backfill of GRS structure is the standard practice, because small settlement with high stability is ensured by good soil compaction in addition to the use of closely-spaced geosynthetic reinforcement layers with a vertical spacing of 30 cm that are firmly connected to FHR facing

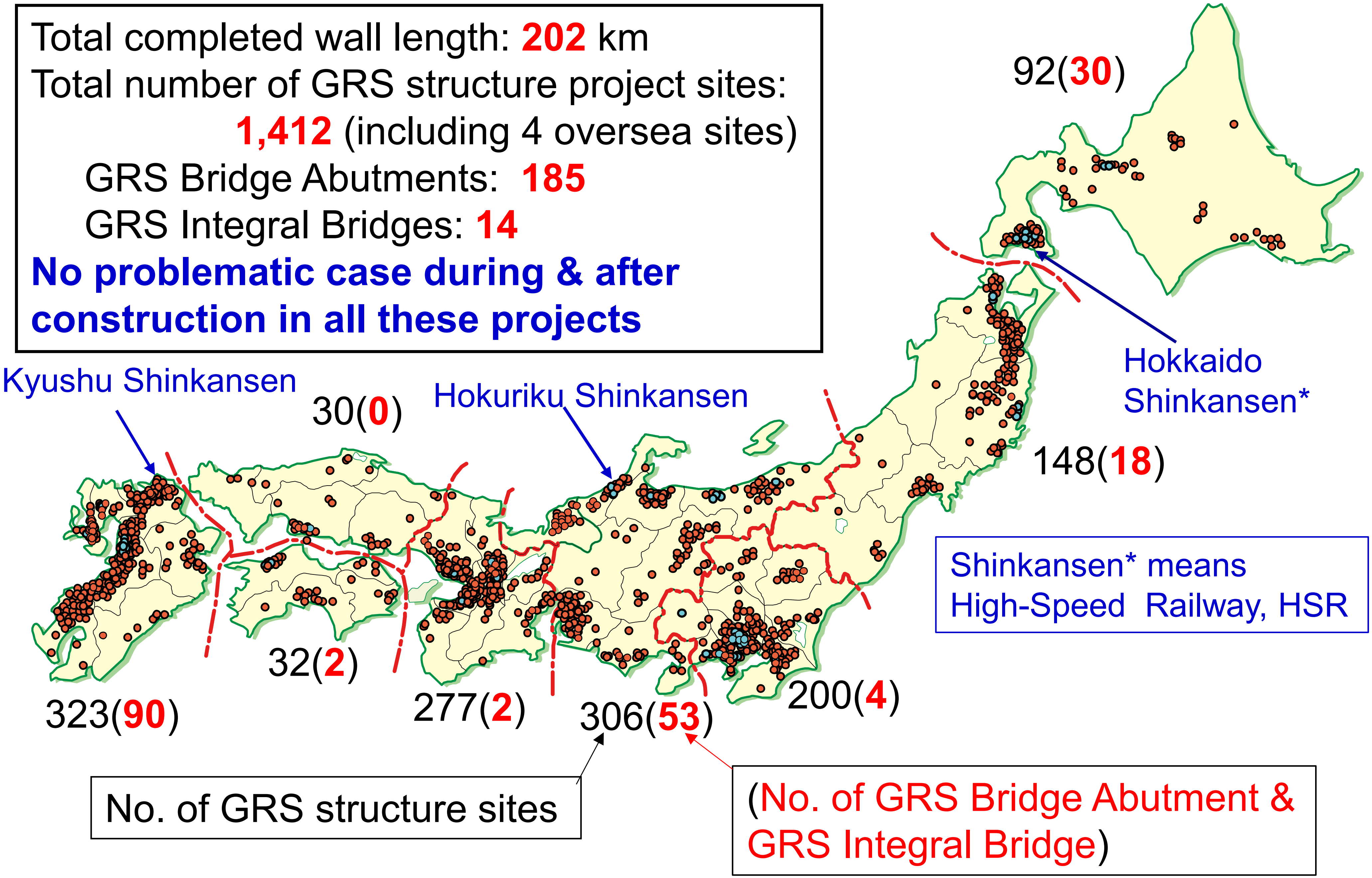
By the courtesy of Japan Railway Construction, Transport and Technology Agency and Watanabe, K. (Univ. of Tokyo)

History of GRS structures (as of April 2022)



Locations of completed GRS RWs with FHR facing, GRS Bridge Abutments, GRS Integral Bridges etc. (April 2022)

Total completed wall length: **202** km
Total number of GRS structure project sites:
1,412 (including 4 oversea sites)
GRS Bridge Abutments: **185**
GRS Integral Bridges: **14**
No problematic case during & after construction in all these projects



Summary:

A number of GRS structures with FHR facing have been constructed in place of conventional type RWs, bridge abutments & simple girder bridges. These GRS structures have become the standard railway soil structures in Japan. GRS structures were constructed also for roads and others and at several oversea sites.

This accomplishment can be attributed to that, compared with conventional type soil structures, these GRS structures exhibit:

1. higher performance
   - under long-term ordinary conditions; and
   - against severe earthquakes, heavy/prolonged rainfalls, strong floods & tsunamis; and
2. lower cost for construction & long-term maintenance.

Contents

1. Recent GRS structures for High-Speed Railways in Japan

2. **Inextensible vs. extensible reinforcement and flexible vs. stiff facing– theoretical & technical background**

3. Multiple functions of full-height rigid (FHR) facing

4. Advantages of the construction of FHR facing after the construction of reinforced backfill

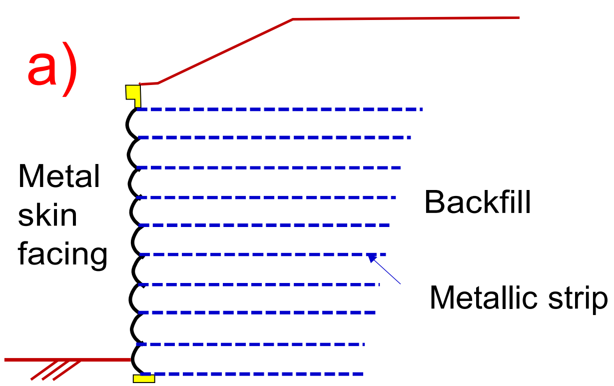
5. GRS Bridge Abutment and GRS Integral Bridge

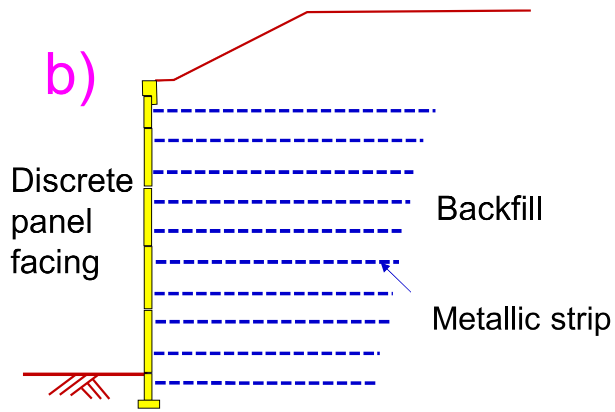
6. Restoration of soil structures that collapsed by earthquakes, floods and tsunamis to GRS structures

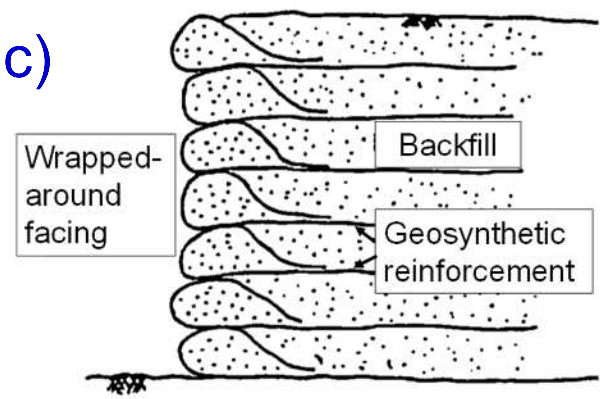
7. Concluding remarks

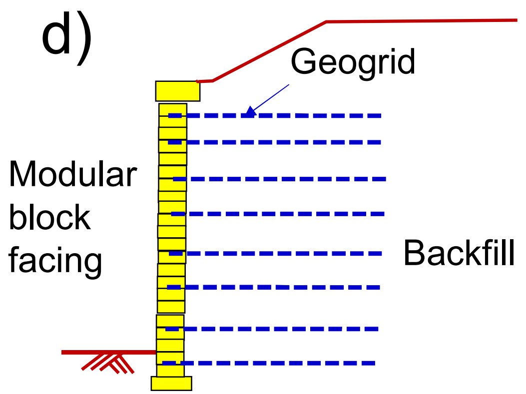
Various types of mechanically stabilized earth (MSE) RW
having different types of facing and reinforcement

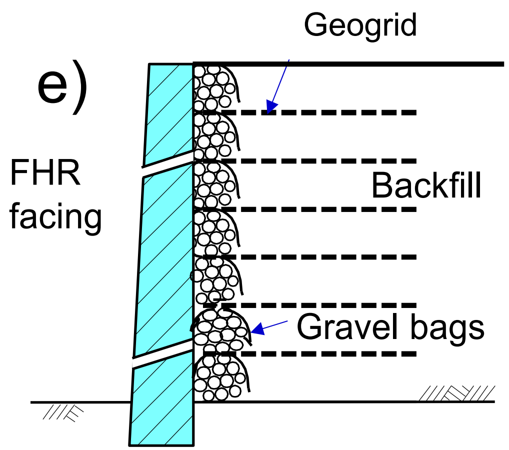
Reinforcement \ Facing	Flexible, not developing high earth pressure on the facing	Stiff, developing high earth pressure on the facing
Inextensible: e.g., metallic strip	a) Metallic skin facing	b) Discrete concrete panel facing
Extensible: typically polymeric planar geogrid	c) Wrapped-around facing	Typically, **d**) Modular block facing; & **e**) Full-height rigid (FHR) facing

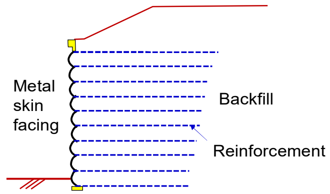
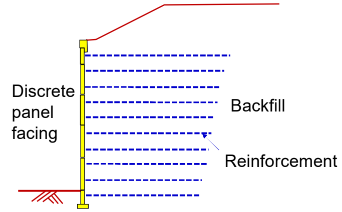
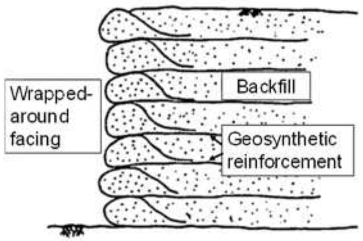
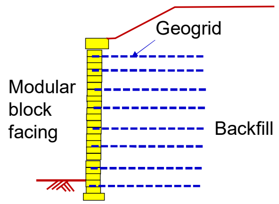
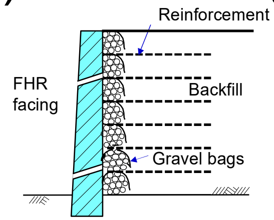






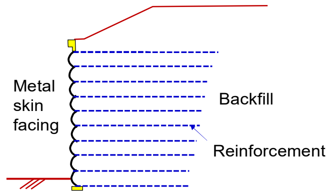
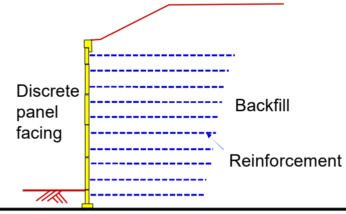




Facing / Reinforcement	Flexible, not developing high earth pressure on the facing	Stiff, developing high earth pressure on the facing
Inextensible: e.g., metallic strip	a) Metallic skin facing 	e.g., b) Discrete concrete panel facing 
Extensible: typically polymeric & planar (e.g., geogrid)	c) Wrapped-around facing 	e.g., d) Modular block facing, & e) FHR facing  

Previously, many considered that:
for small wall deformation and high wall stability:
- it is necessary to use **inextensible reinforcement, such as metallic strips (i.e., a)**.

Although metallic strips are inextensible, they have the following two major potential problems:
1) corrosion; and
2) low pull-out strength (discussed later).

<table>
<tr><th>Facing
Reinforcement</th><th>Flexible, not developing high earth pressure on the facing</th><th>Stiff, developing high earth pressure on the facing</th></tr>
<tr><td>Inextensible:
e.g., metallic strip</td><td>a) Metallic skin facing

</td><td>b) Discrete concrete panel facing

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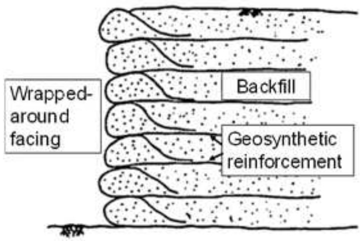
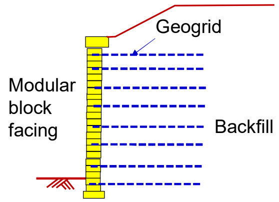
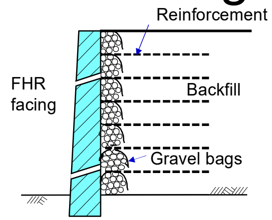
<tr><td>Extensible: typically polymeric planar geogrid</td><td>c) Wrapped-around facing

</td><td>Typically, d) Modular block facing, & e) FHR facing
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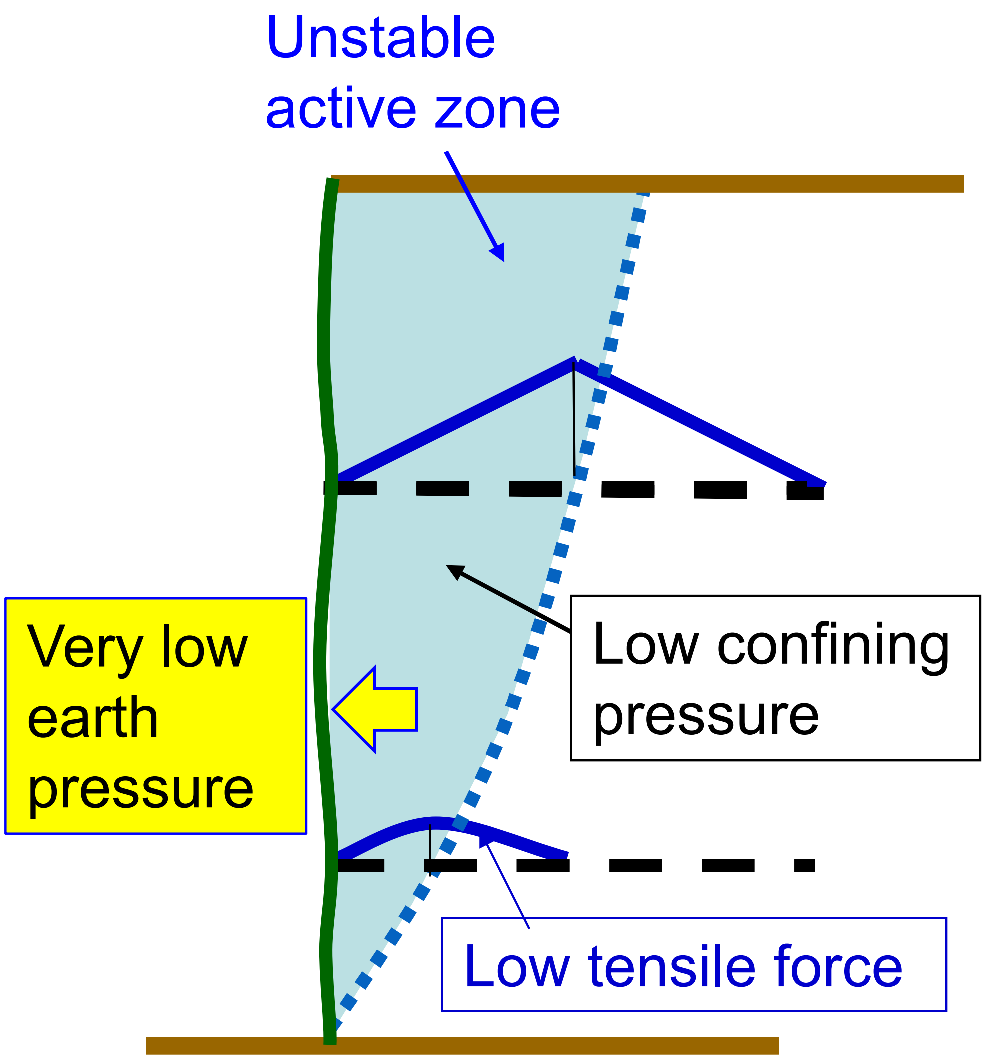
</table>

Previously, many considered that:

- facing is only to prevent the spilling out of backfill; and
- for small wall deformation and high wall stability, the earth pressure on the facing should be kept **low**; so, **flexible facing** (e.g., a or **c**) is sufficient.

However, we have often observed that:
when using flexible facing (e.g., **a** or **c**), the earth pressure is low, whereas **the wall deformation is large, sometimes too large,** indicating the paramount importance of using stiff facing.

When the facing is flexible ……….



Very low earth pressure on the facing, which results into:

→ Low tensile forces in the reinforcement, in particular at low levels

→ In the active zone, low confining pressure, therefore, low strength & stiffness of the backfill.

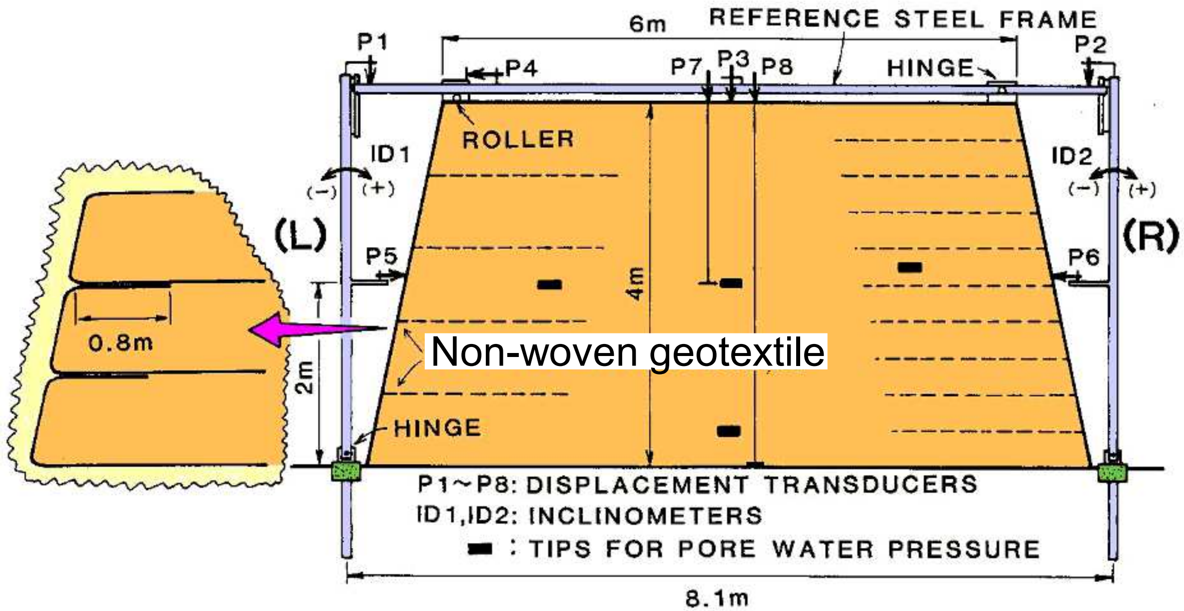
So, large wall deformation & low stability of the wall

Chiba No. 1 embankment of clay backfill

- Constructed in 1982

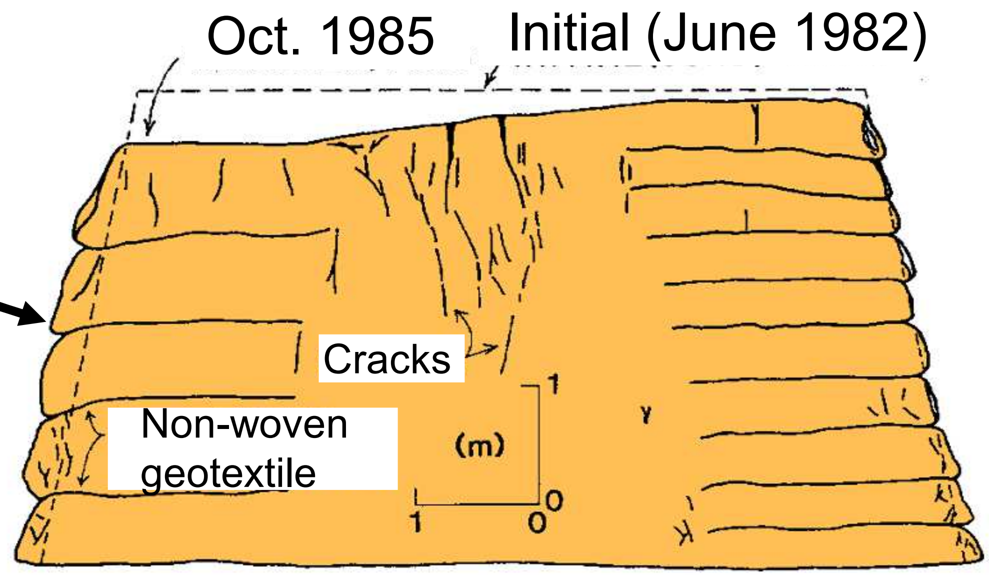
to examine whether stable reinforced clay walls can be constructed

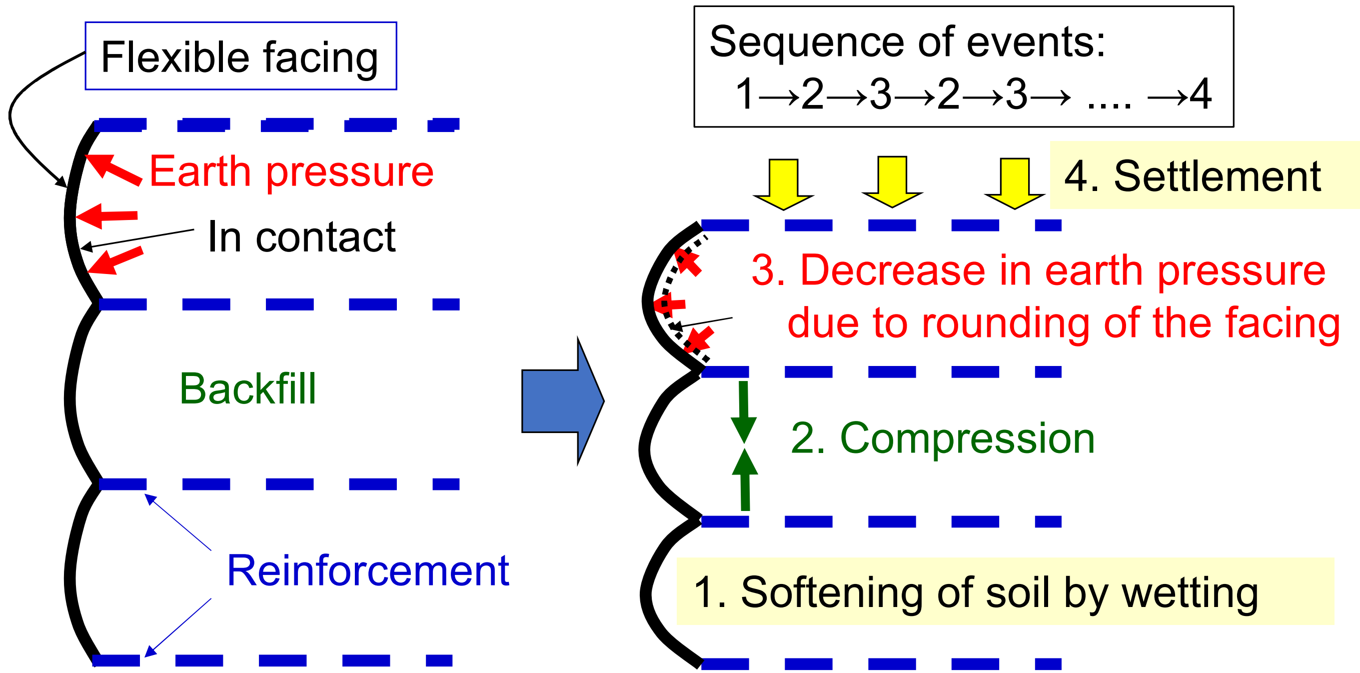
- Non-woven geotextile (spun-bonded 100 % poly-propylene), usually used as a drain material but not as reinforcement due to very low tensile stiffness.
- Flat wrapped-around wall face.

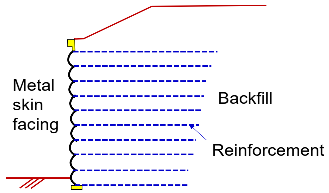
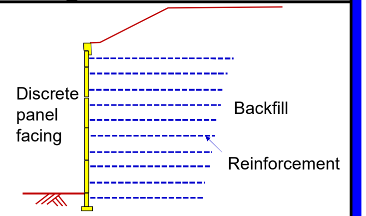
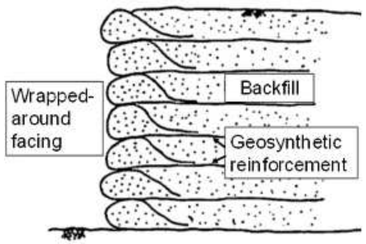
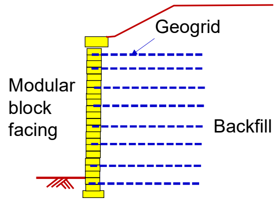
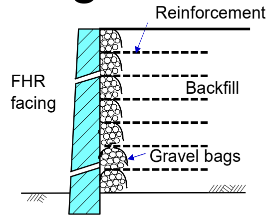


The walls were basically stable for a long time, but …..

Flexible wrapped-around facing exhibited large deformation already during construction and additionally by rainfalls after construction. Besides, this facing is not durable and vulnerable to UV light….. so, not acceptable for important permanent walls.





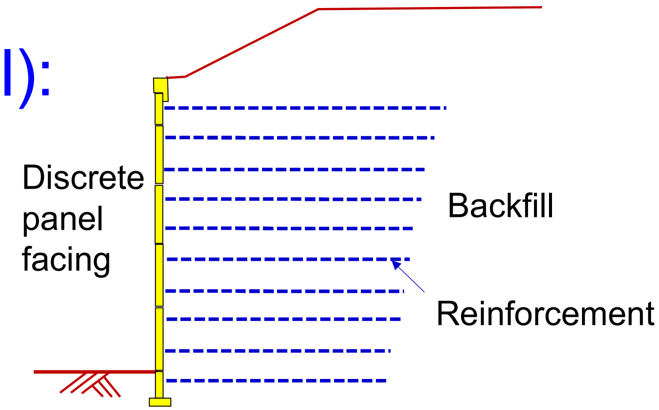
Facing / Reinforcement	Flexible, not developing high earth pressure on the facing	Stiff, developing high earth pressure on the facing
Inextensible: e.g., metallic strip	a) Metallic skin facing 	b) Discrete concrete panel facing 
Extensible: typically polymeric planar geogrid	c) Wrapped-around facing 	Typically, d) Modular block facing, & e) FHR facing  

On the other hand, we have consistently observed that:
the stiff facing firmly connected to the reinforcement layers (e.g., **b**, **d** & **e**) develops large earth pressure, which results in small wall deformation and high wall stability.

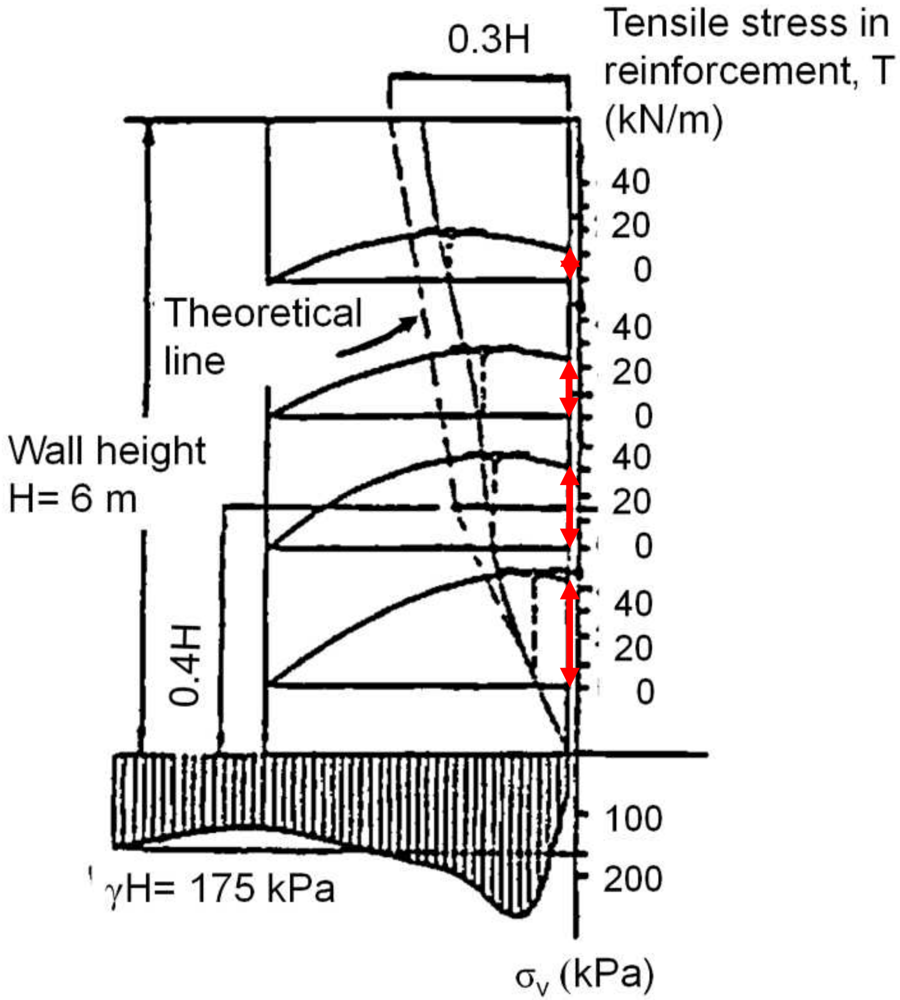
Terre Armée RW (discrete panel facing; and metallic strip reinforcement with sandy soil backfill):

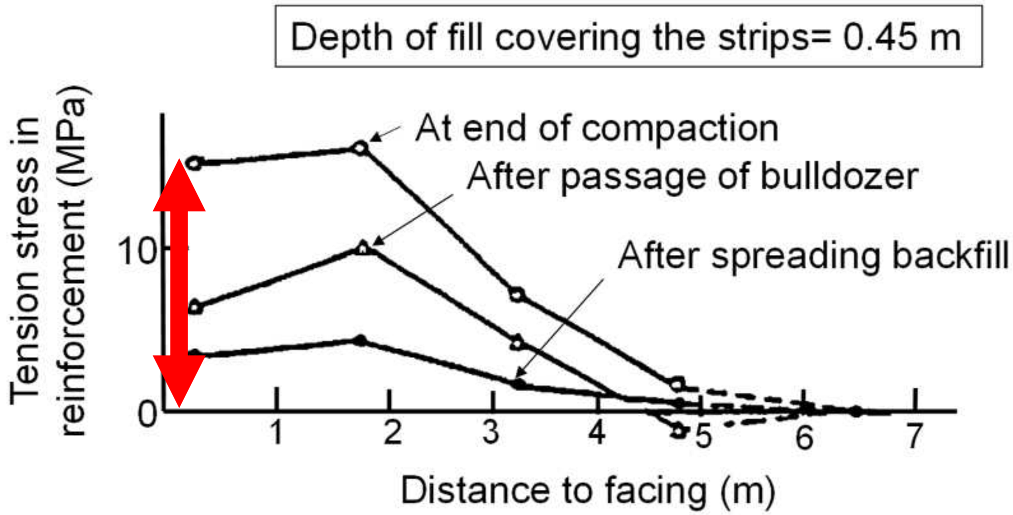
⇒ High connection forces, showing high earth pressure on the facing and high tensile forces in the reinforcements, so high confining pressure in the backfill (even at low levels);

⇒ Stable wall behaviour with small wall deformation.

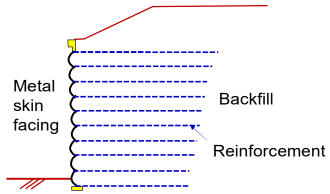
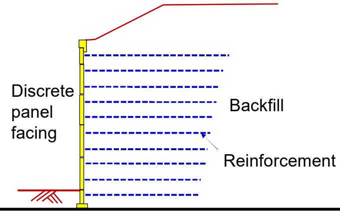
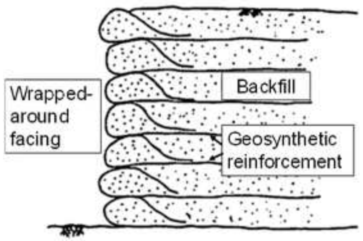
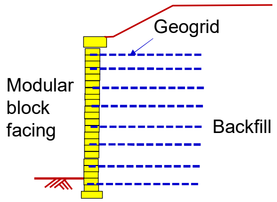
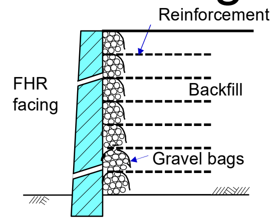


6 m-high test RW





Schlosser, F. (1990): Mechanically stabilized earth retaining structures in Europe, *Design and Performance of Earth Retaining Structures, Geotechnical Special Publications No.25, ASCE* (Lambe and Hansen eds.), pp.347-378.

Facing / Reinforcement	Flexible, not developing high earth pressure on the facing	Stiff, developing high earth pressure on the facing
Inextensible: e.g., metallic strip	a) Metallic skin facing 	b) Discrete concrete panel facing 
Extensible: typically polymeric planar geogrid	c) Wrapped-around facing 	d) Modular block facing  **e) FHR facing** 

Facing of discrete panels or modular blocks (i.e., **b** or **d**) can effectively decrease the wall deformation and increase the wall stability.

However, for small wall deformation and high wall stability,

e) full-height rigid (FHR) facing is more effective; and its use is very advantageous in many aspects,

as explained in the following.

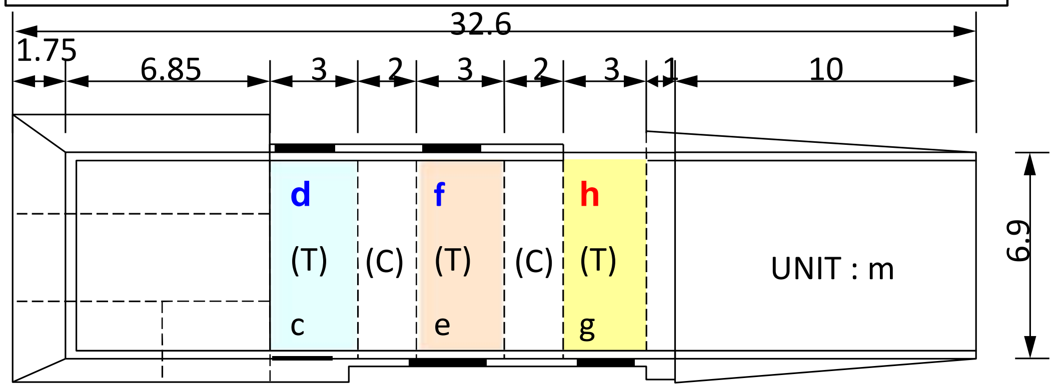
Two test embankments at Railway Technical Research Institute, Japan (constructed 1987 – 1988), to confirm the advantages of FHR facing and its staged-construction

JR No.1 (sand backfill)

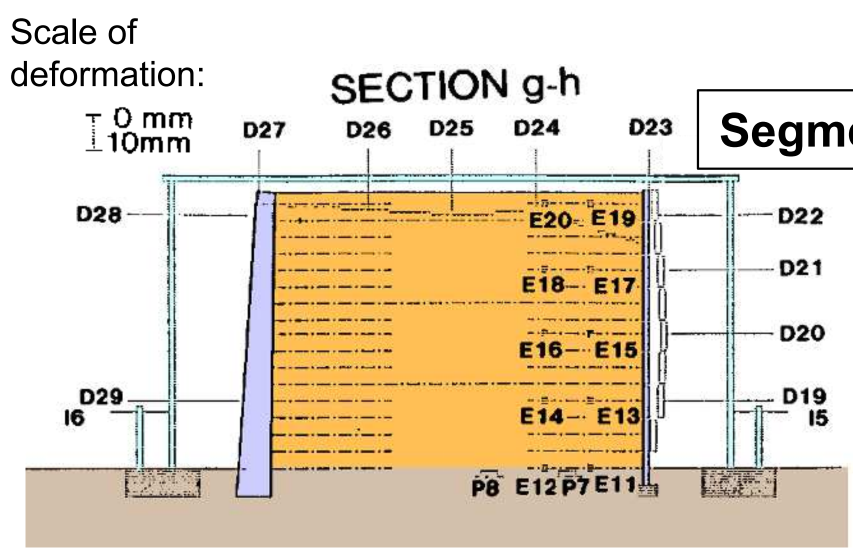
Post-construction behaviour for two years:

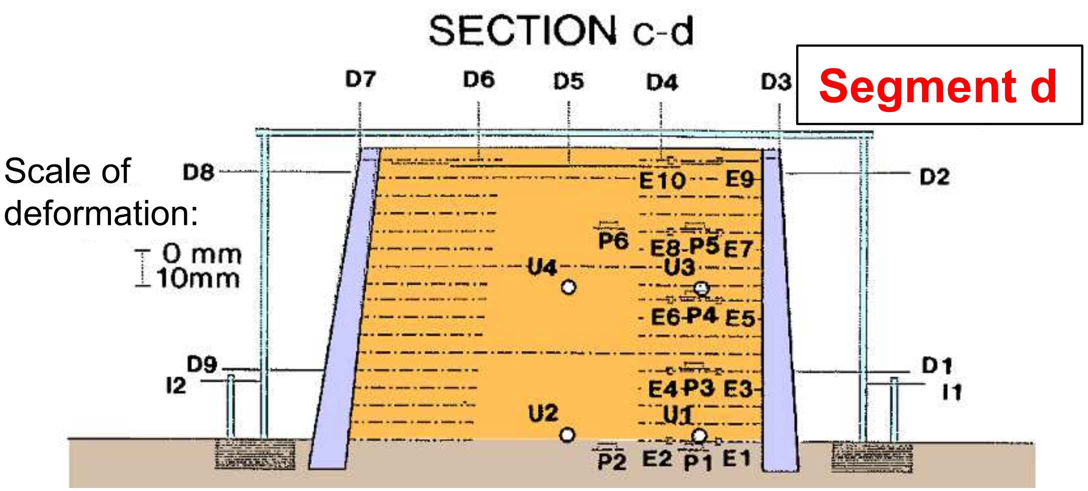
- segment h (discrete panel facing)⇒ relatively large deformation
- segments d, f & others (FHR facing)⇒ all very small deformation

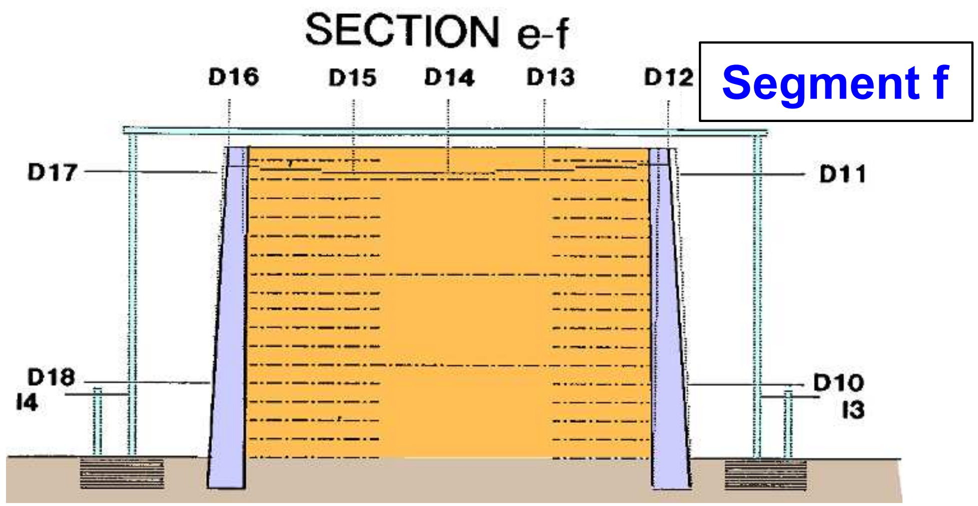
In all the test segments, gravel bags connected to geogrid layers were used.



(T) test section; (C) control section

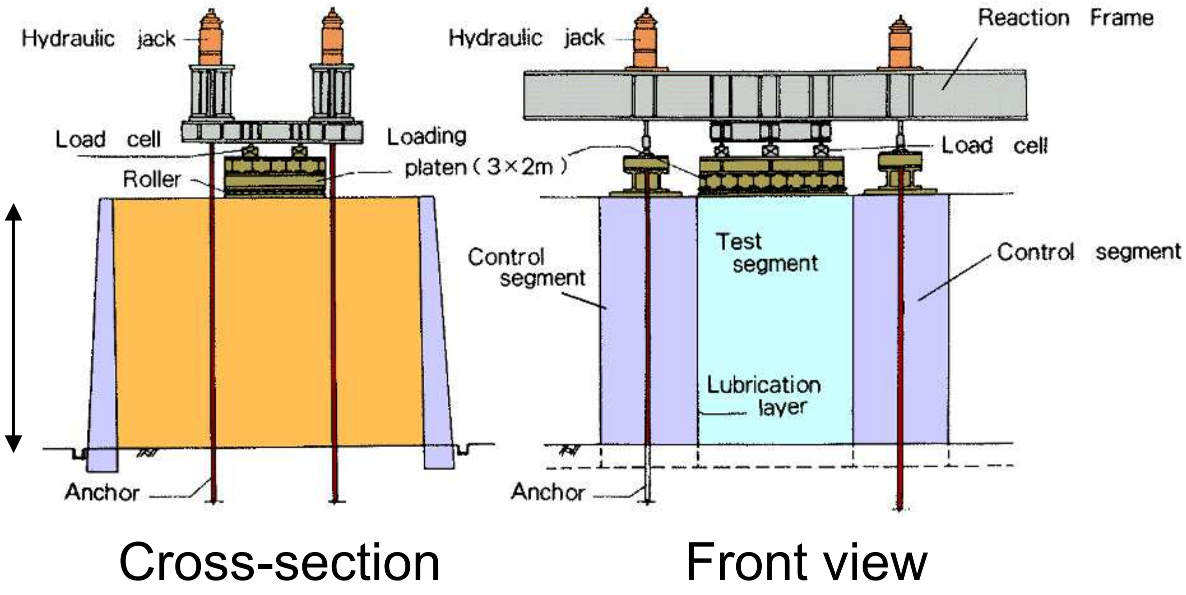


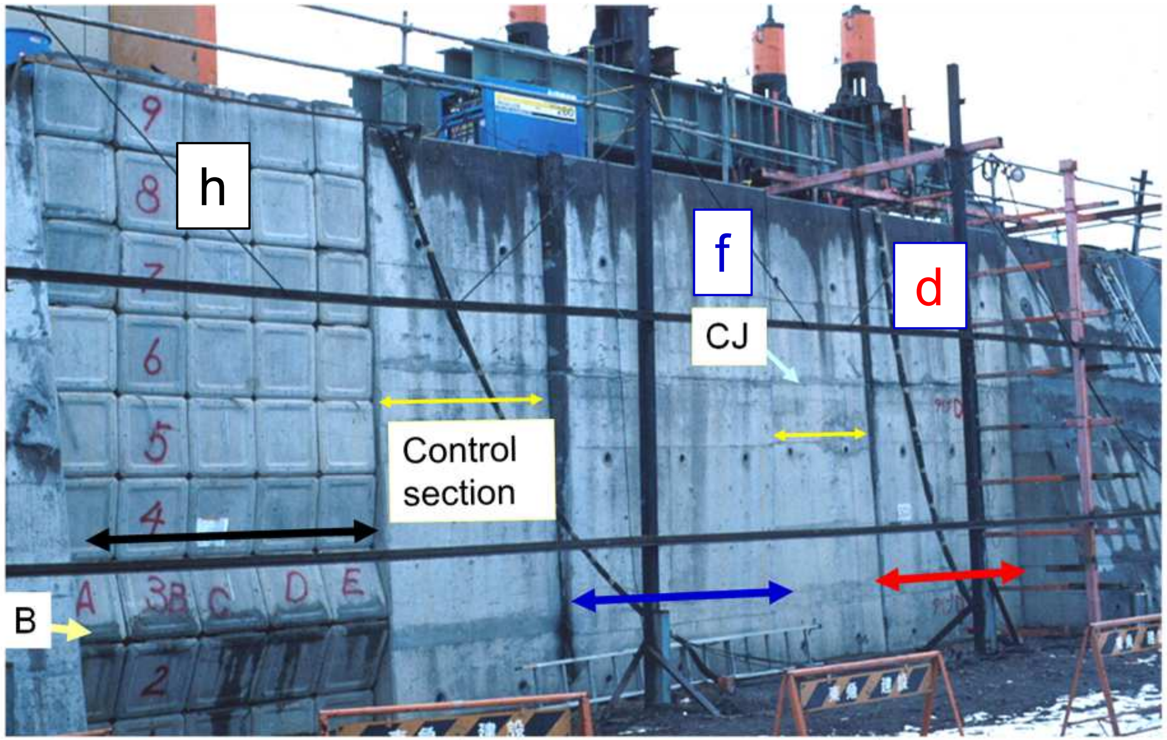




Vertical loading at the crest of JR No.1 (sand backfill)

Wall height= 5 m





Front view of segments h, f & d

h (Geogrid length L= 2 m) discrete panel facing (after loading test)
B: buckling of the facing

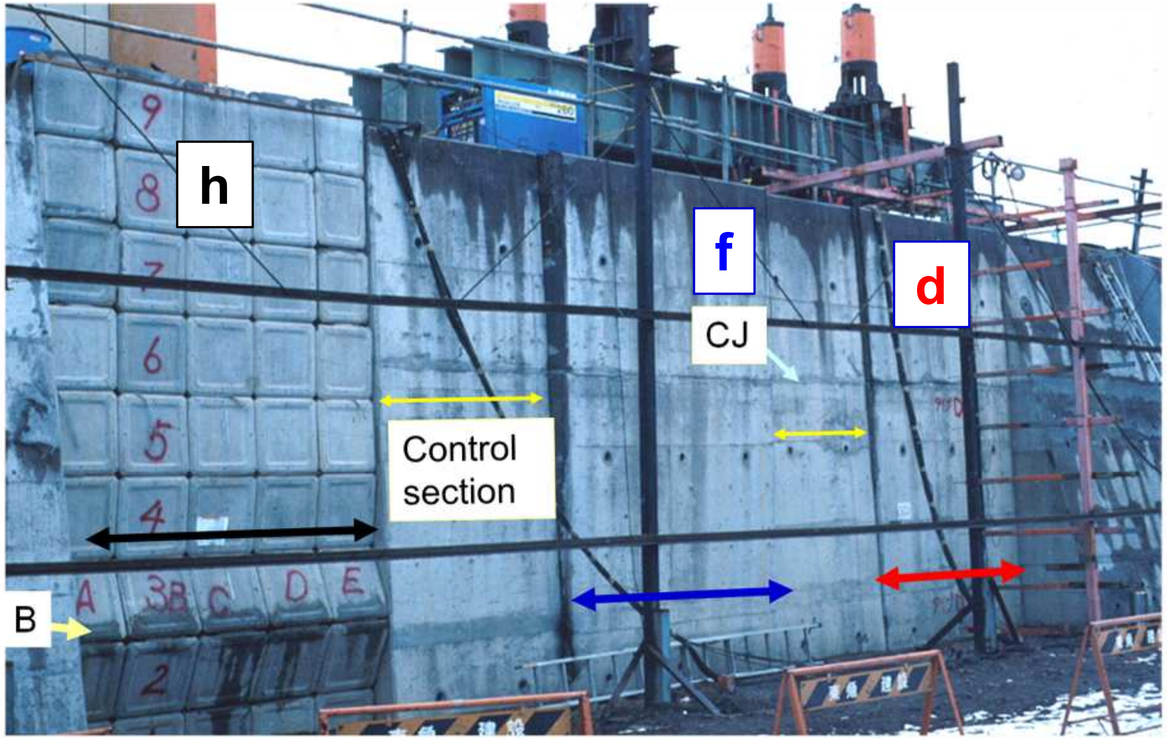
f (L= 1.5m) full-height concrete facing (after loading test)

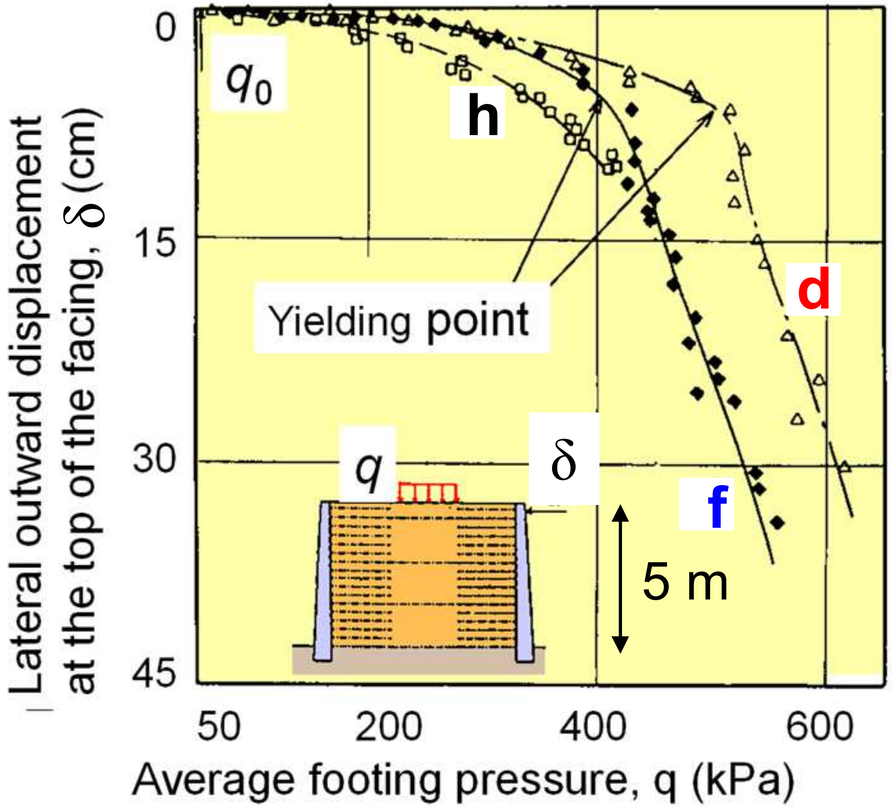
d (L= 2 m) full-height concrete facing (under loading test)

For wall height H= 5 m:

Segment h (discrete panel facing & geogrid length L= 2 m)

- the facing buckled, which resulted in the lowest wall stability



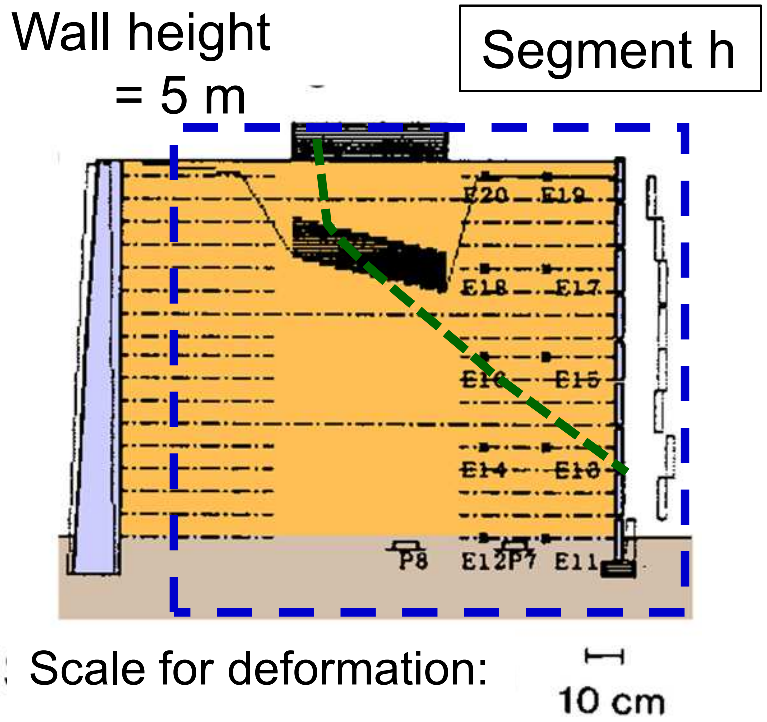


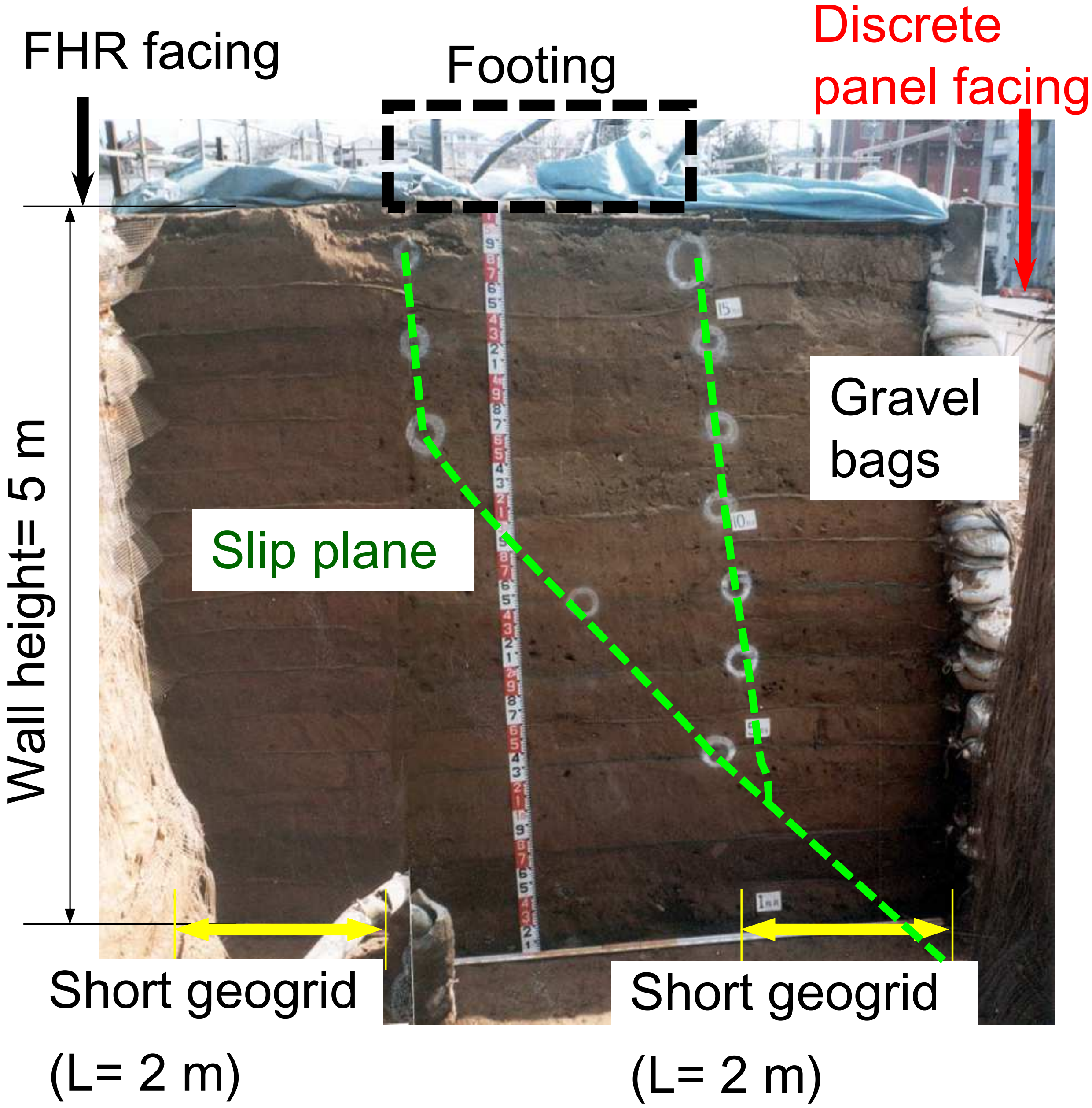
h (Geogrid length L= 2 m)
discrete panel facing
(after loading test)
B: buckling of the facing

f (L= 1.5m)
full-height
concrete facing
(after loading test)

d (L= 2 m)
full-height concrete
facing (under
loading test)

Cross-section of segment h, exposed by excavation





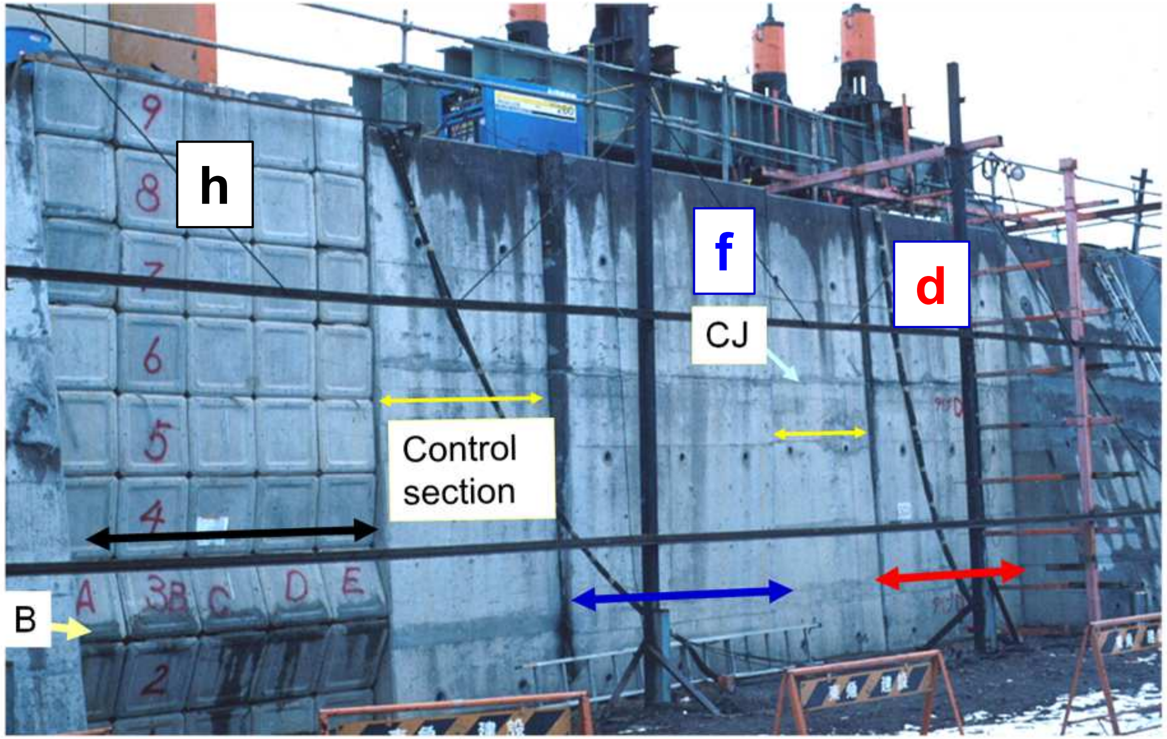
A global slip plane developed toward buckled panels

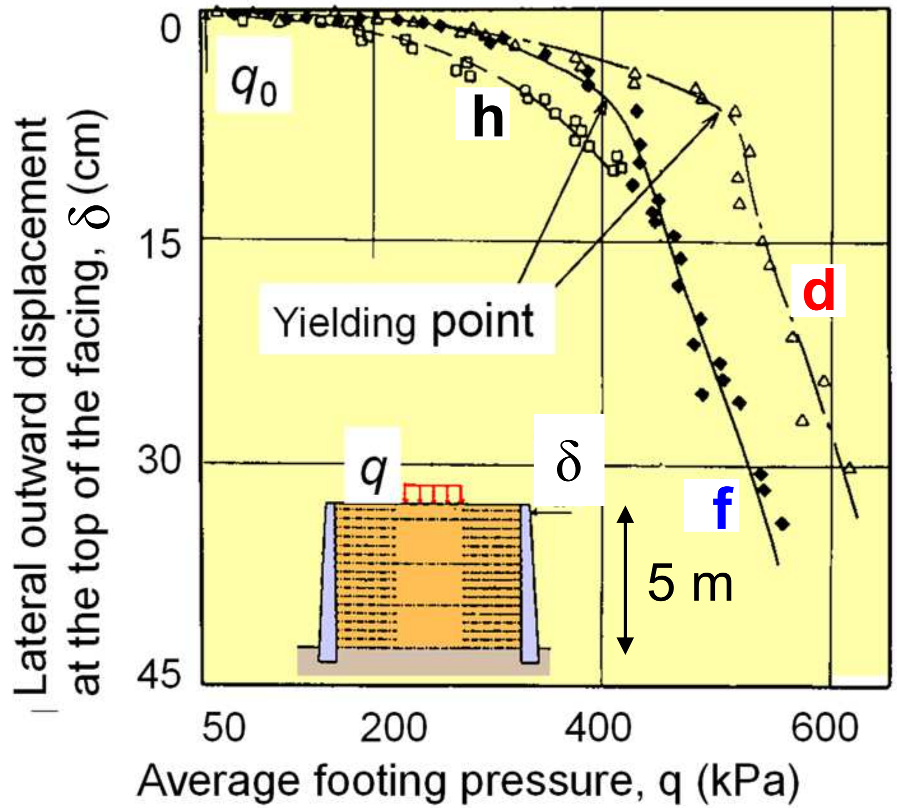
Exposed vertical face: very stable due to apparent cohesion by suction in unsaturated sand

For wall height H= 5 m:

Segment h (discrete panel facing & geogrid length L= 2 m)
- the facing buckled, which resulted in the lowest wall stability

Segment f (FHR facing & L= 1.5 m);
- more stable than segment h due to the use of FHR facing, despite the use of a shorter geogrid



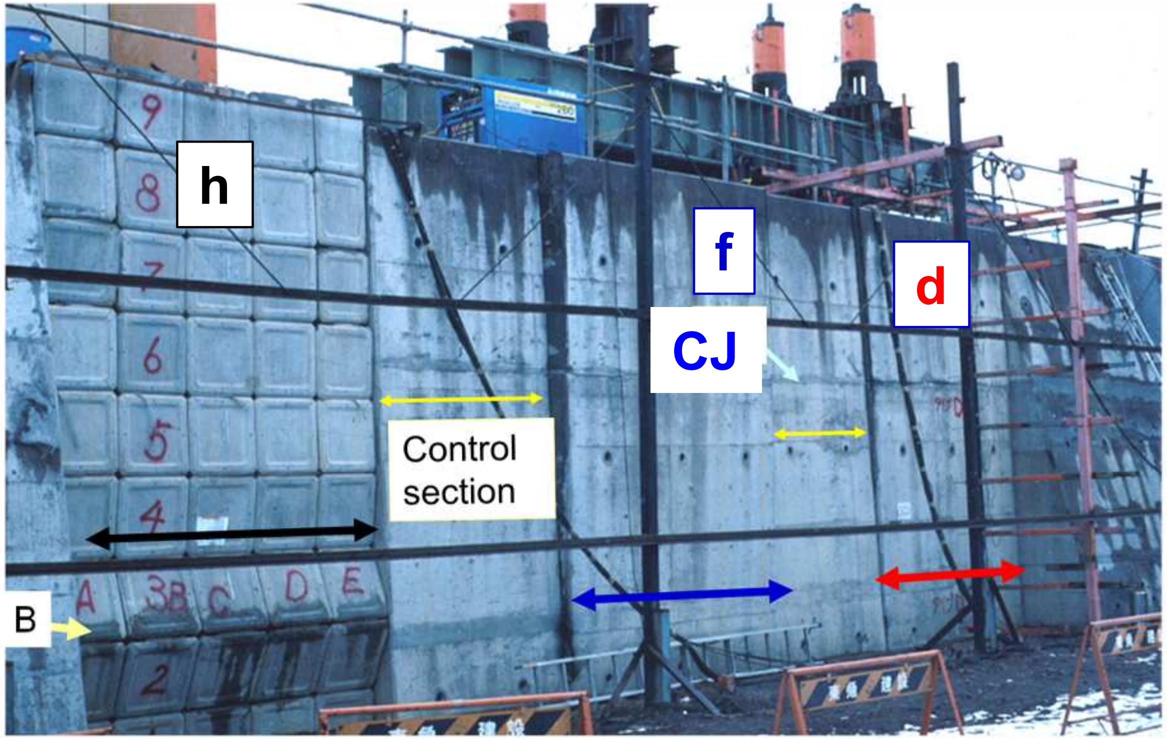


h (Geogrid length L= 2 m) discrete panel facing (after loading test) B: buckling of the facing	f (L= 1.5m) full-height concrete facing (after loading test)	d (L= 2 m) full-height concrete facing (under loading test)

Segment d (FHR facing & L= 2 m):

- more stable than segment f (L= 1.5 m) due to a longer geogrid;
- much more stable than segment h due to the use of FHR facing.

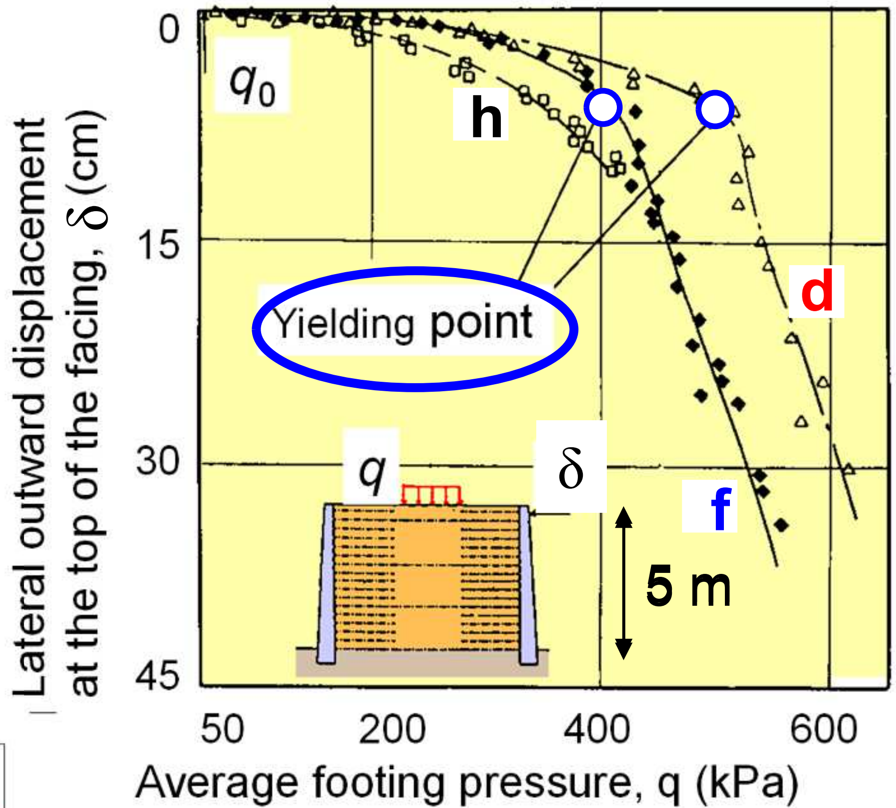
The stability of segments f & d was restrained by the yielding of construction joint CJ in the concrete facing (not steel-reinforced).
⇒ All the FHR facings of the prototype GRS RWs constructed subsequently are all lightly steel-reinforced.



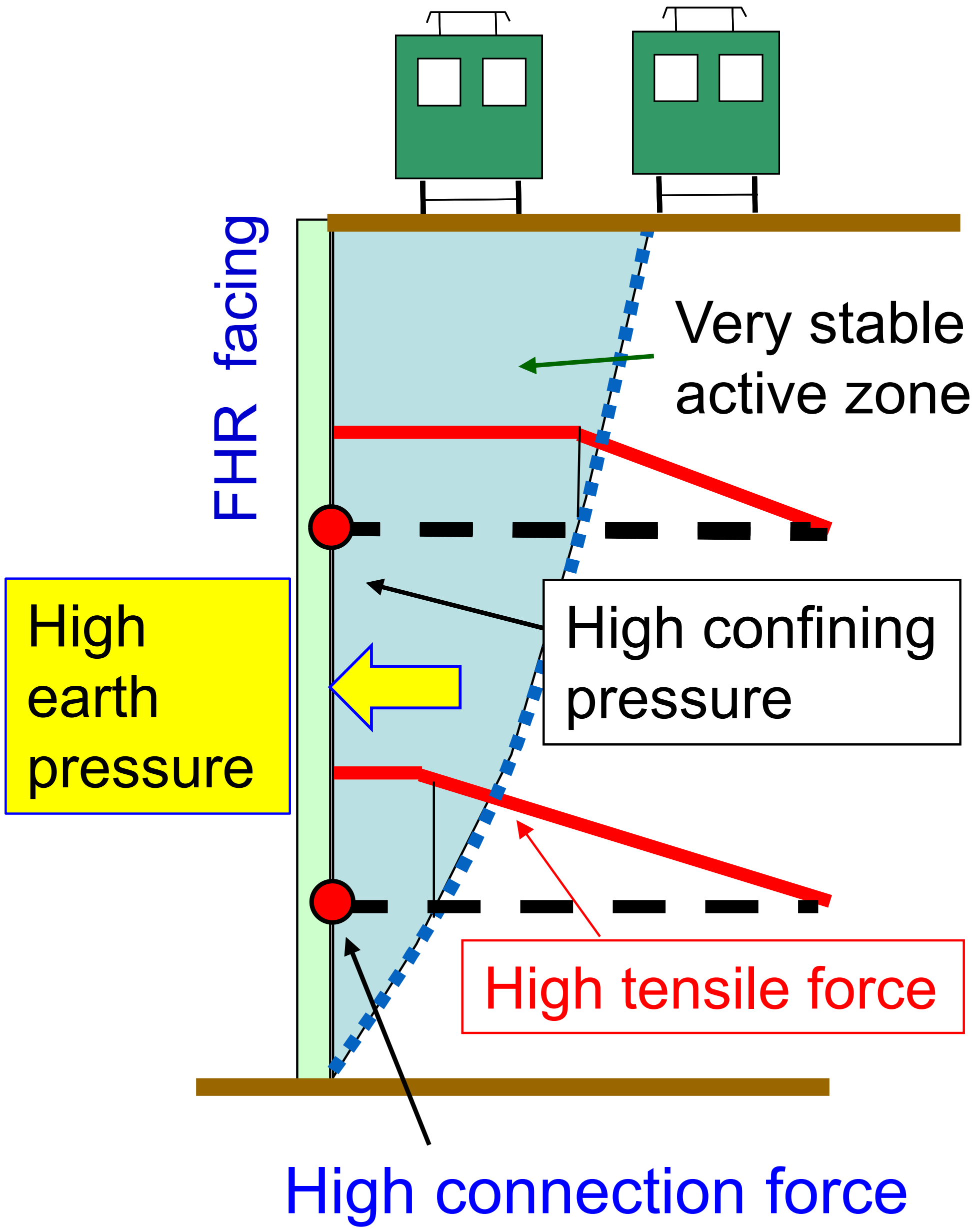
h (Geogrid length L= 2 m) discrete panel facing (after loading test) B: buckling of the facing

f (L= 1.5m) full-height concrete facing (after loading test)

d (L= 2 m) full-height concrete facing (under loading test)



When FHR facing is firmly connected to reinforcement....



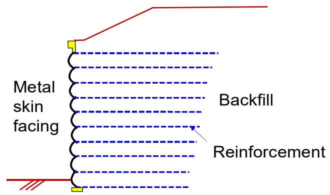
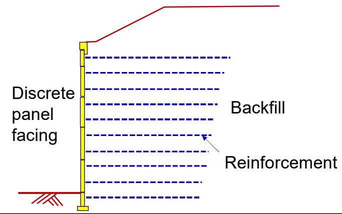
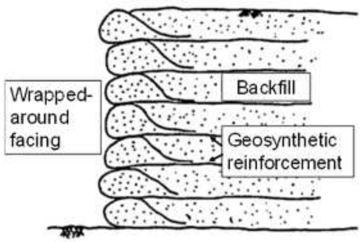
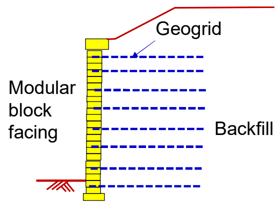
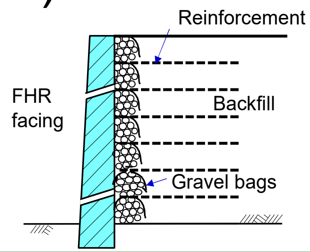
High earth pressure on the facing, which results into:

→ High tensile forces in the reinforcement (even at low levels)

→ In the active zone, high confining pressure, therefore, high strength & stiffness of the backfill

So, small wall deformation & high stability of the wall, even immediately back of the facing.

Summary:

Facing / Reinforcement	Flexible, not developing high earth pressure on the facing	Stiff, developing high earth pressure on the facing
Inextensible: e.g., metallic strip	a) Metallic skin facing 	b) Discrete concrete panel facing 
Extensible: typically polymeric & planar (e.g., geogrid)	c) Wrapped-around facing 	Typically, d) Modular block facing, & e) FHR facing  

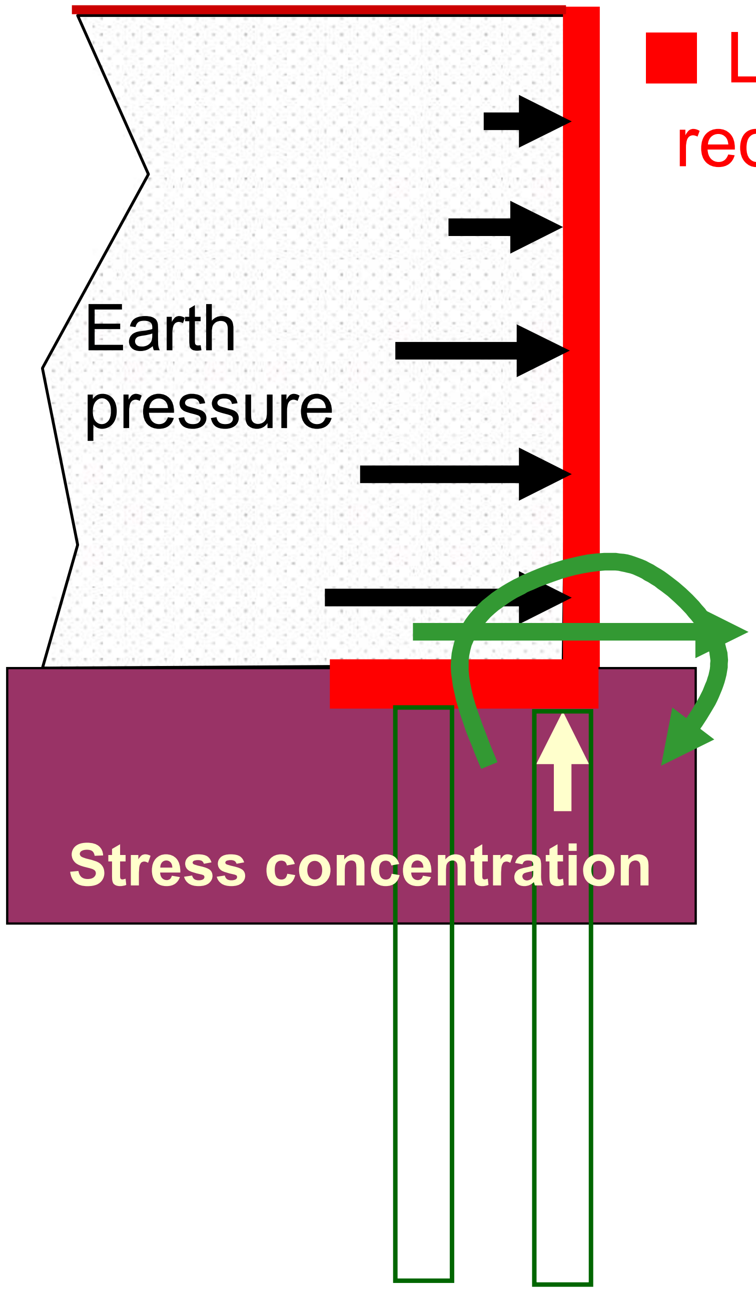
e) FHR facing firmly connected to the reinforcement layers ensures small wall deformation & high wall stability in spite of the use of relatively short so-called extensible reinforcement (i.e., geogrid) .

- Besides FHR facing exhibits good durability & aesthetics.

These features of FHR facing are discussed in the next section.

Contents

First of all, conventional RW is a cantilever structure!

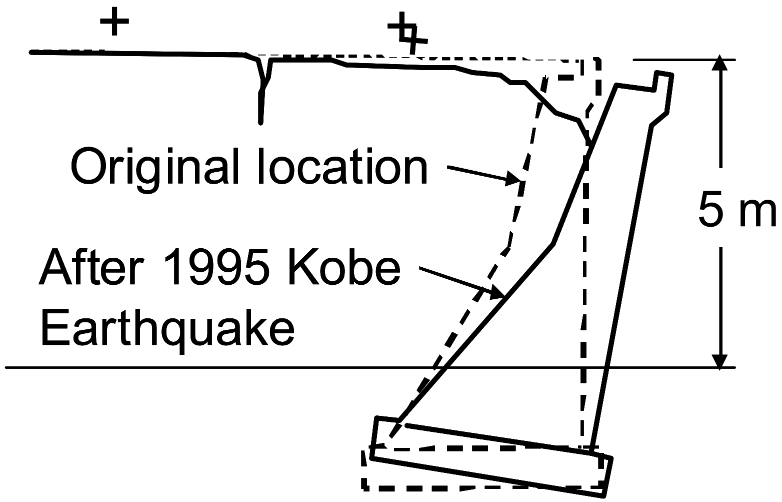


■ Large forces in the facing, requiring massive & strong facing

■ Large overturning moment & large lateral thrust load at the facing base, resulting in
- unstable behaviour, particularly by severe seismic loads; and
- large stress concentration at the facing base.

So, usually a pile foundation is required.

Collapse of gravity wall (i.e., cantilever RW) Ishiyagawa,1995 Kobe Earthquake



Very dense gravelly subsoil, no pile

Overturning failure, despite seismic design using k_h= 0.2 with $(F_s)_{allowable}$= 1.5.

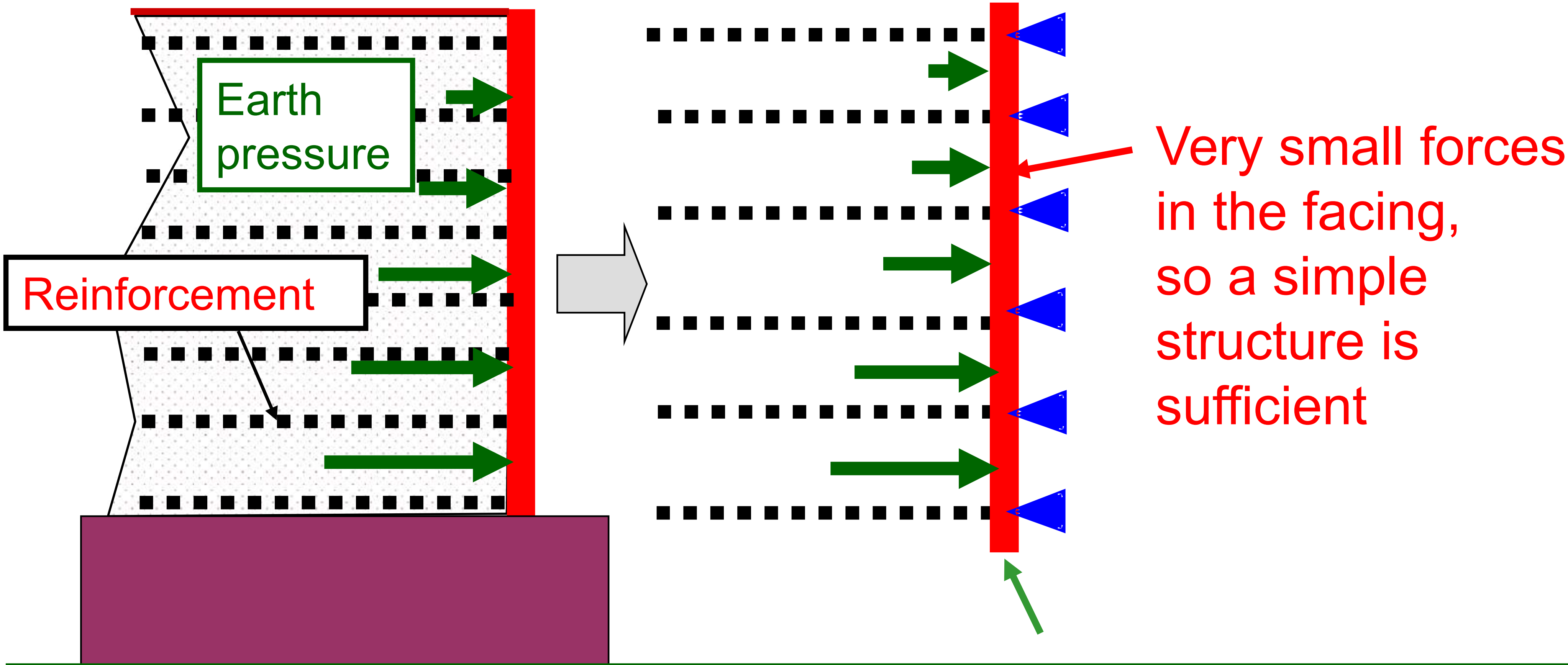
⇒ The conventional seismic design is not sufficient.

⇒ More stable wall type is required

→ GRS RW with FHR facing

On the other hand, FHR facing for GRS RW is "a continuous beam supported by many reinforcement layers at a small span (usually 30 cm)"

⇒ the behaviour unlike a cantilever structure

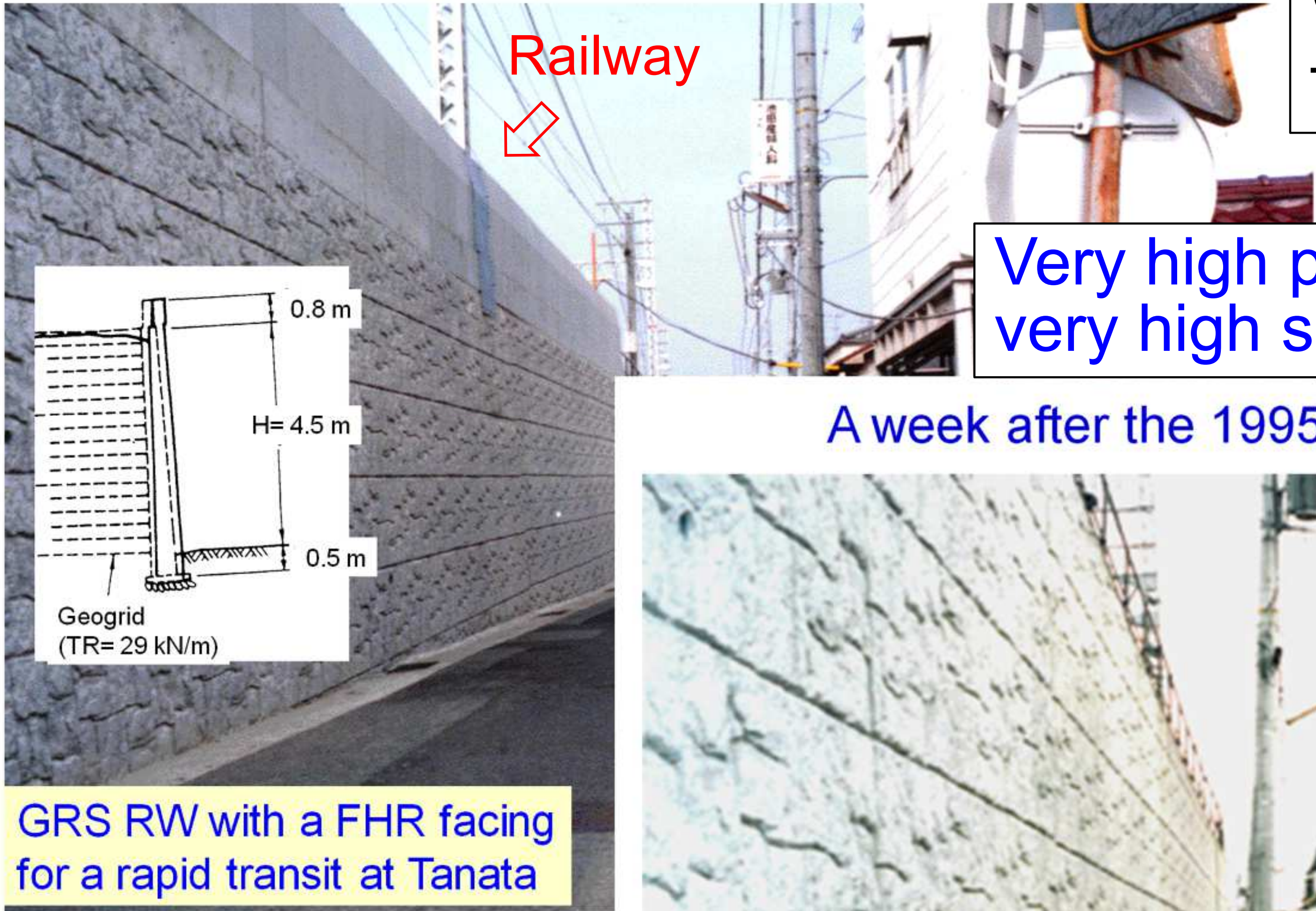


Small overturning moment & small lateral thrust load at the facing base

⇒ a pile foundation becomes unnecessary, and the wall could be stable even against severe seismic loads

Immediately after completion, 1992

GRS RW with FHR facing at Tanata

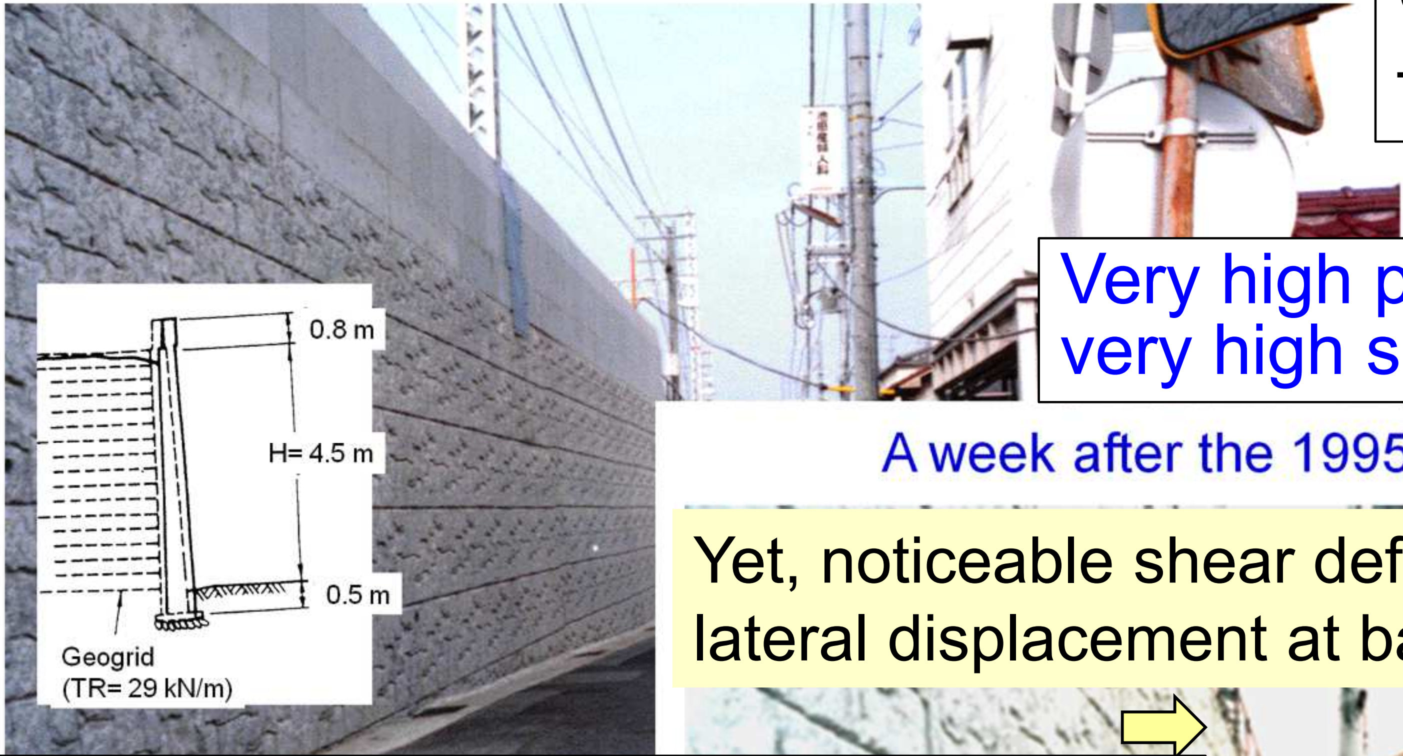


Very high performance against very high seismic load

A week after the 1995 Kobe Earthquake

GRS RW with FHR facing at Tanata

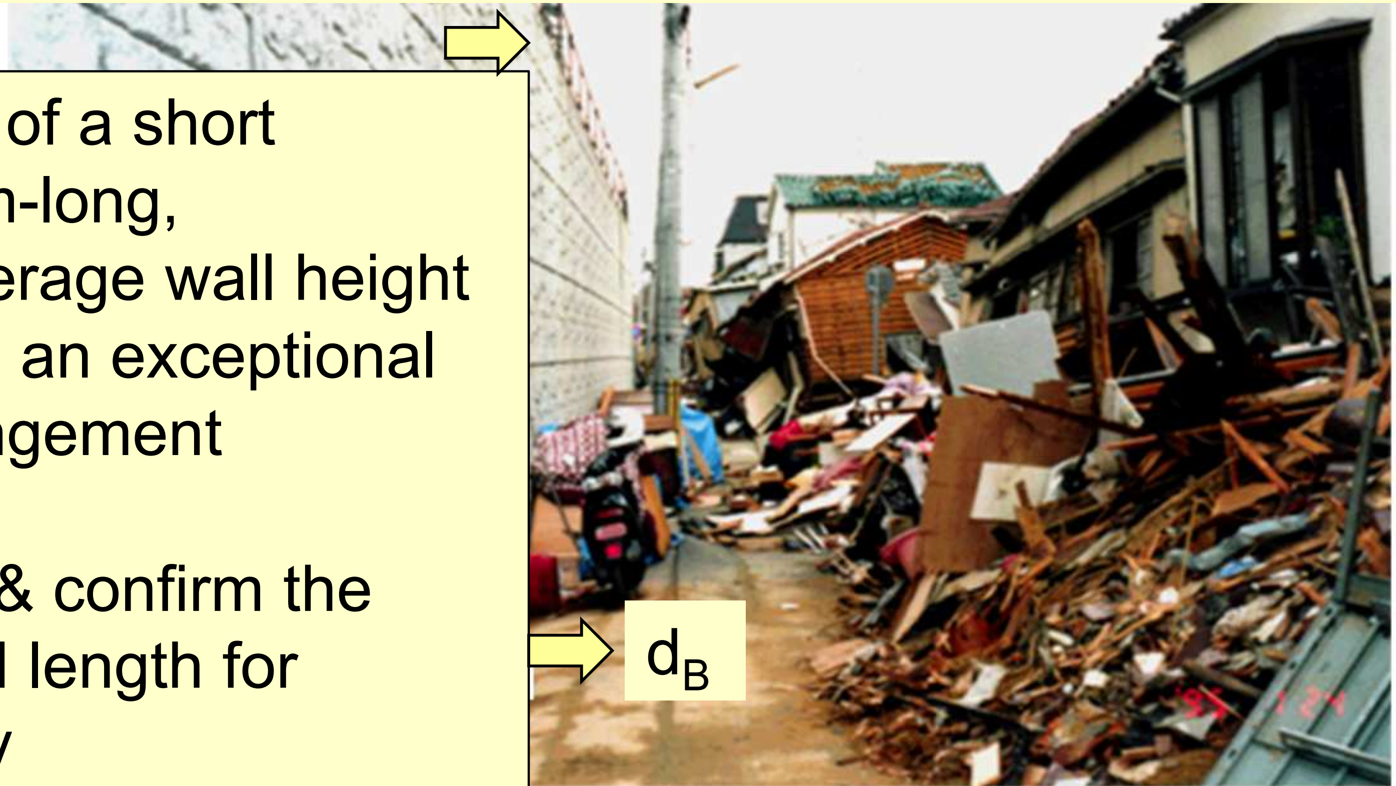
Immediately after completion, 1992



Very high performance against very high seismic load

A week after the 1995 Kobe Earthquake

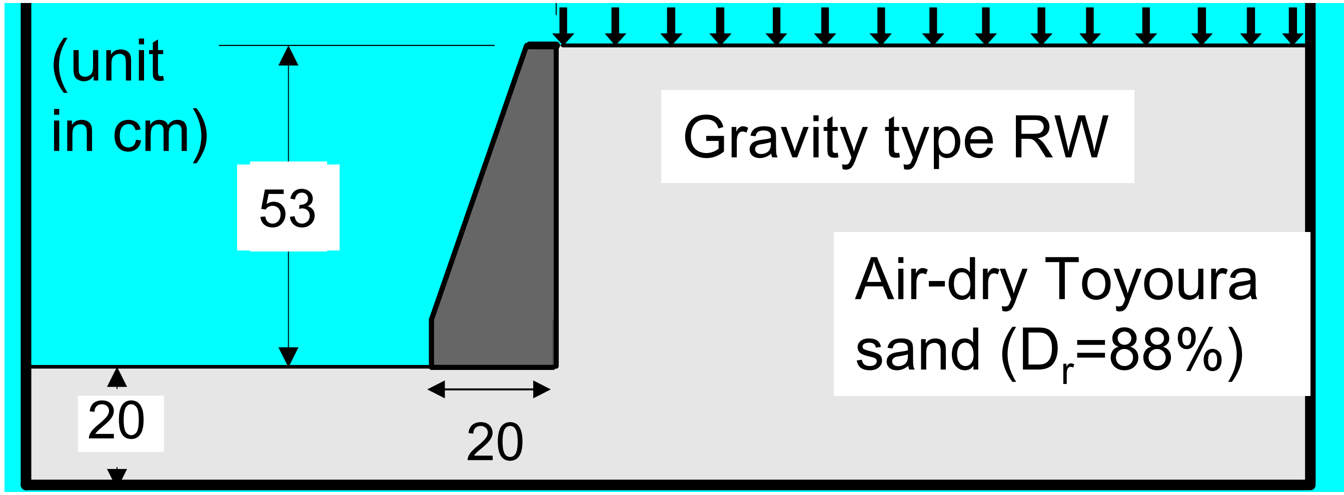
Yet, noticeable shear deformation ≈ 2.7 % & lateral displacement at base $d_B/H \approx 2$ %



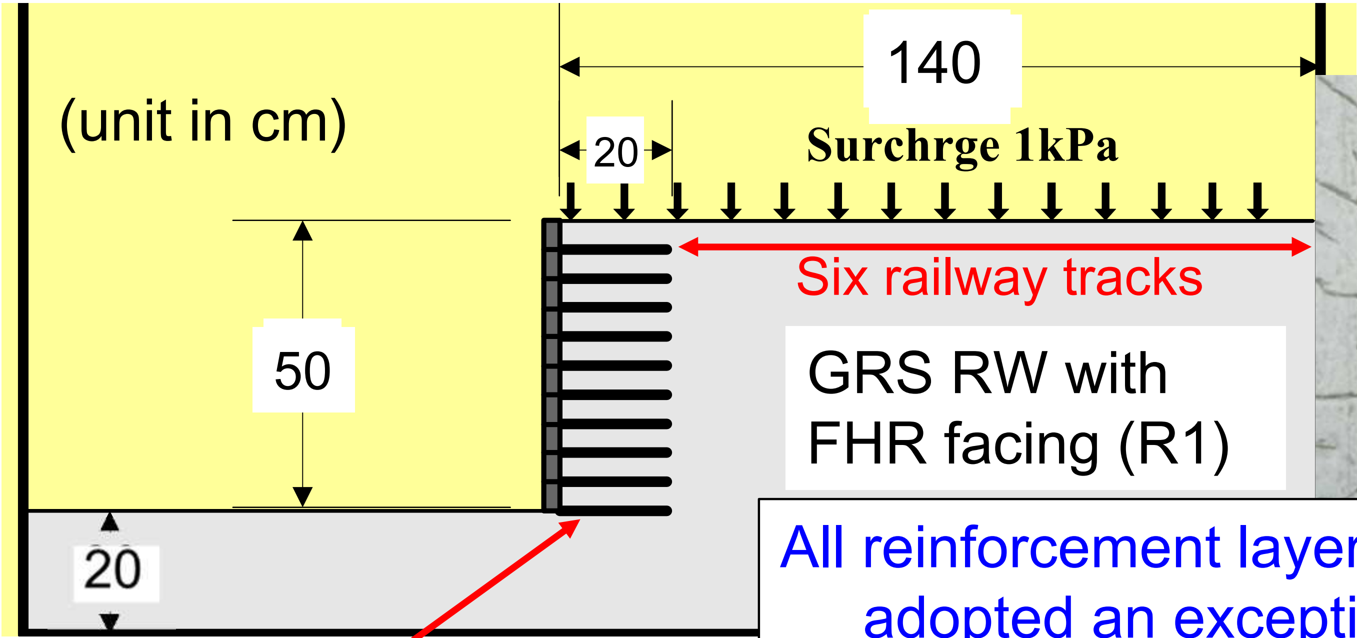
… due likely to the use of a short geogrid (i.e., only 2 m-long, about 40 % of the average wall height H= 5 m), adopted as an exceptional case of geogrid arrangement

⇒ Investigation to find & confirm the cost-effective geogrid length for sufficient wall stability

Shaking table tests simulating RWs during the 1995 Kobe E.Q.



Fully collapsed



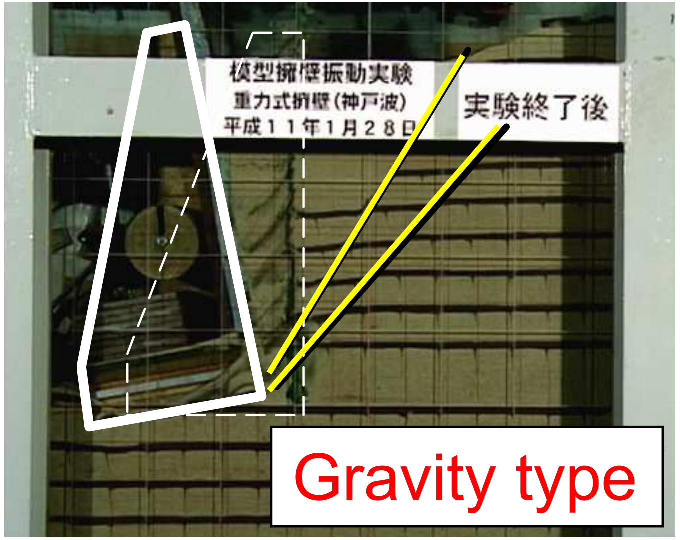
Not collapsed, but some shear deformation

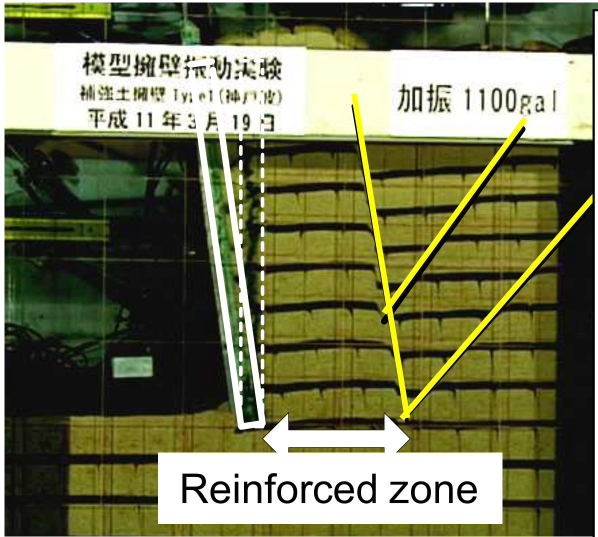
Reinforcement (10 layers): grid of phosphor-bronze strips (t=0.2mm)

(Koseki et al., 2008)

All reinforcement layers are very short (L/H= 0.4); adopted an exceptional case, as geogrid layers could not be arranged below a railway track in operation.

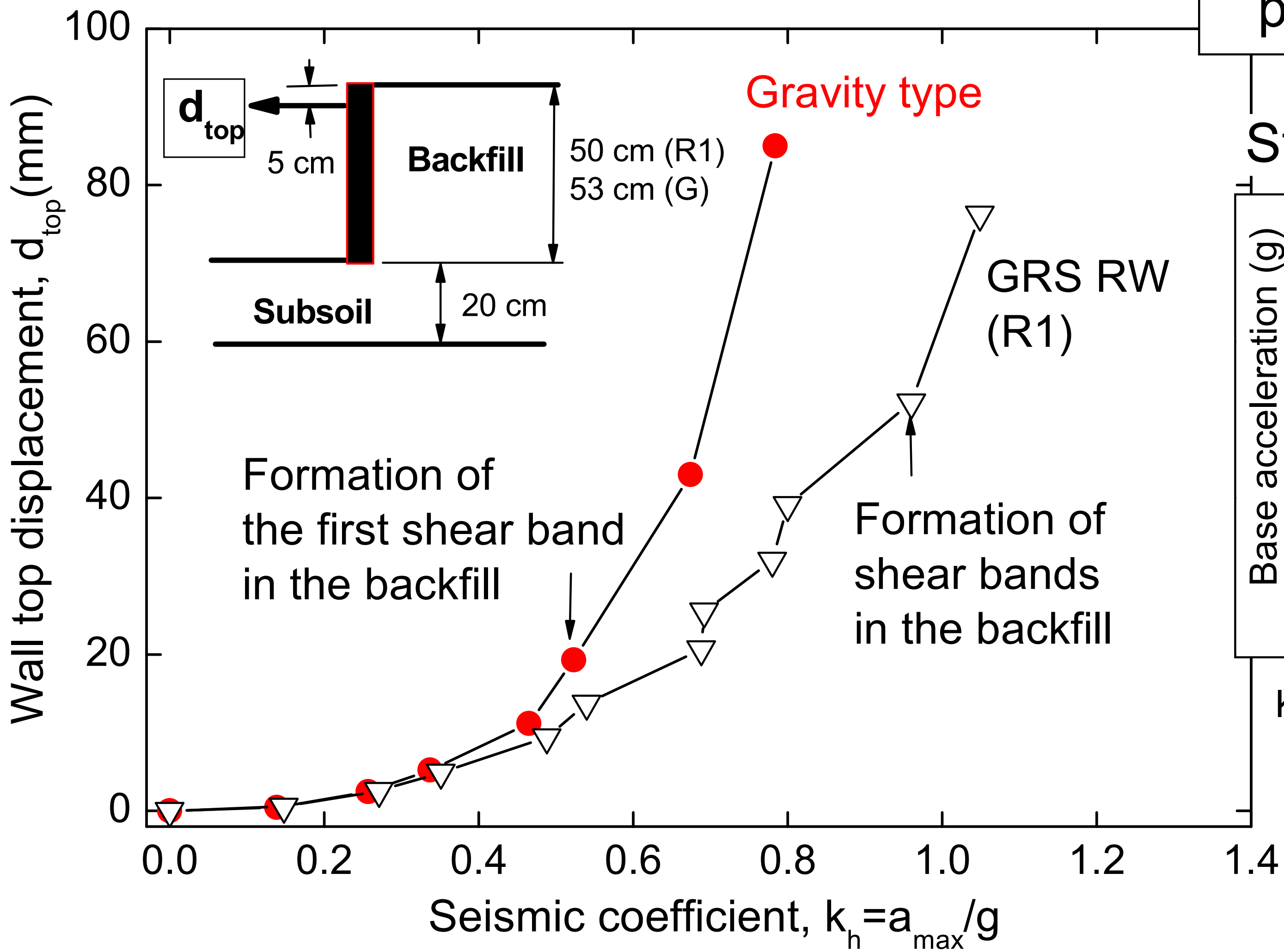
- Seismic-designed by the old code, specifying a low k_h= 0.2 and $(F_s)_{allowable}$= 1.5



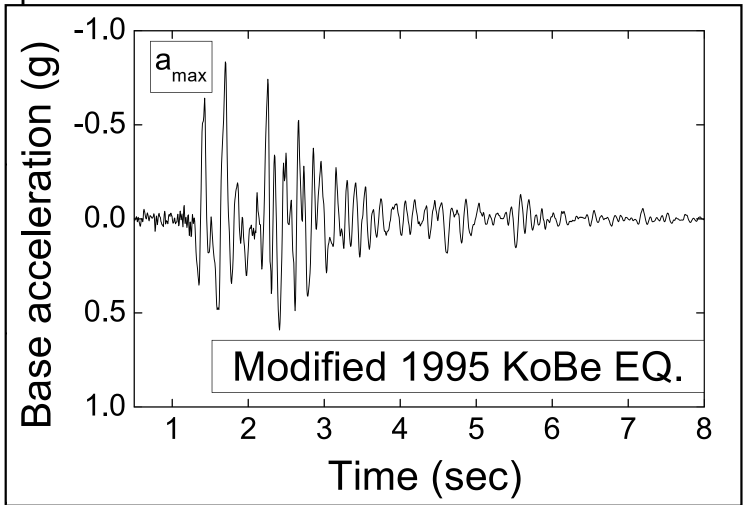


GRS RW (R1): more stable than the gravity wall, but noticeable shear deformation

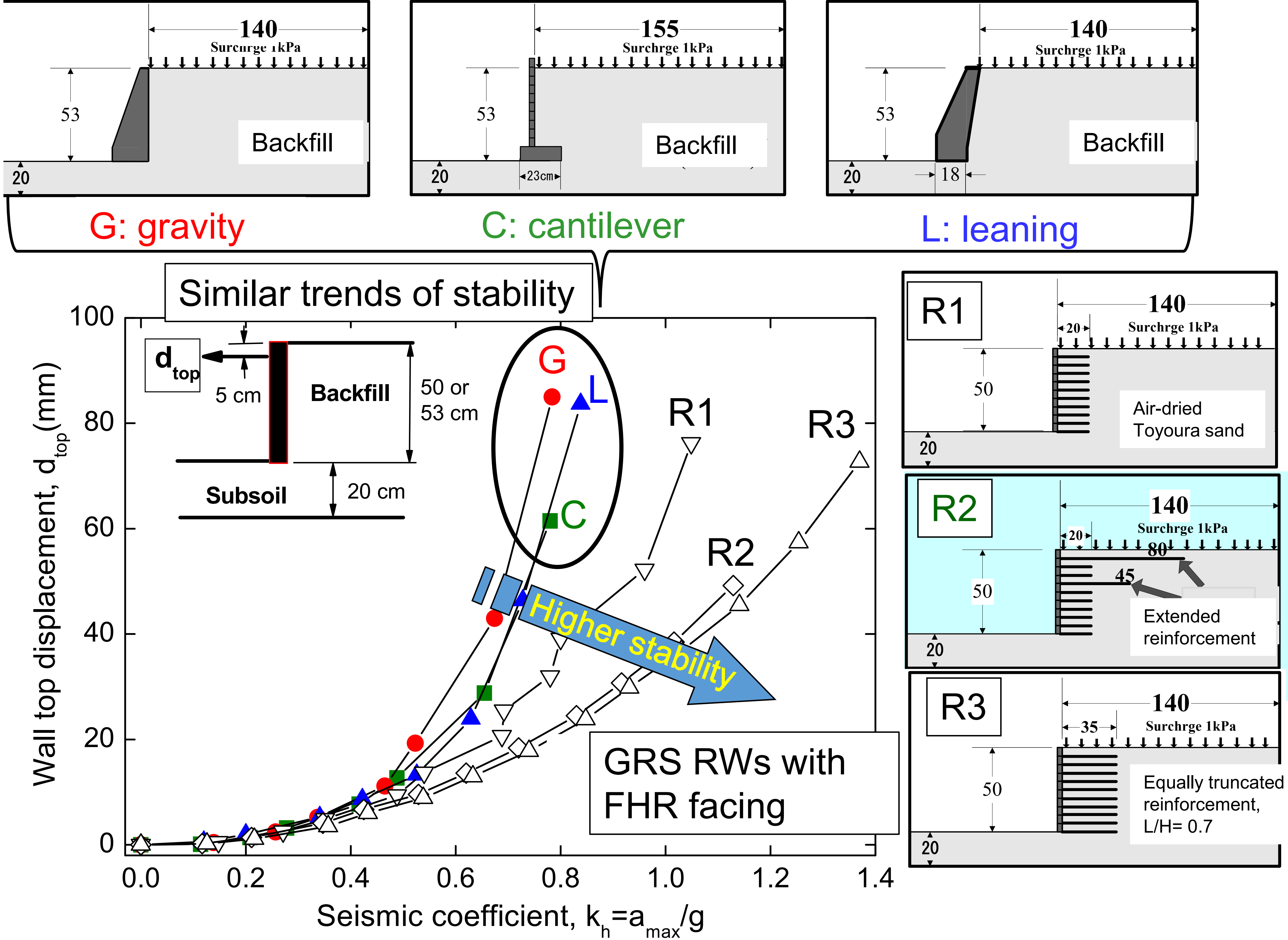
– These behaviours of the two models are consistent with those of the prototype walls.



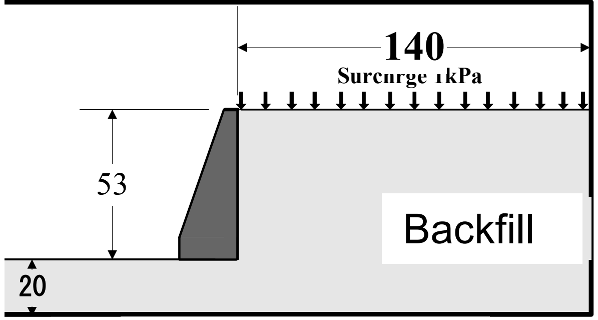
Step-wise increase in α_{max}



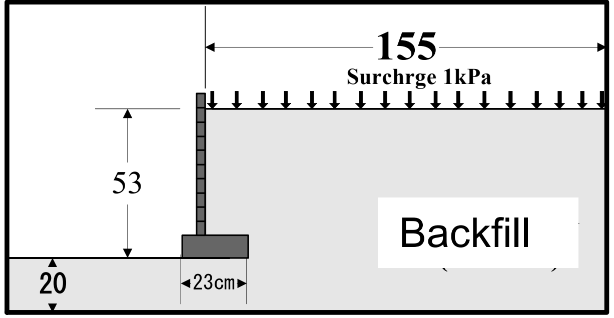
Koseki, J., Tateyama, M., Watanabe, K and Nakajima, S. 2008. Stability of earth structures against high seismic loads, Keynote Lecture, *Proc. 13th ARC on SMGE*, Kolkata, Vol. 2, pp.222-241.



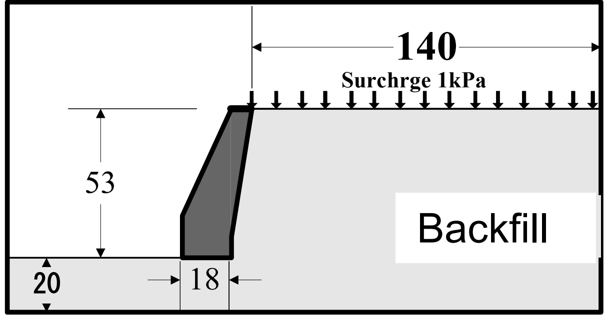
(Koseki et al., 2008)



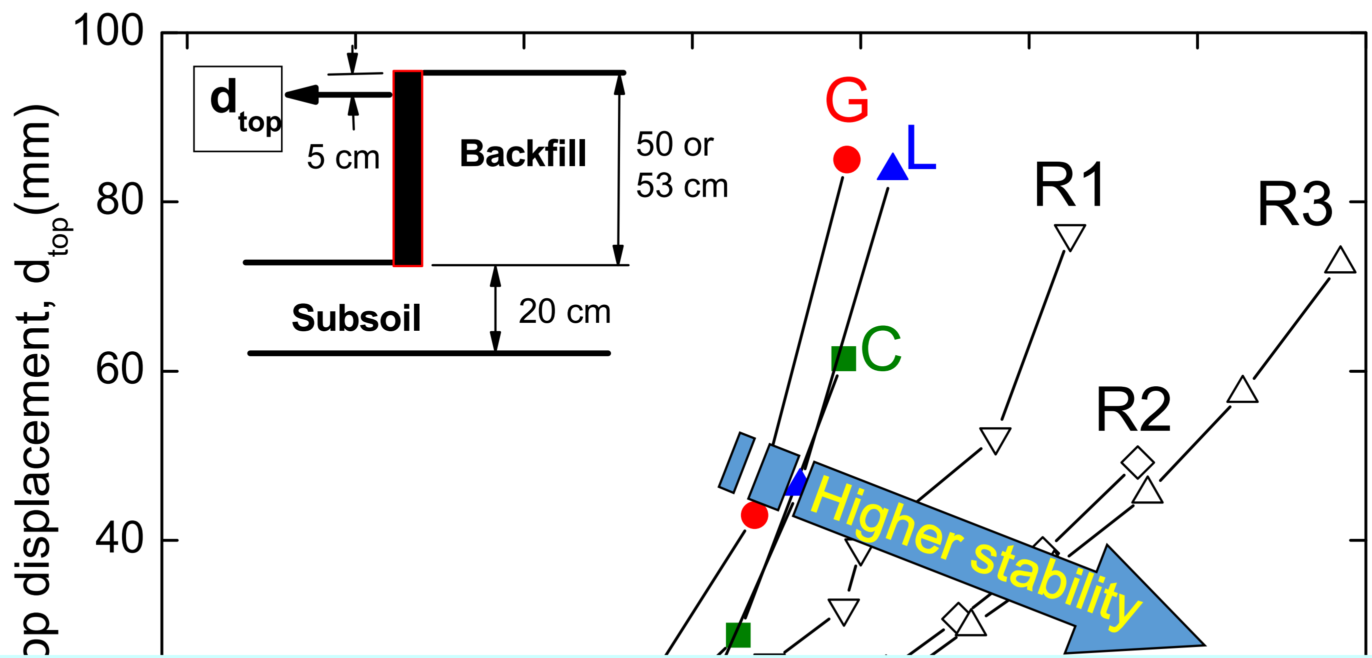
G: gravity

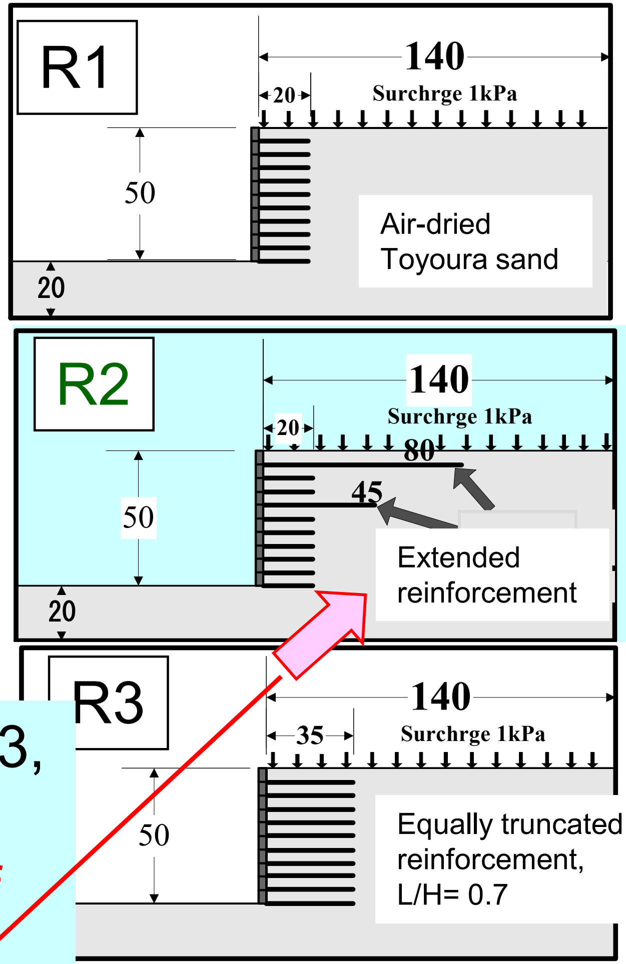


C: cantilever



L: leaning





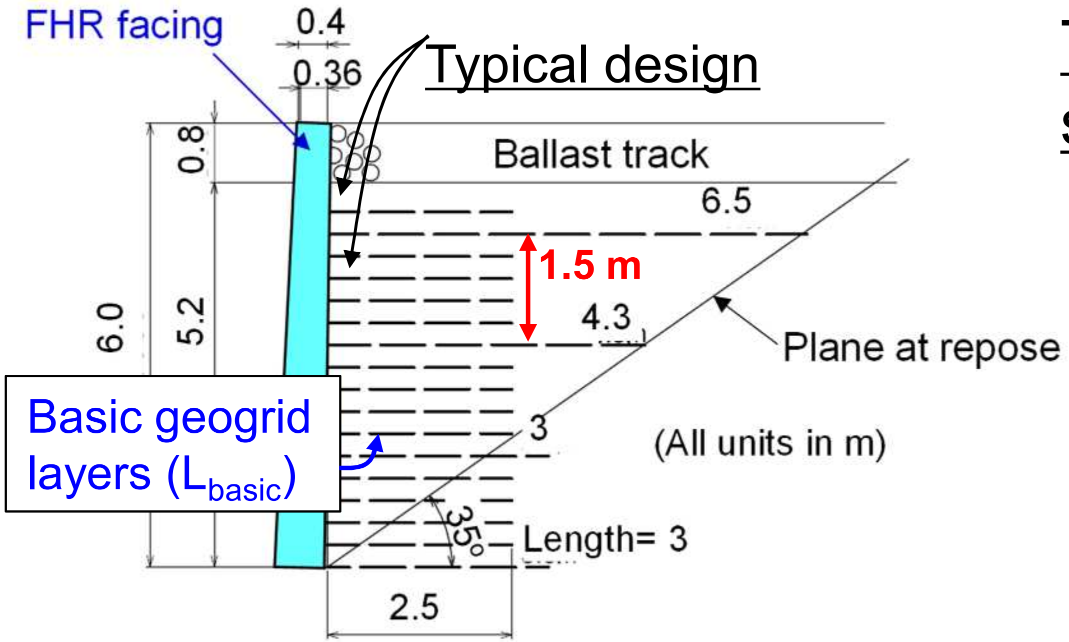
R2: more stable than R1, while similar behaviour as R3, whereas more cost-effective than R3 because of:

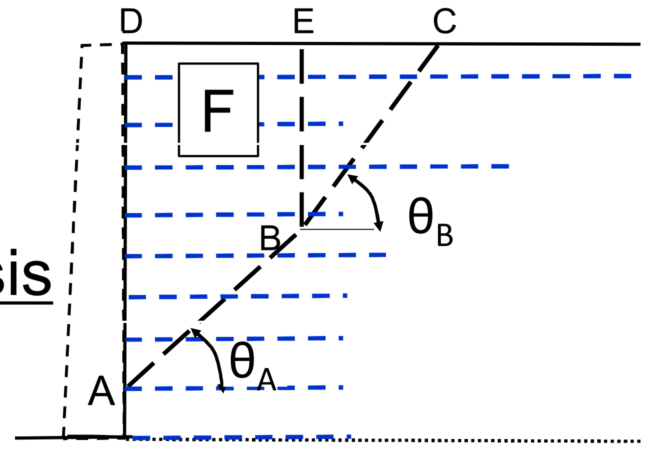
1) a less amount of geogrid; and 2) a less amount of excavation when constructed on a slope

⇒ R2 is recommended as the standard type in the current design code.

(Koseki et al., 2008)

Geogrid arrangement by the current design





The stability of "facing & front wedge F together" is examined for all possible locations of points A & B and all possible angles θ_A & θ_B of trial slip plane.

The length L_{basic} of the basic geogrid layers is the largest value among 1), 2) & 3):

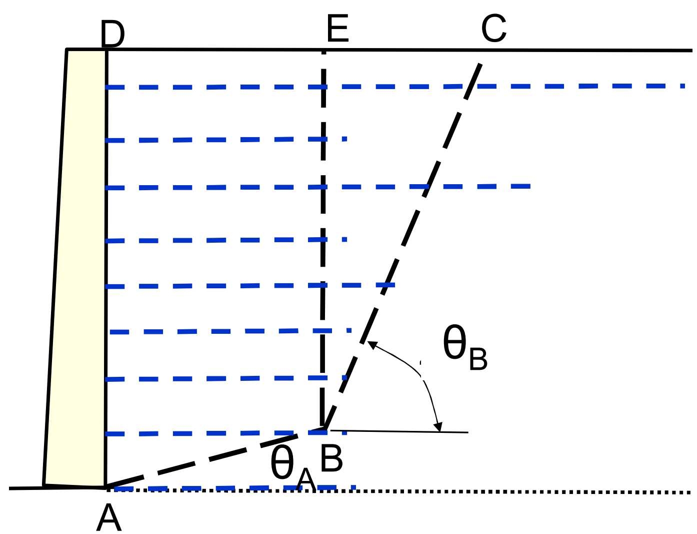
1) 35 % of wall height; 2) 1.5 m; and

3) the length for <u>the residual wall deformations</u>* to be lower than allowable values.

⇒ In this case, L_{basic}= 2.5 m by 3).

* the value by over-turning & lateral sliding evaluated by "the Newmark method based on the TW stability analysis" plus the value by shear deformation of reinforced zone

When using FHR facing, …

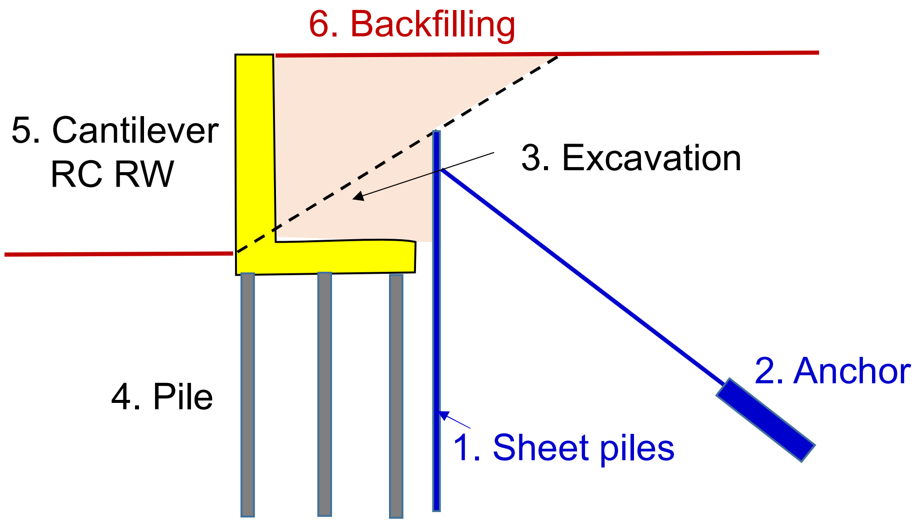


… point A is always at the heel of the footing, which largely increases the wall stability.

At many places in urban areas, strong need for the reconstruction of a gentle slope to a vertical wall

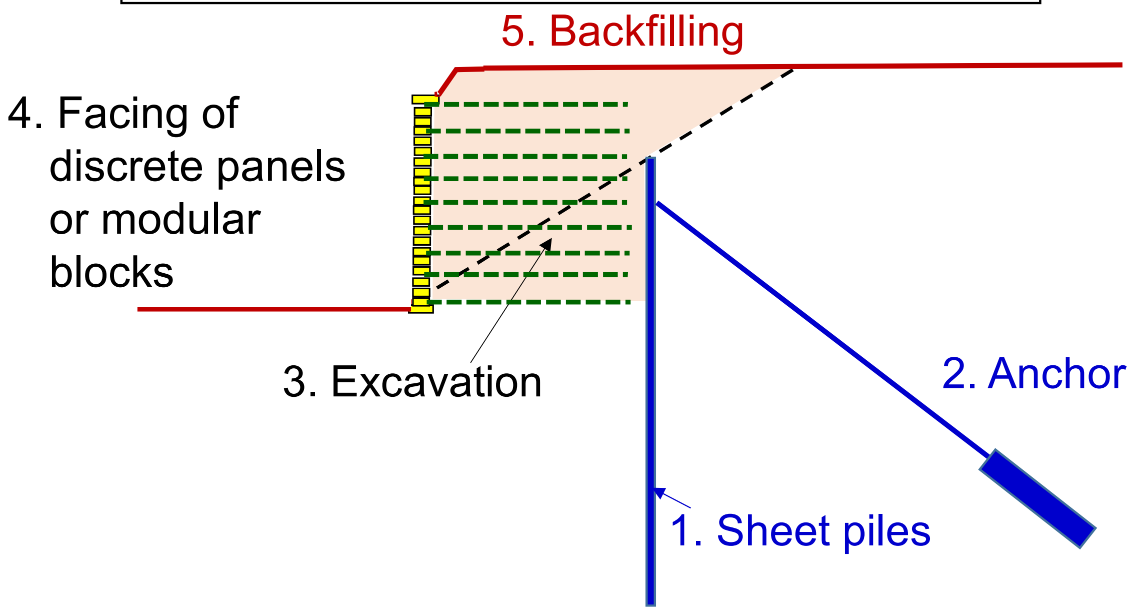
However, the construction of a RW on a slope may require a large amount of slope excavation and the use of temporary anchored sheet piles ⇒ an increase in the construction cost & period.

Conventional cantilever RW



Large excavation due to a relatively wide base of cantilever RW

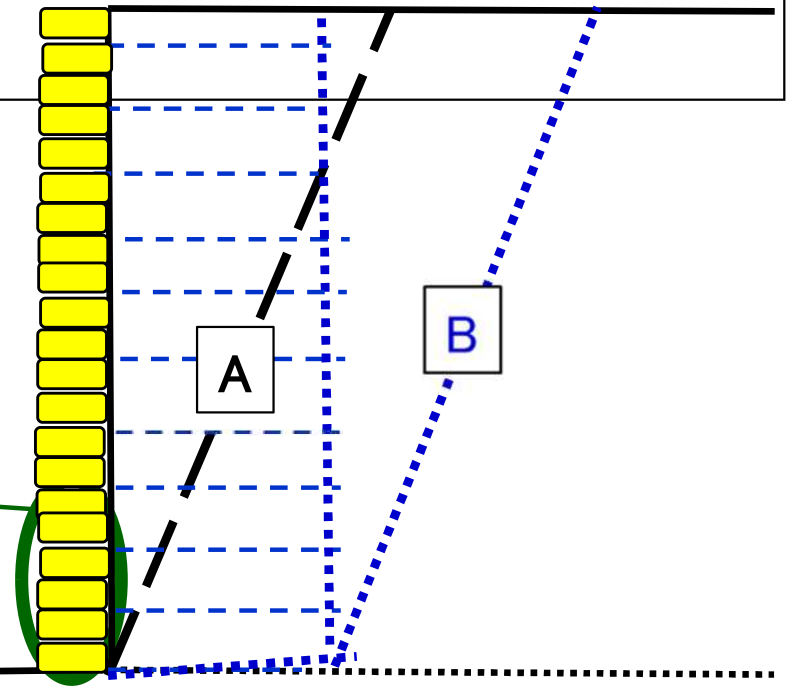
MSE RW having facing of discrete panels or modular blocks



Large excavation due to the use of relatively long reinforcement required for sufficient wall stability (as explained next)

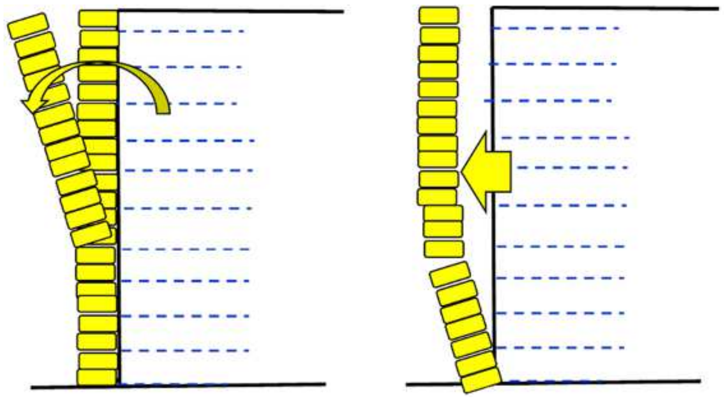
When all the reinforcement layers are relatively short, not fully crossing the active failure plane **A** in the unreinforced backfill, the failure plane in the reinforced backfill becomes shallow as **B** ⇒ **low wall stability**

⇒ Particularly when the facing is discrete panels or modular blocks, the wall stability against lateral sliding & over-turning becomes rather low…..

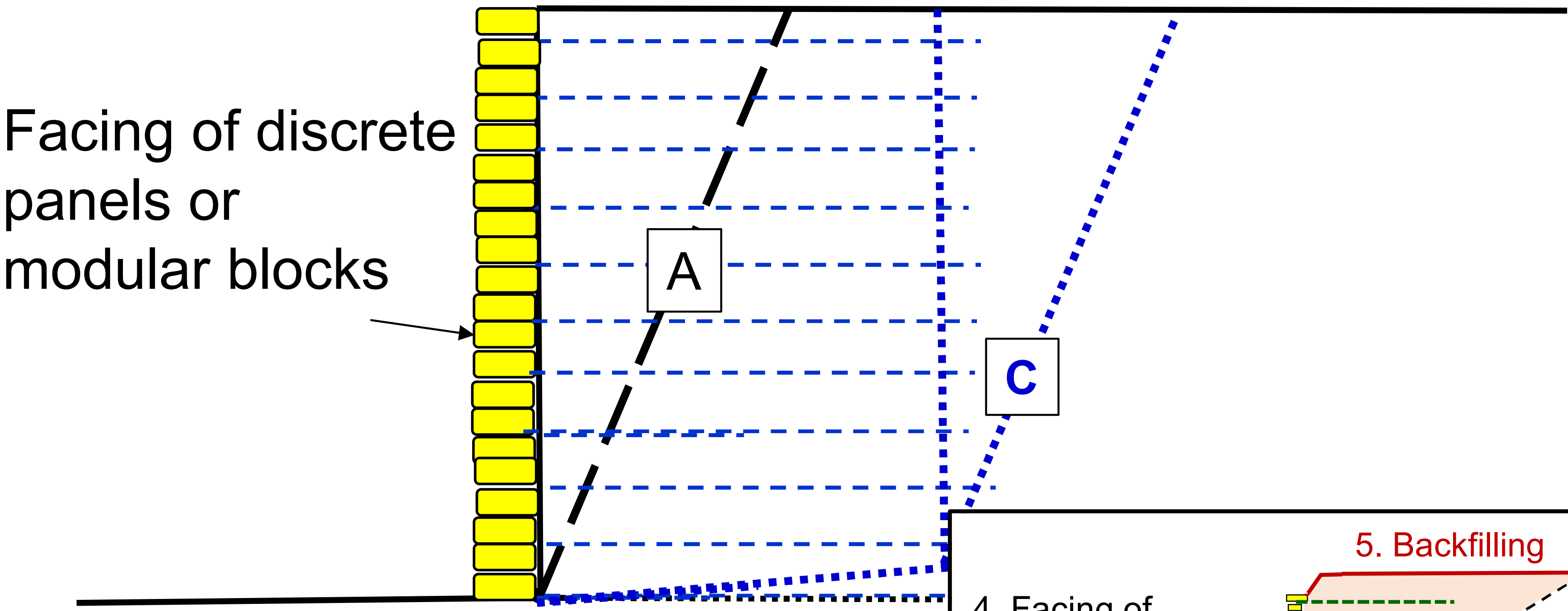


… because:
as the facing is not strong enough to prevent local failure of facing, particularly when large overturning moment develops by severe seismic loads;

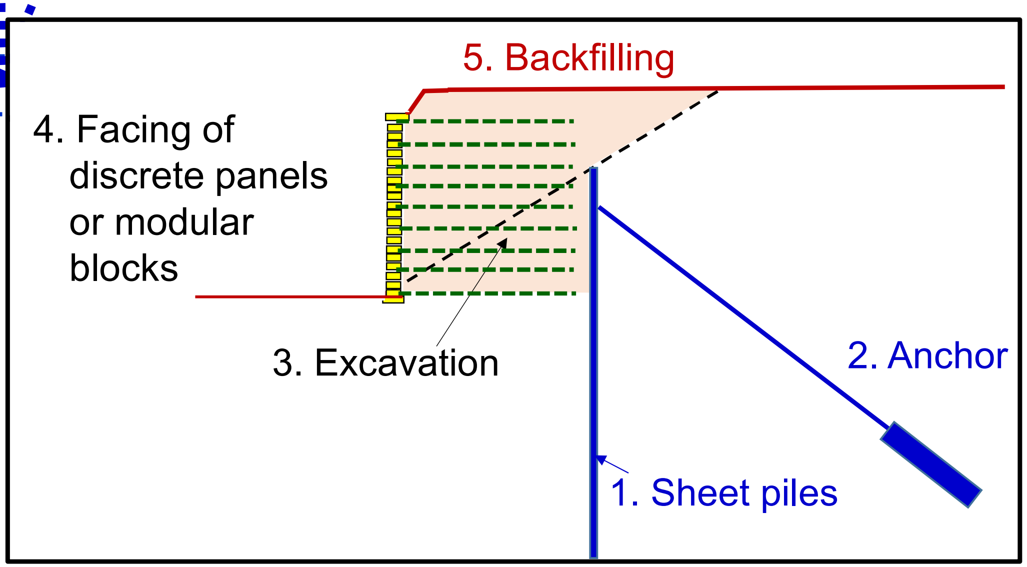
and other local facing failure may take place



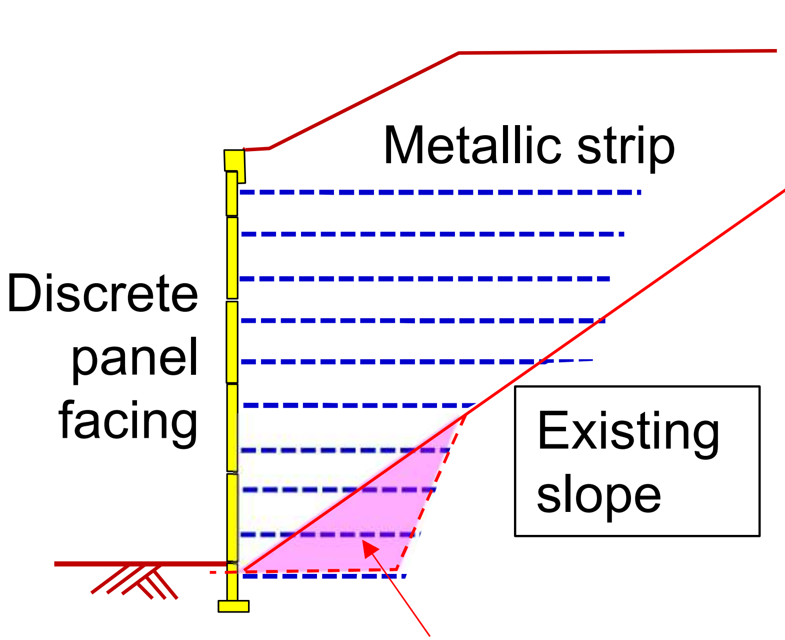
So, when the facing is discrete panels or modular blocks, to ensure sufficient wall stability, long reinforcement (usually L/H ≥ 0.7) that fully crosses the active failure plane **A** developing a deep failure plane **C** becomes necessary.



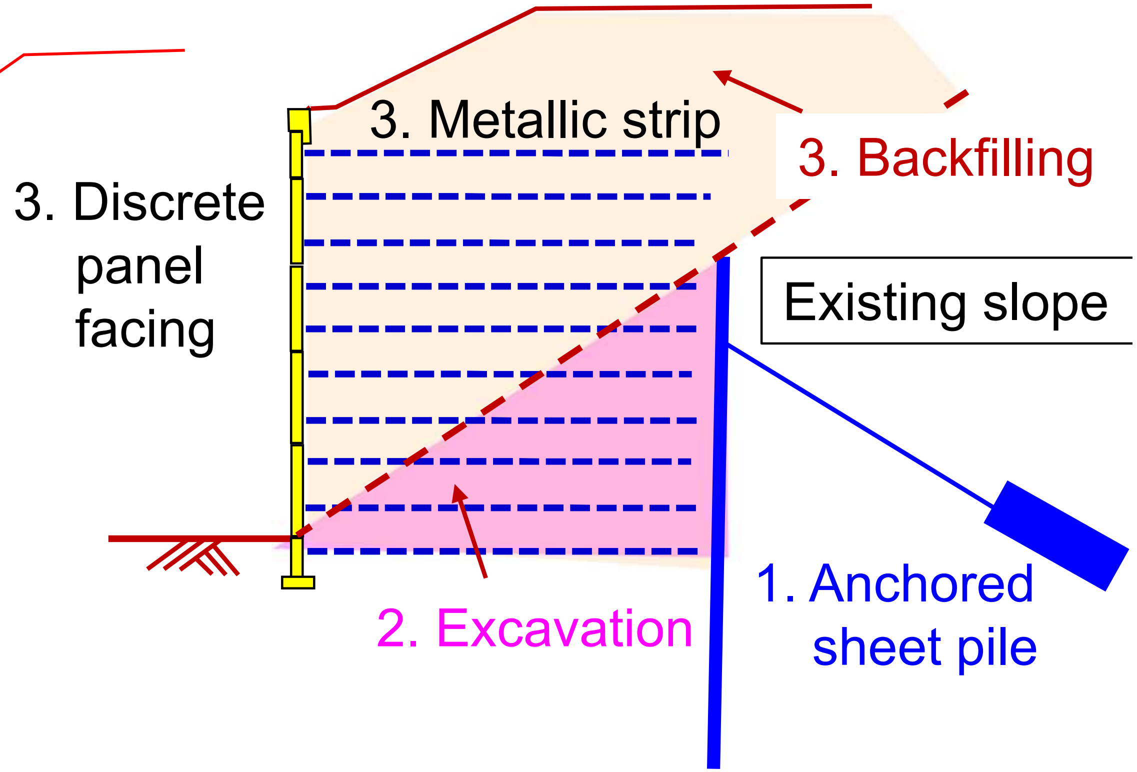
- Then, large slope excavation becomes necessary and the use of anchored sheet piles may be required.



Besides ……



the use of relatively short metallic strips to reduce the amount of excavation may result in insufficient pull-out resistance.

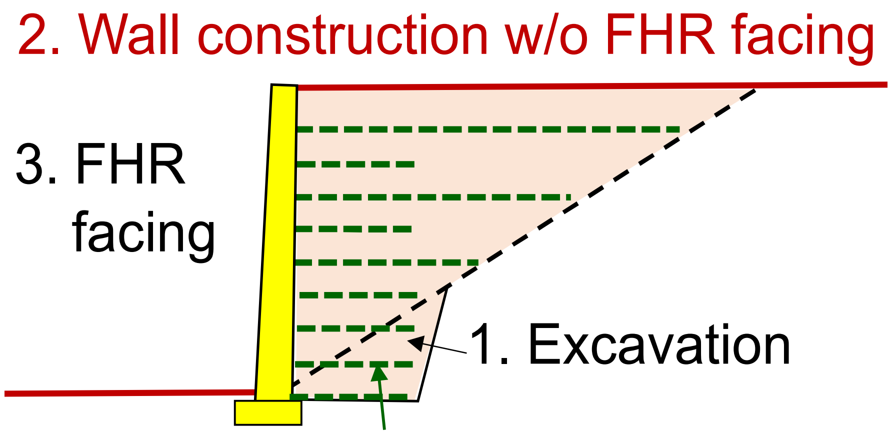


The use of long metallic strips to prevent their pull-out failure results in:

⇒ an increase in the slope excavation and the use of anchored sheet piles;

⇒ an increase in the construction cost & period

GRS RW with FHR facing



Short basic geogrid layers
⇒ a reduction in slope excavation and no use of anchored sheet piles

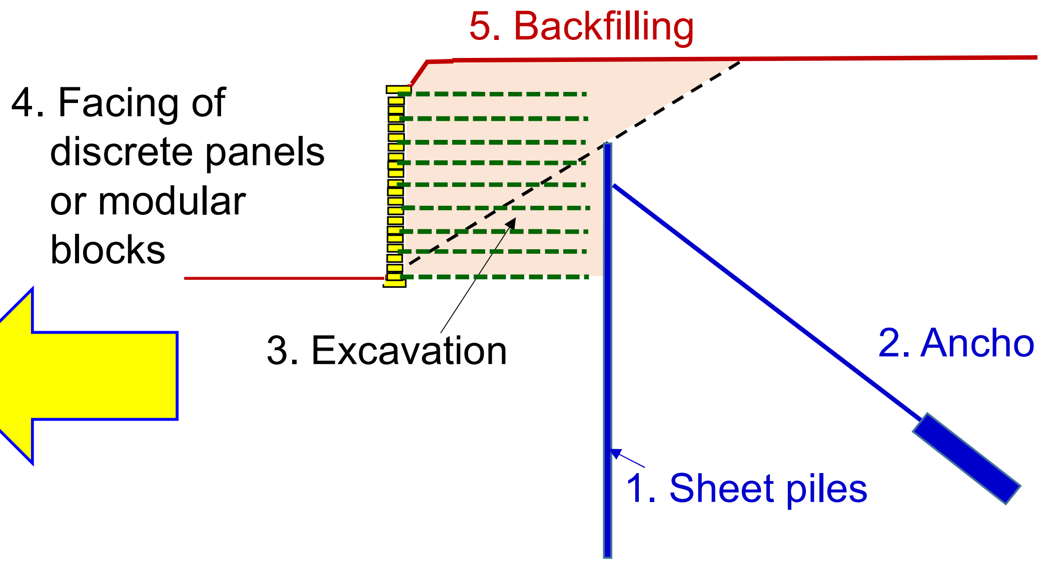
A reduction in the wall stability by the use of short basic geogrid layers is covered by:

1. taking advantages of high pull-out strength of planar geogrid;

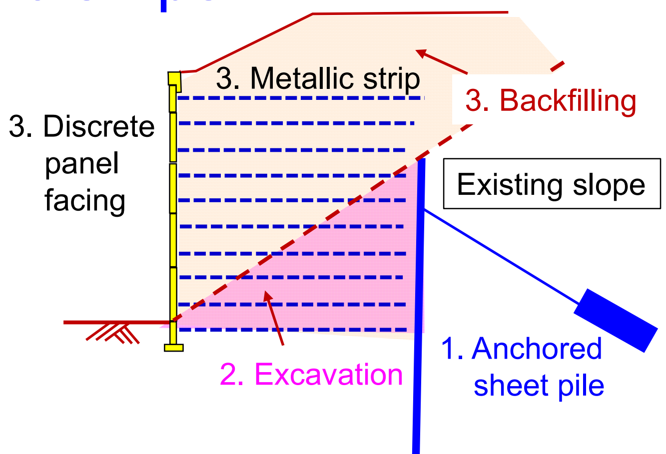
and the use of:

2. several long geogrid layers; &
3. FHR facing.

MSE RW having facing of discrete panels or modular blocks and using relatively long geogrid layers

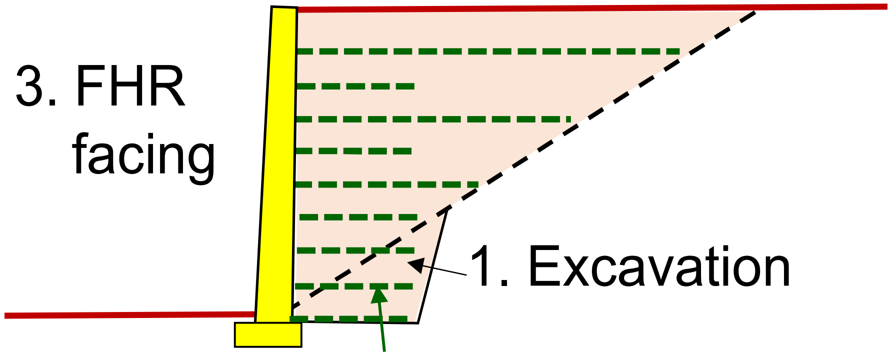


MSE RW having facing of discrete panels and using long metallic strips



GRS RW with FHR facing

2. Wall construction w/o FHR facing



Short basic geogrid layers
⇒ a reduction in slope excavation and no use of anchored sheet piles

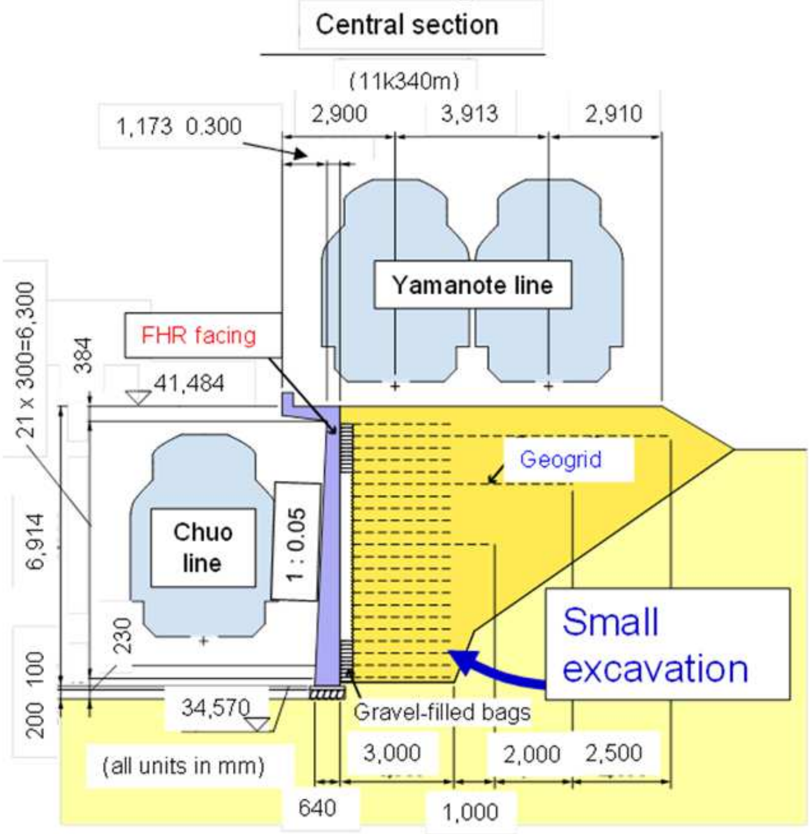
A reduction in the wall stability by the use of short basic geogrid layers is covered by:

1. taking advantages of high pull-out strength of planar geogrid;

and the use of:

2. several long geogrid layers; &
3. FHR facing.

Near Shinjuku Station, Tokyo, constructed during 1995 – 2000

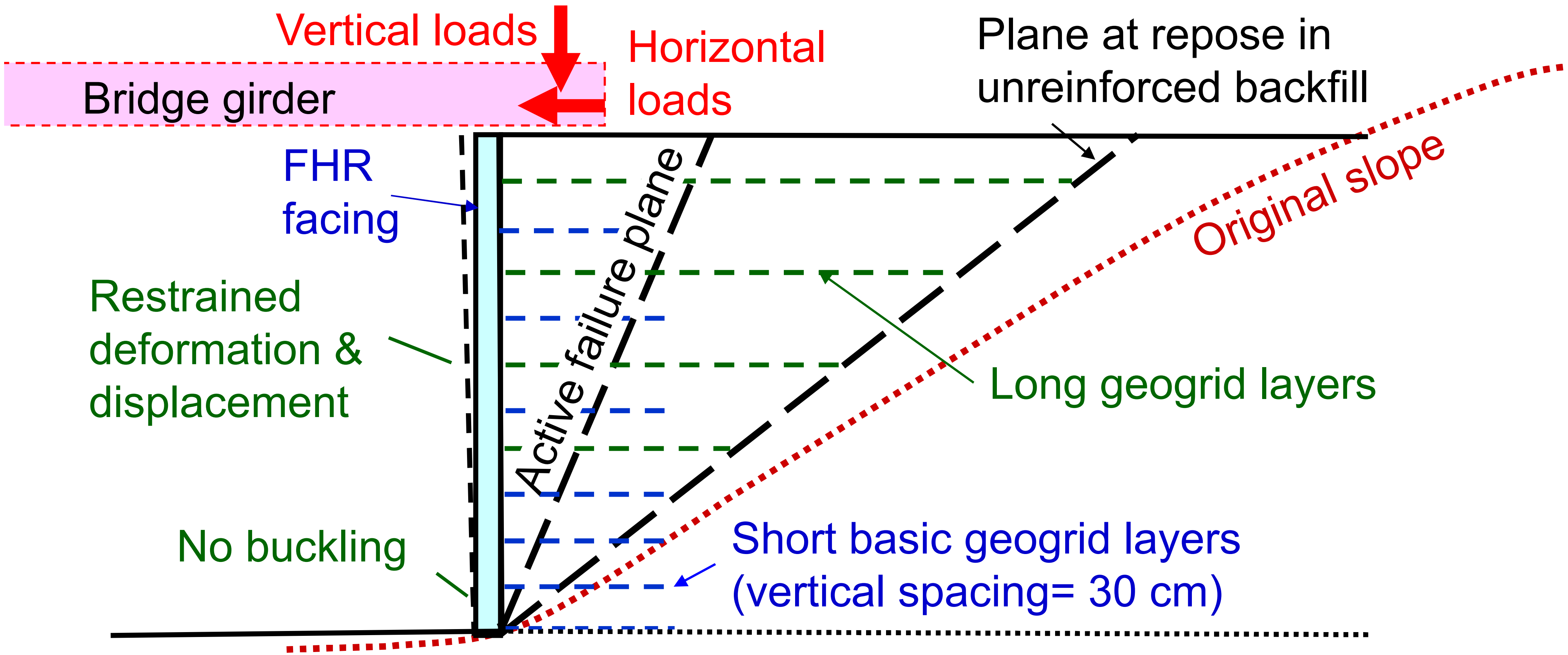


The use of <u>FHR facing and closely-spaced short basic geogrid layers together with several long geogrid layers</u> enhances monolithic behaviour of <u>the FHR facing plus reinforced zone</u> as a composite, not developing local failure,

⇒ high wall stability against over-turning & lateral sliding and small shear deformation when subjected to:

a) not only static and seismic earth pressures from the backfill,

b) but also external loads at or near the FHR facing !



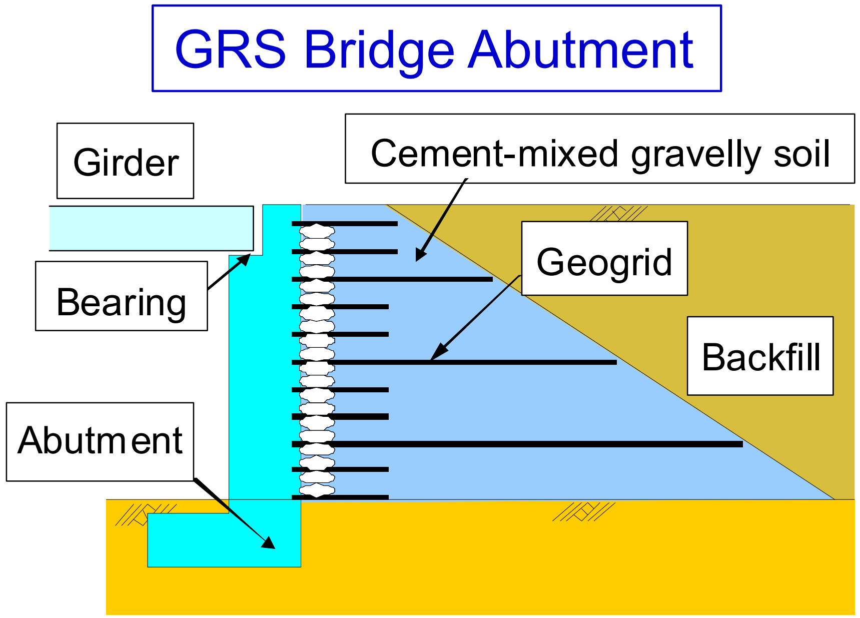
The use of FHR facing and closely-spaced short basic geogrid layers together with several long geogrid layers enhances monolithic behaviour of the FHR facing plus reinforced zone as a composite, not developing local failure,

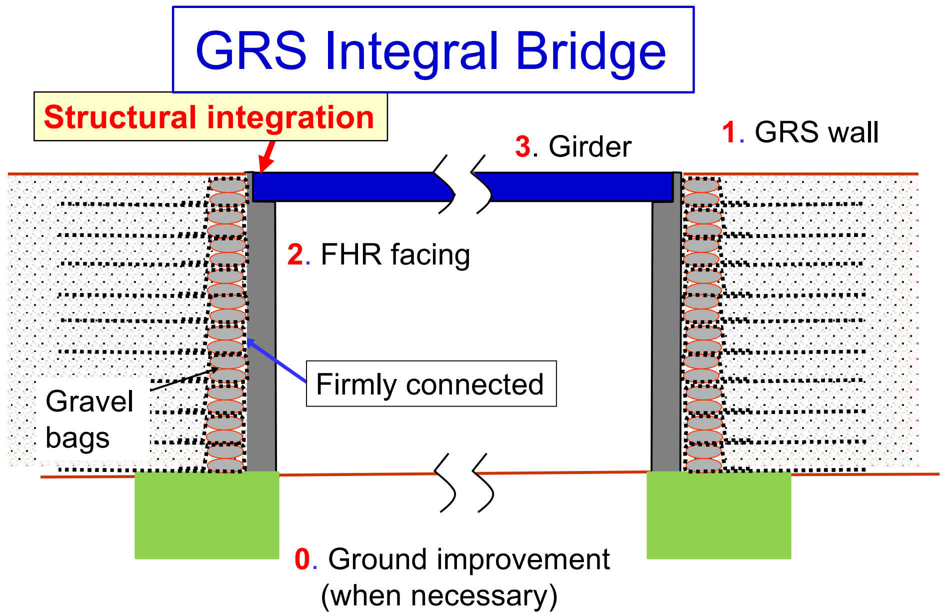
⇒ high wall stability against over-turning & lateral sliding and small shear deformation when subjected to:

a) not only static and seismic earth pressures from the backfill,

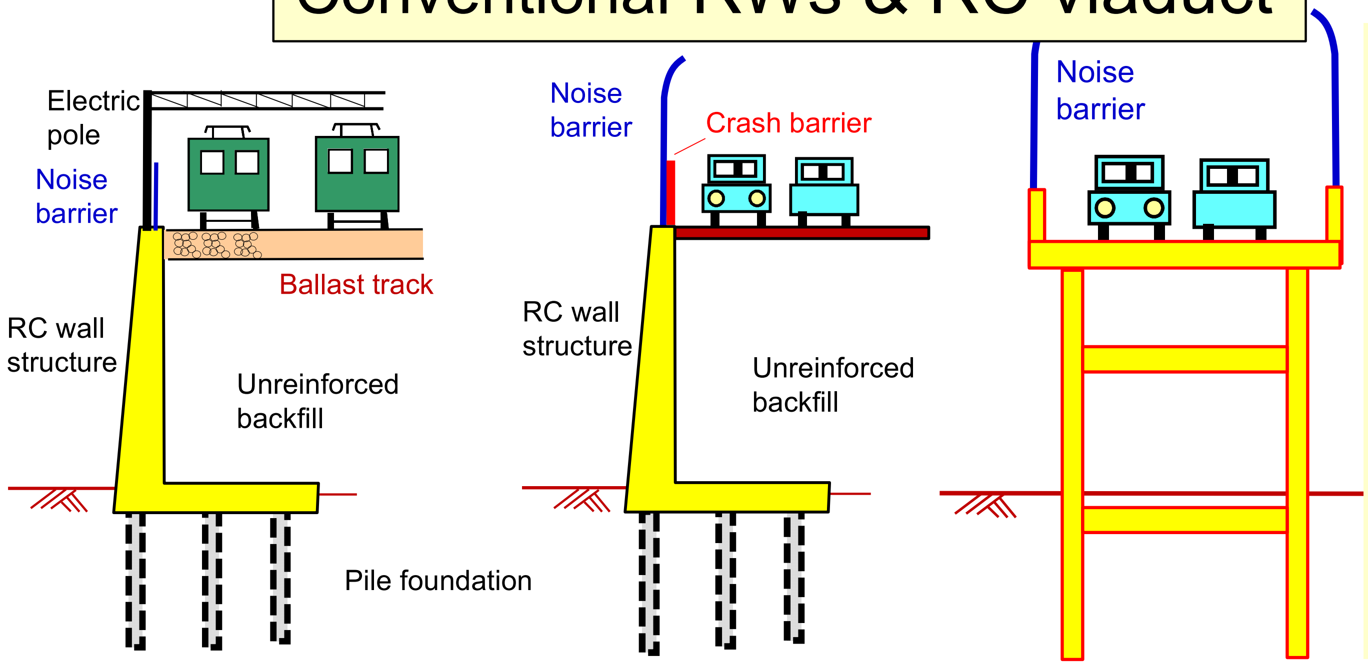
b) but also external loads at or near the FHR facing !

These features led to the developments of GRS bridge structures:





Conventional RWs & RC viaduct



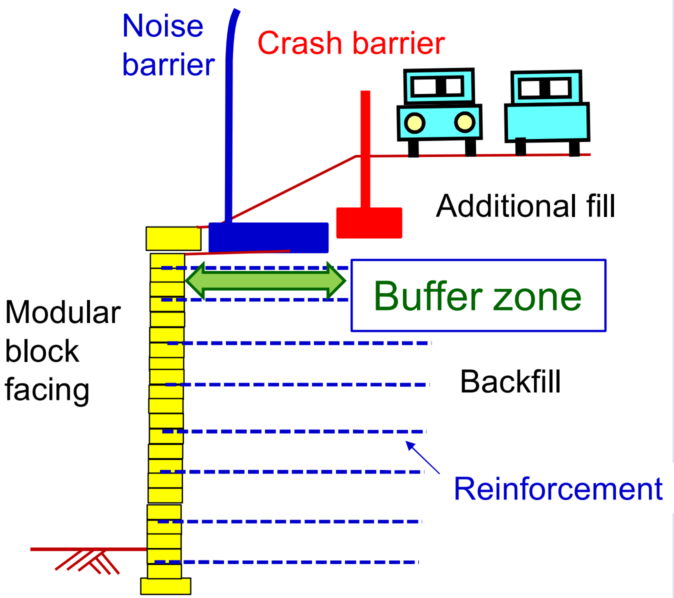
<u>Disadvantages</u>

Costly

<u>Advantages</u>

- Limited occupied space
- Ability to support other structures

GRS RWs with facing of modular blocks or discrete panels

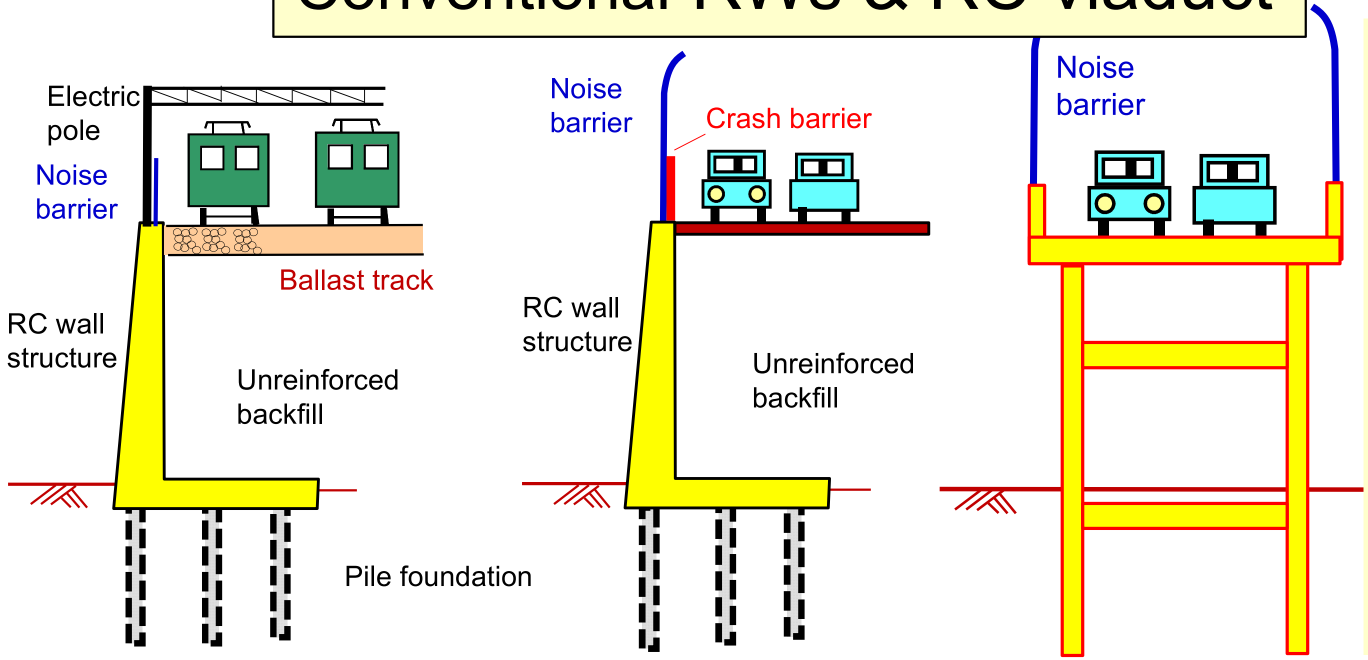


Less costly,

but, <u>unlike conventional RWs & RC viaduct</u>,

- a buffer zone is required to ensue the safe operation of road & railway, so wide occupied space required; and
- the facing cannot effectively support other structures, so, additionally foundations become necessary.

Conventional RWs & RC viaduct



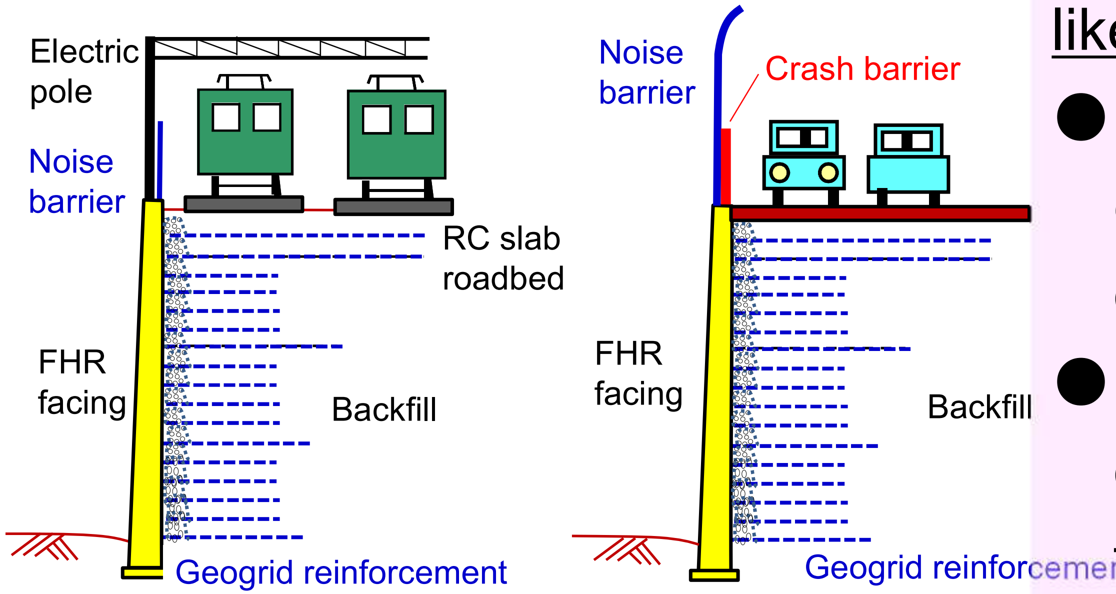
<u>Disadvantages</u>

Costly

<u>Advantages</u>

- Limited occupied space
- Ability to support other structures

GRS RWs with FHR facing

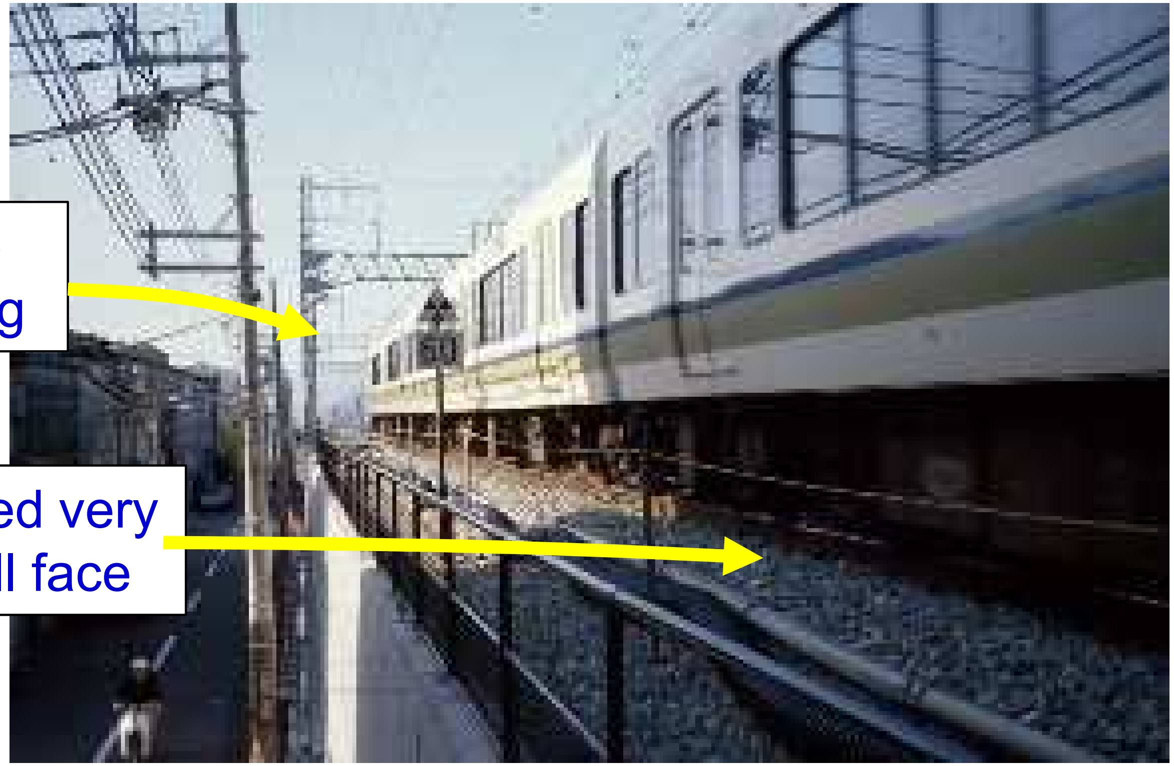


Less costly; and,

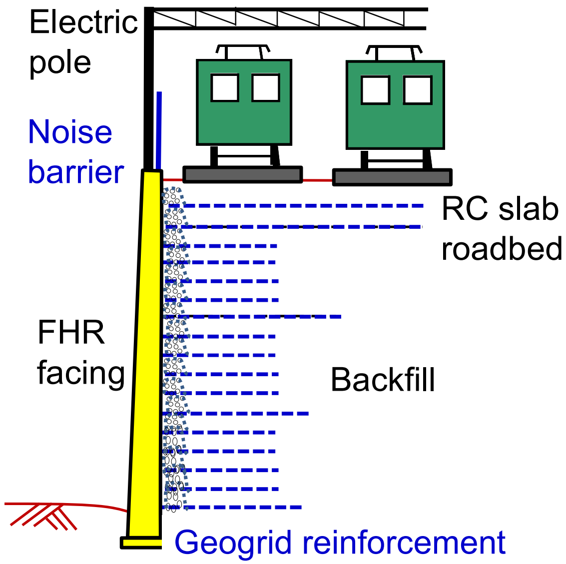
<u>like conventional RWs & RC viaduct,</u>

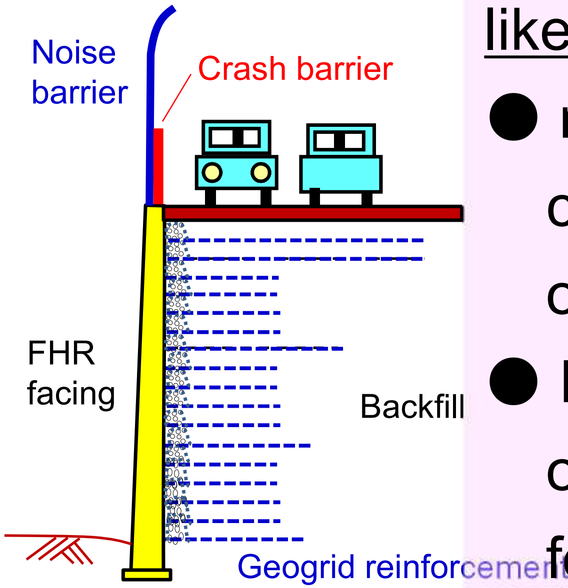
- railway & road can be arranged very close to the wall face, so narrow occupied space; and
- FHR facing can effectively support other structures, so no need for foundations.

JR Kobe line, Amagasaki



GRS RWs with FHR facing





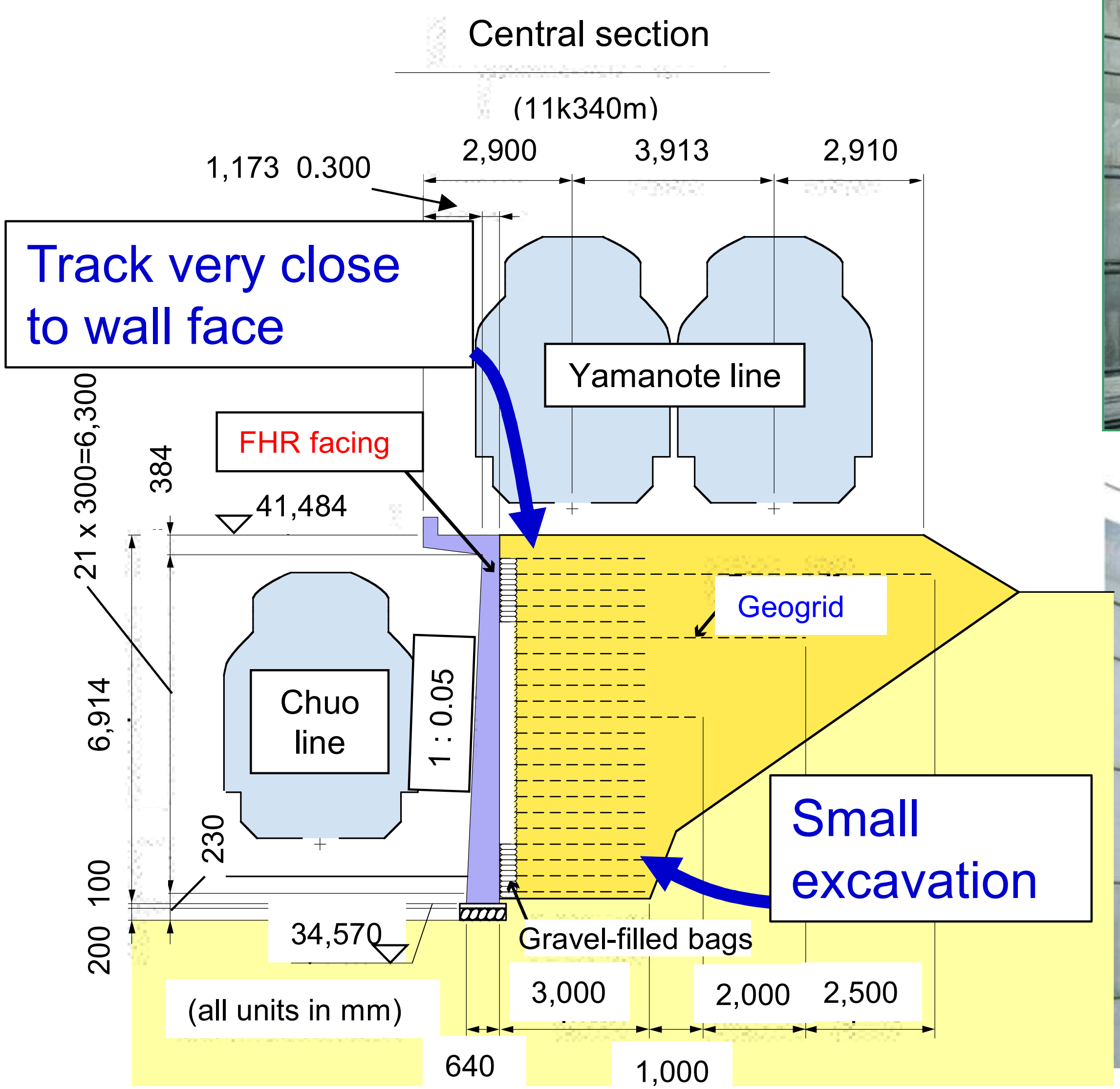
Less costly; and,

<u>like conventional RWs & RC viaduct,</u>

- railway & road can be arranged very close to the wall face, so narrow occupied space; and
- FHR facing can effectively support other structures, so no need for foundations.

GRS RW with FHR facing supporting a commuter railway

Near Shinjuku Station, Tokyo,
constructed during 1995 – 2000



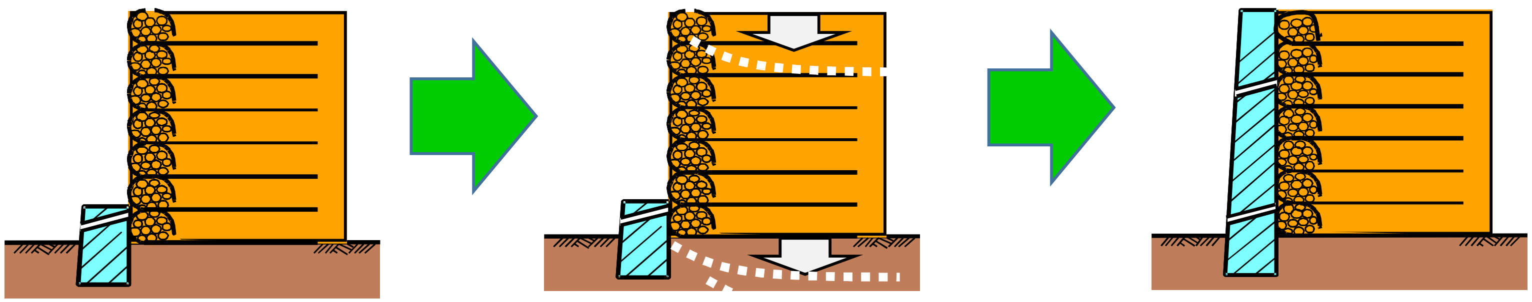
Multiple functions of FHR facing (summary)

1) The facing is the important and **essential structural component** that confines the backfill, develops large tensile forces in the reinforcement and can support other structures. So, **during service**, the facing should be **stiff enough**.

↕

2) On the other hand, **during the construction of reinforced backfill**, the facing should be **deformable enough** to accommodate the deformation of backfill & subsoil.

↕ This contradiction can be solved by staged-construction.

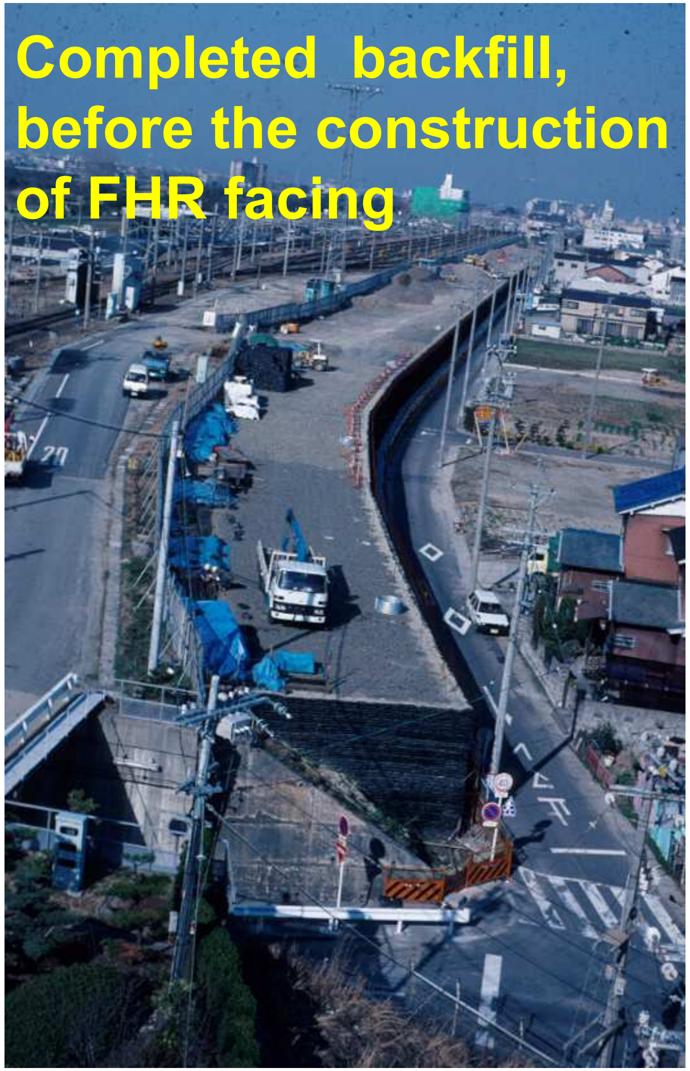


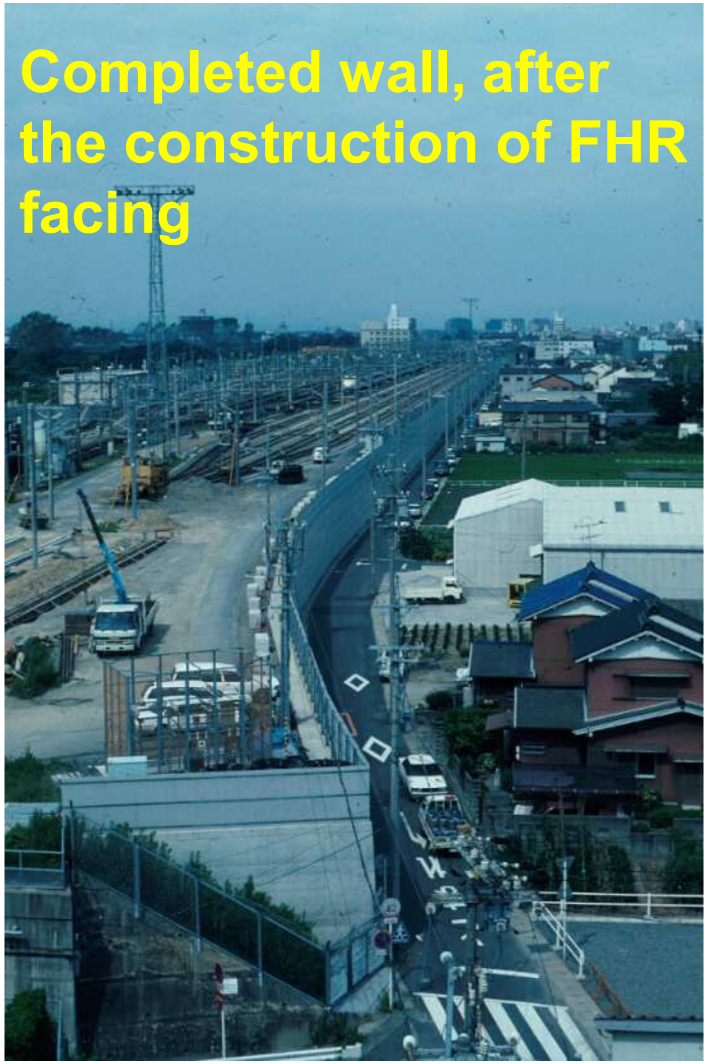
Deformable facing — Settlement — Full-height rigid facing

Contents

Staged construction of GRS RW with FHR facing

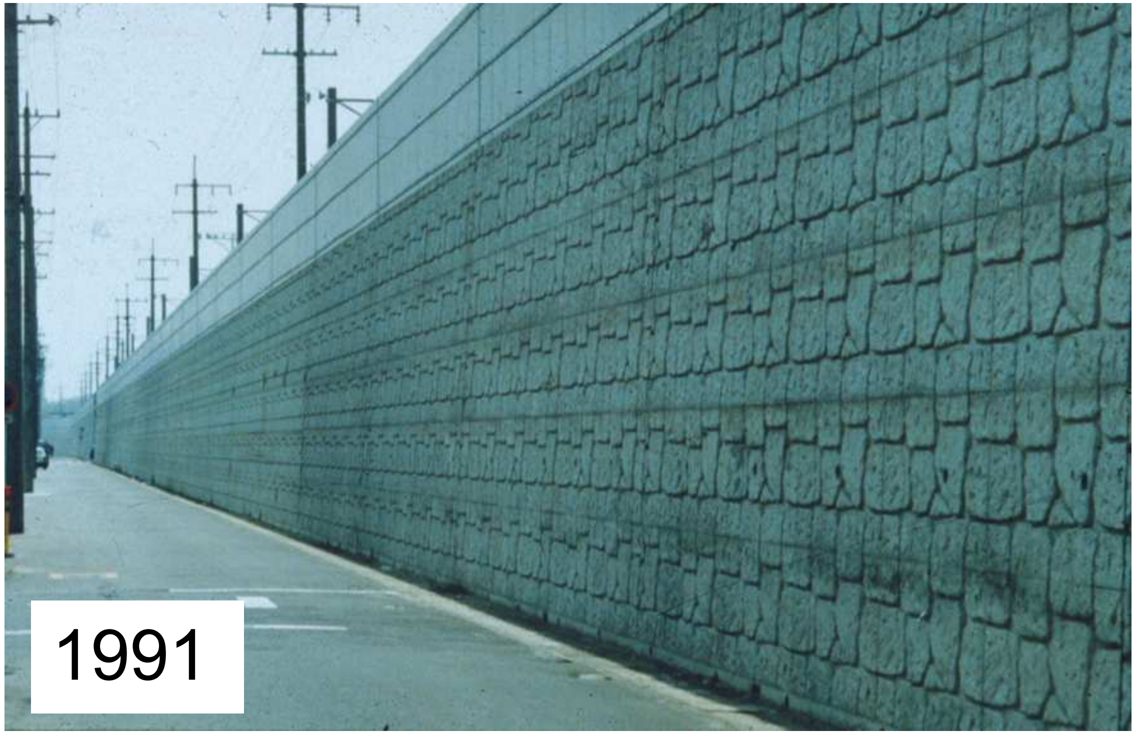
Depot for HSR (Shinkansen) at Biwajima, Nagoya, 1990 - 1991
- average wall height= 5 m & total wall length= 930 m

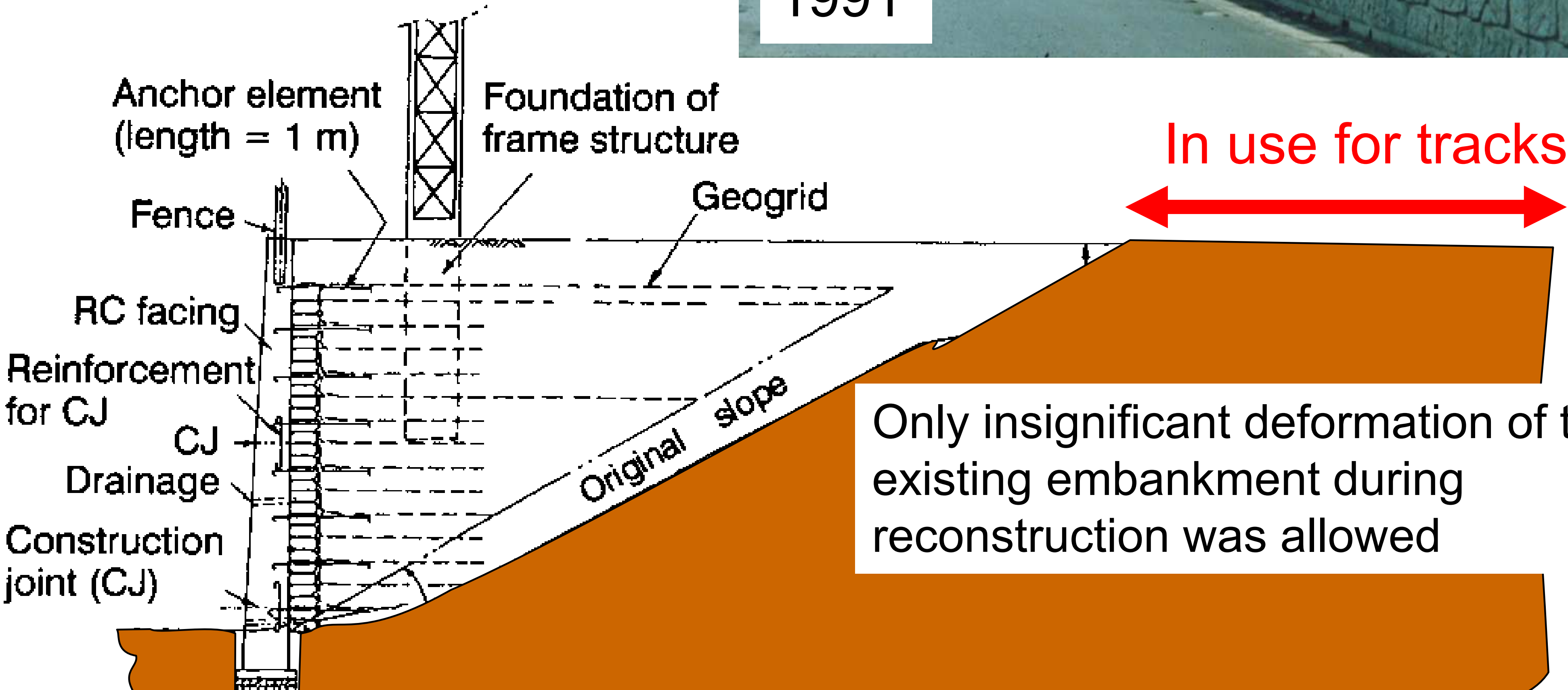




GRS RW with FHR facing

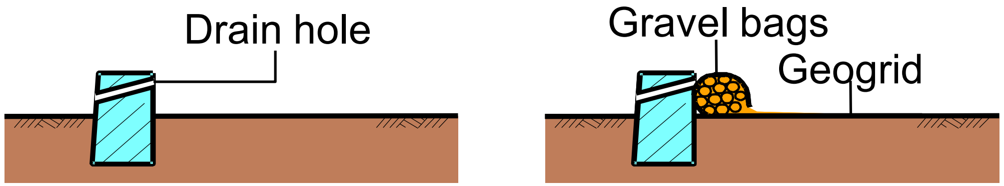
Re-construction of a gentle slope to a vertical wall for the depot of HSR (Shinkansen) at Biwajima, Nagoya





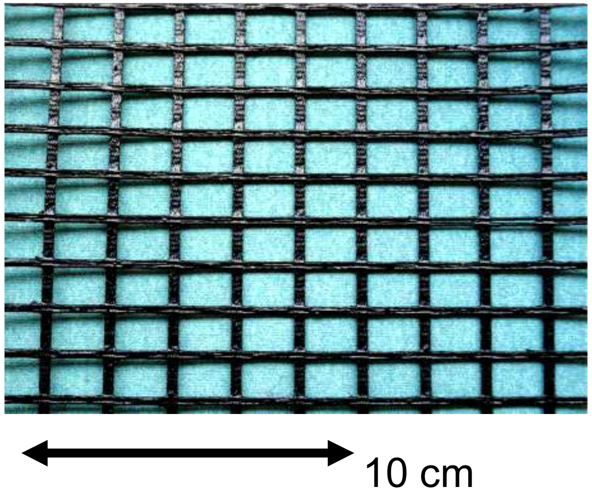
Staged construction: 1) & 2)

- Start of construction



1) Levelling pad for facing

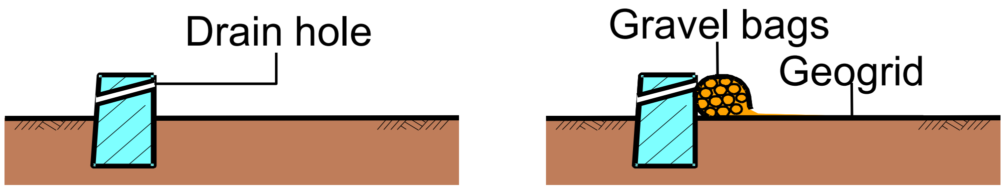
2) Placing gravel bags wrapped-around with geogrid



Typical polymer geogrid: bi-axial PVA grid:

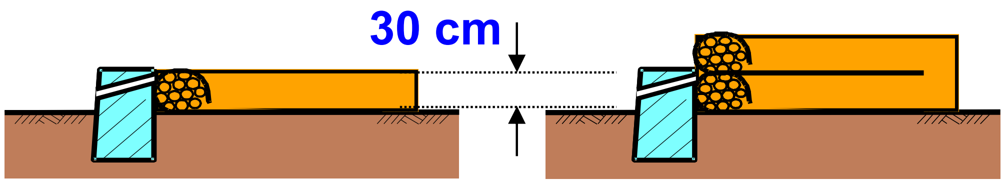
Staged construction: 3) & 4)

- Compaction of the backfill with a help of gravel bags placed at the shoulder of each soil layer



1) Levelling pad for facing

2) Placing gravel bags wrapped-around with geogrid



3) Backfilling & compaction

4) Second layer

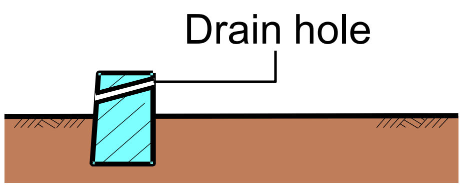
Good compaction of the backfill is achieved by:

1) a small lift (15 cm) ensured by a small vertical spacing (30 cm) between geogrid layers; and
2) no rigid facing existing during backfill compaction

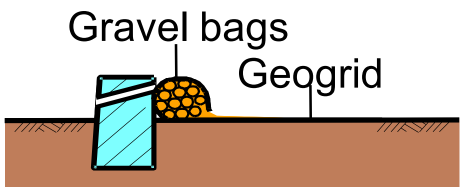
Besides, a small vertical spacing (30 cm) results in a large contact area between the geogrid and the backfill, which contributes to a high stability of the reinforced backfill as a composite.

Staged construction: 5)

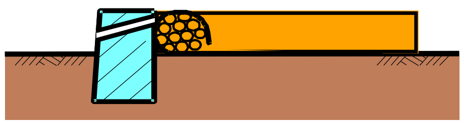
- Construction of the full-height geogrid-reinforced backfill without using FHR facing



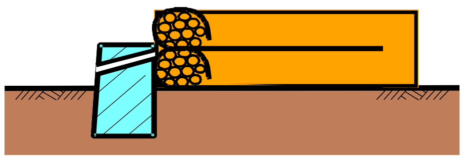
1) Levelling pad for facing



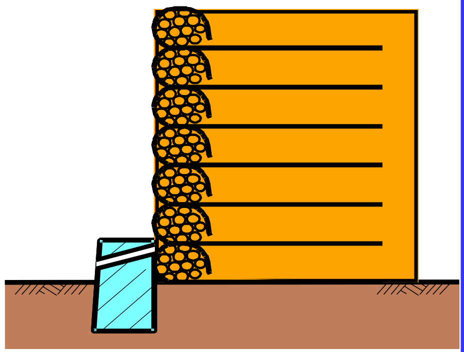
2) Placing gravel bags wrapped-around with geogrid



3) Backfilling & compaction



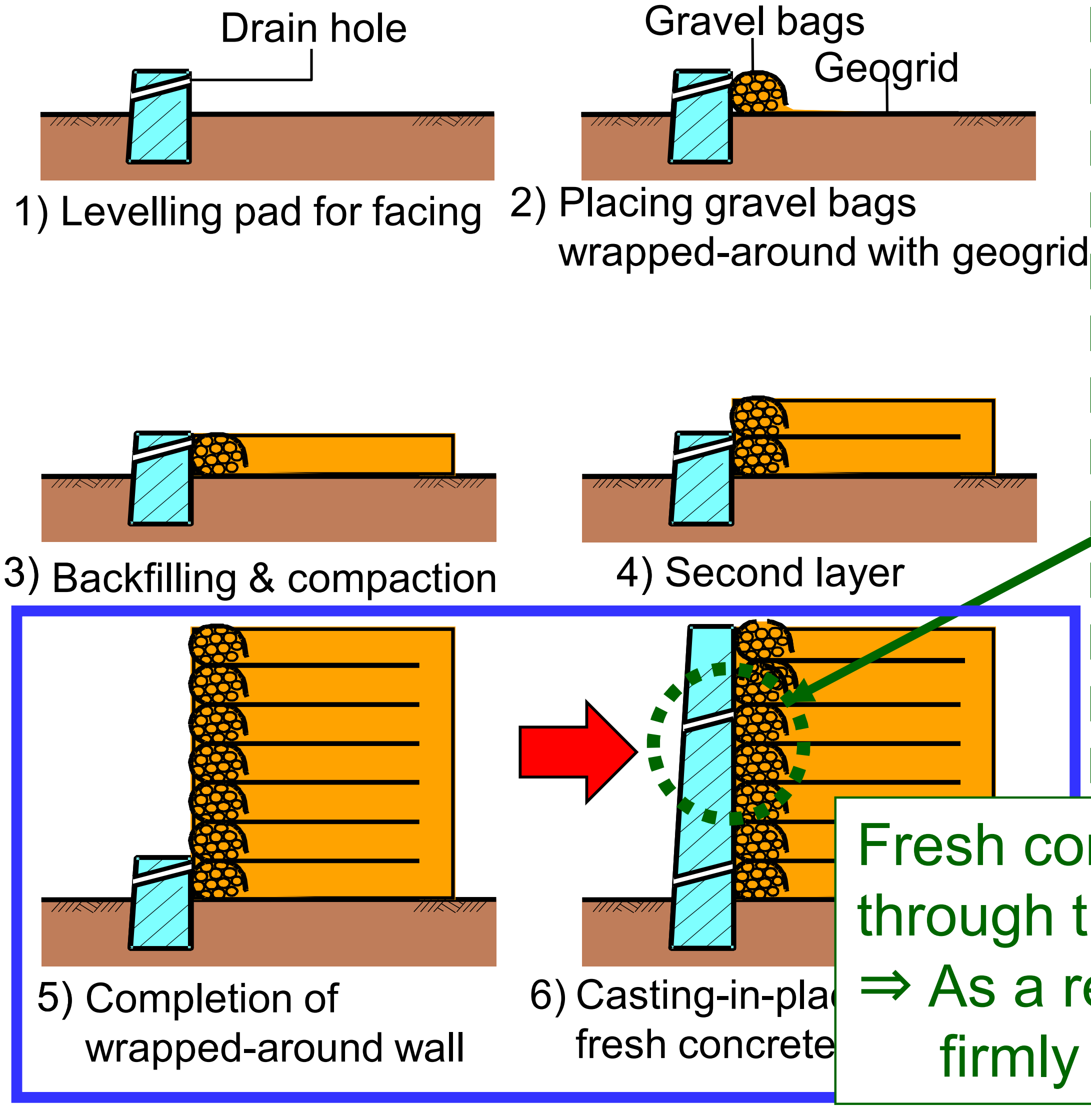
4) Second layer

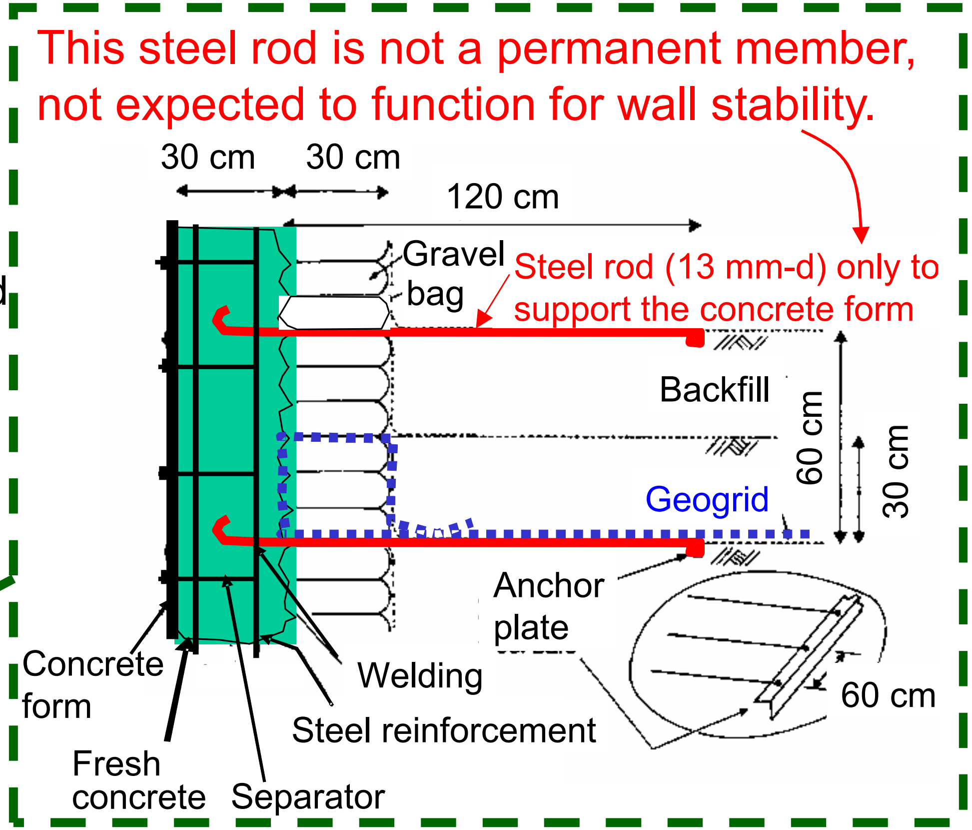


5) Completion of wrapped-around wall

Staged construction from step 5) to step 6):

- After sufficient compression of the backfill & subsoil has taken place, FHR facing is constructed by casting-in-place fresh concrete directly on the geogrid-wrapped-around wall face.

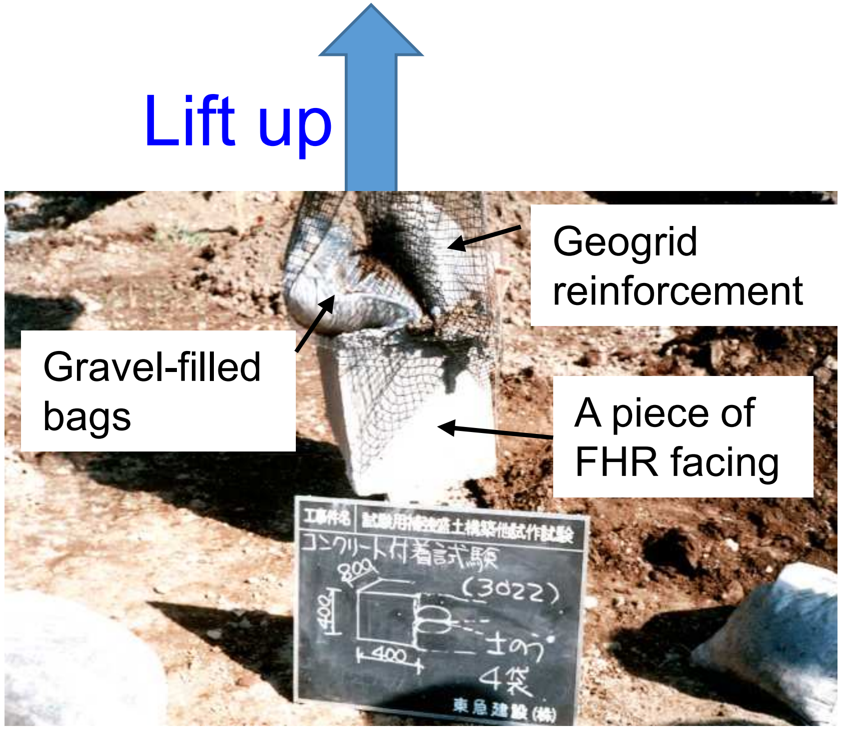




Fresh concrete enters the gravel-filled bags through the aperture of the geogrid.
⇒ As a result, FHR facing & geogrid layers are firmly connected to each other.

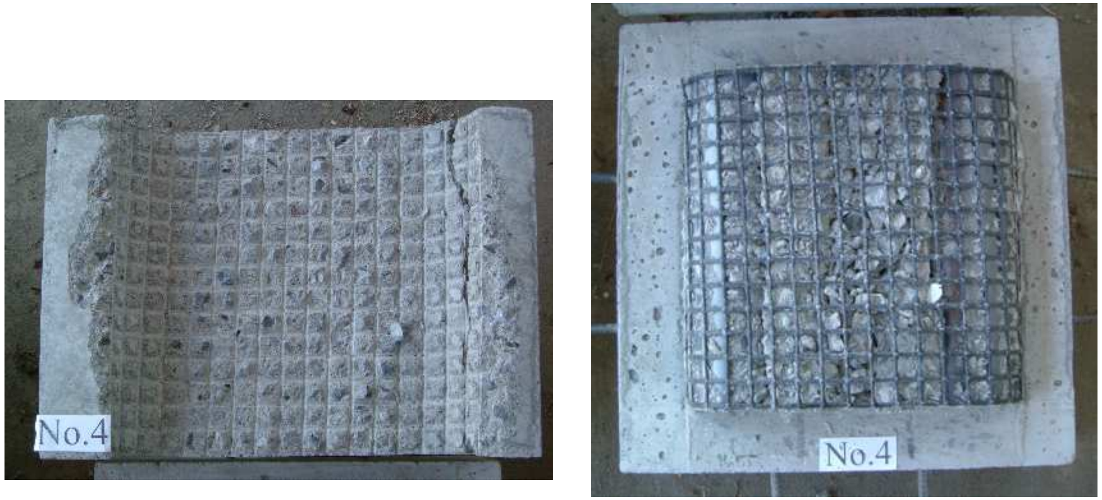
Field & laboratory tests to confirm high separation strength

Field separation test

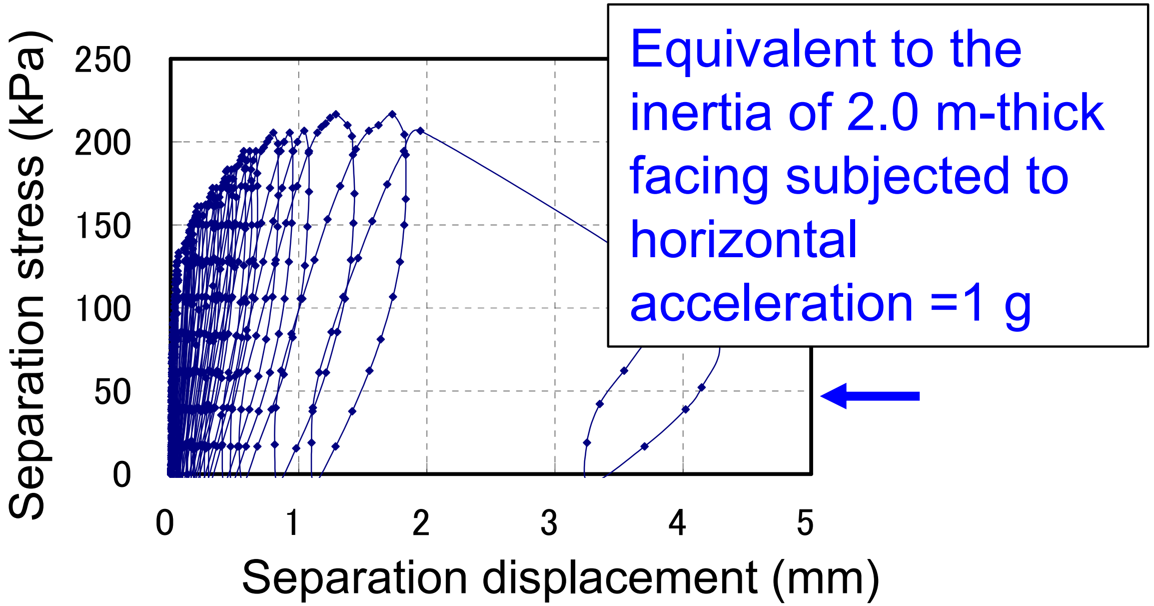


Test specimen (cut out from 40 cm-thick full-scale FHR facing), hung under 1 g:
⇒ no separation

Laboratory separation test



Specimen after separation

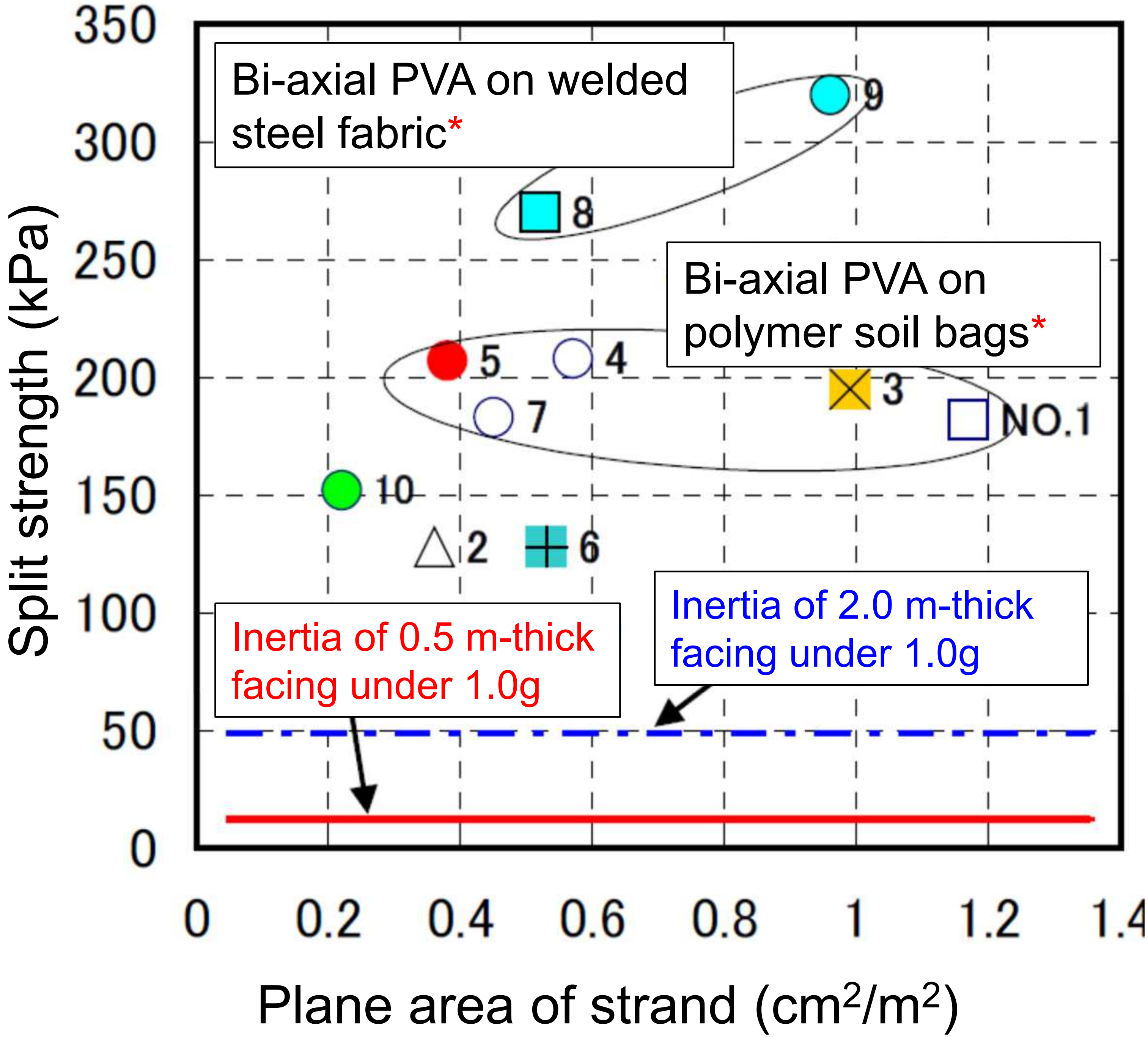


Split strength of the connection

* recommendable

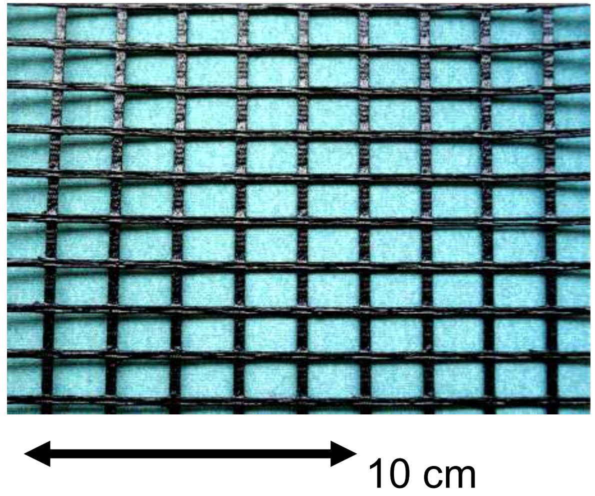
<u>Relatively low split strength:</u>

2. Uni-axial HDPE on polymer soil bags (due to low adhesive property with concrete)
6. Bi-axial PVA on polymer soil bags (by tensile rupture of the thread before splitting due to low rupture strength)
10. Uni-axial PE on polymer soil bags (due to a small contact area)



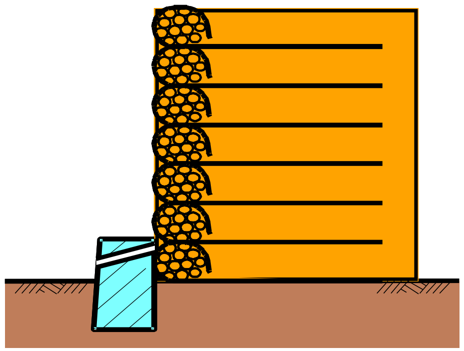
The properties required for the geogrid:

1) Sufficient strength & stiffness with low creep deformation
2) **High anchorage strength in concrete & backfill**
3) **Good adhesiveness with concrete**
4) **High long-term resistance against high pH of concrete**

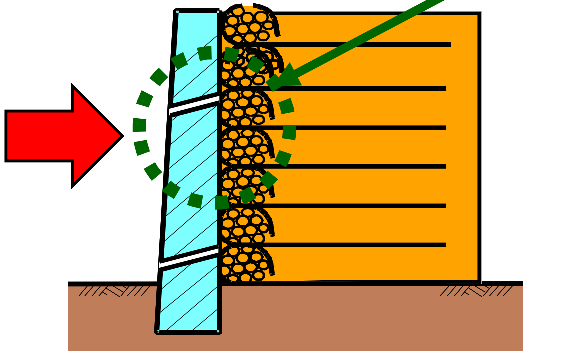


Bi-axial PVA geogrid, satisfying 1) – 4).

2), 3) & 4) are important, as the geogrid is in direct contact with fresh concrete.

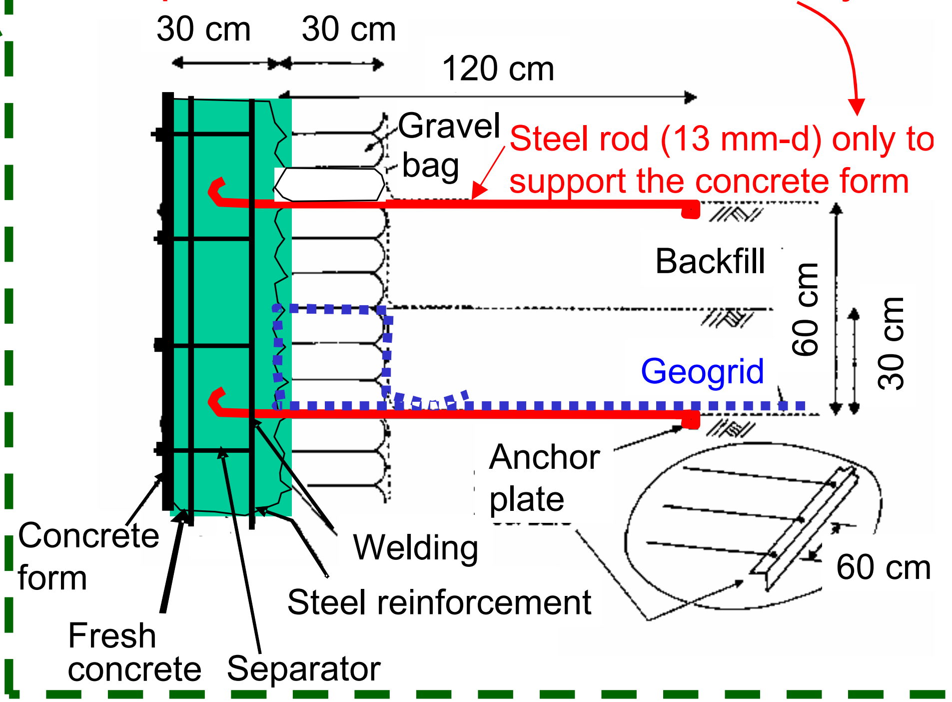


5) Completion of wrapped-around wall

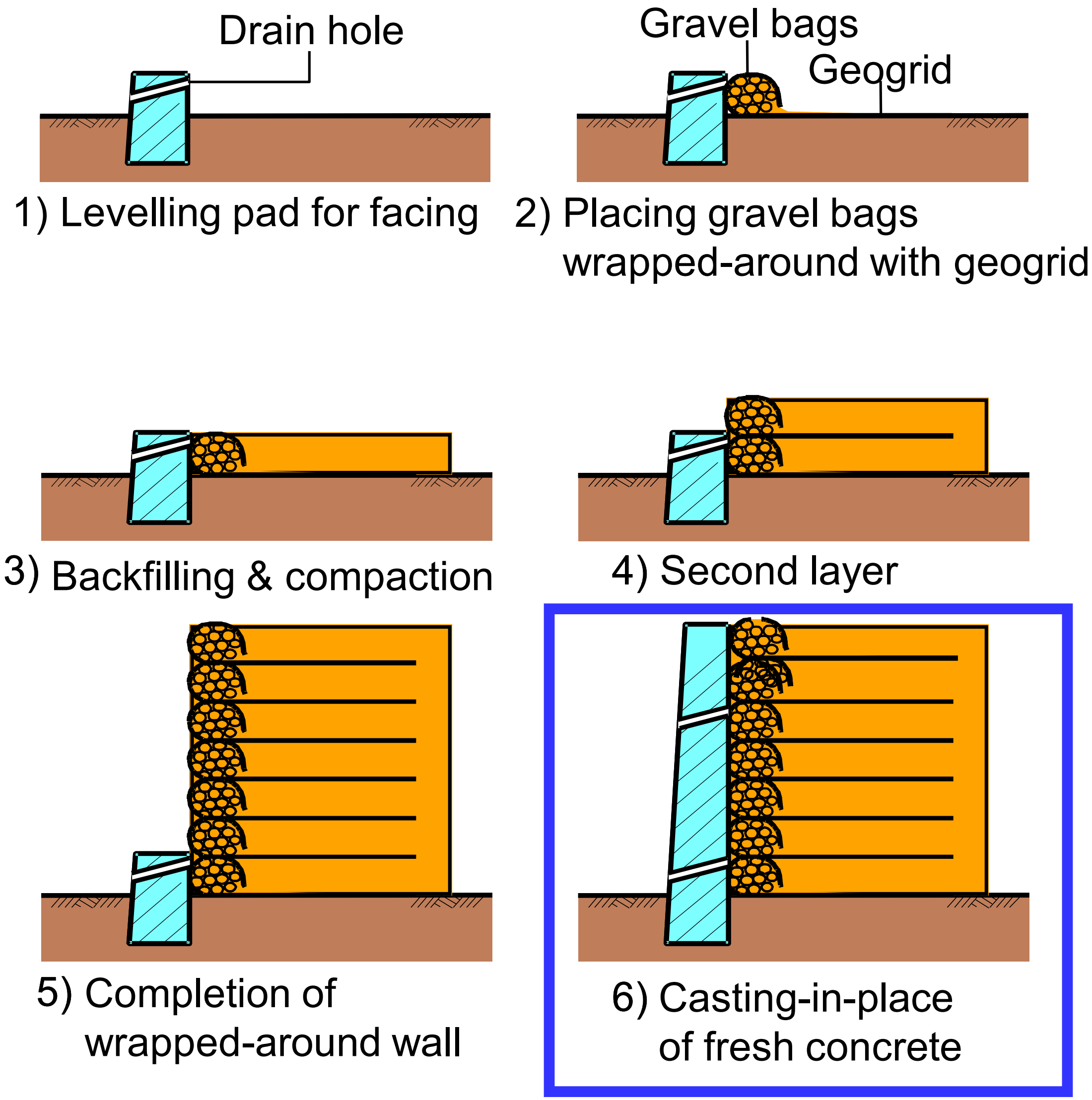


6) Casting-in-place of fresh concrete

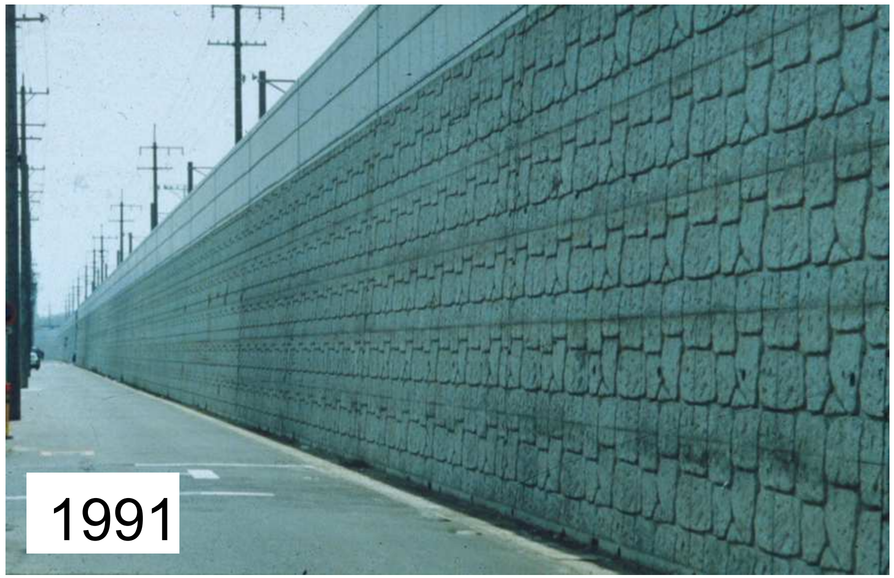
This steel rod is not a permanent member, not expected to function for wall stability.



Staged construction: 6)
Completion of GRS RW by the construction of FHR facing

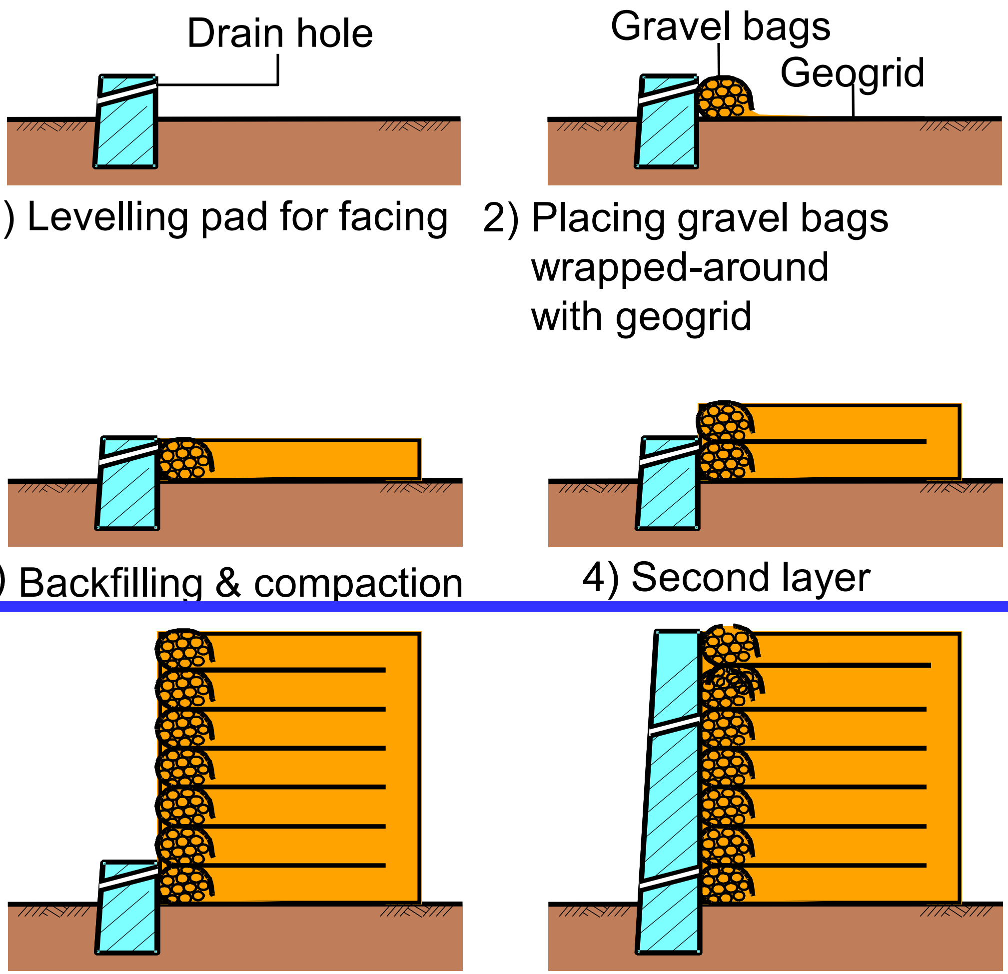


Typical completed GRS RW, depot for HSR (Shinkansen) at Biwajima, Nagoya



Staged construction from step 5) to step 6):

- After sufficient compression of the backfill & subsoil has taken place, FHR facing is constructed by casting-in-place fresh concrete directly on the geogrid-wrapped-around wall face.



1) Levelling pad for facing
2) Placing gravel bags wrapped-around with geogrid
3) Backfilling & compaction
4) Second layer
5) Completion of wrapped-around wall
6) Casting-in-place of fresh concrete

Advantages:

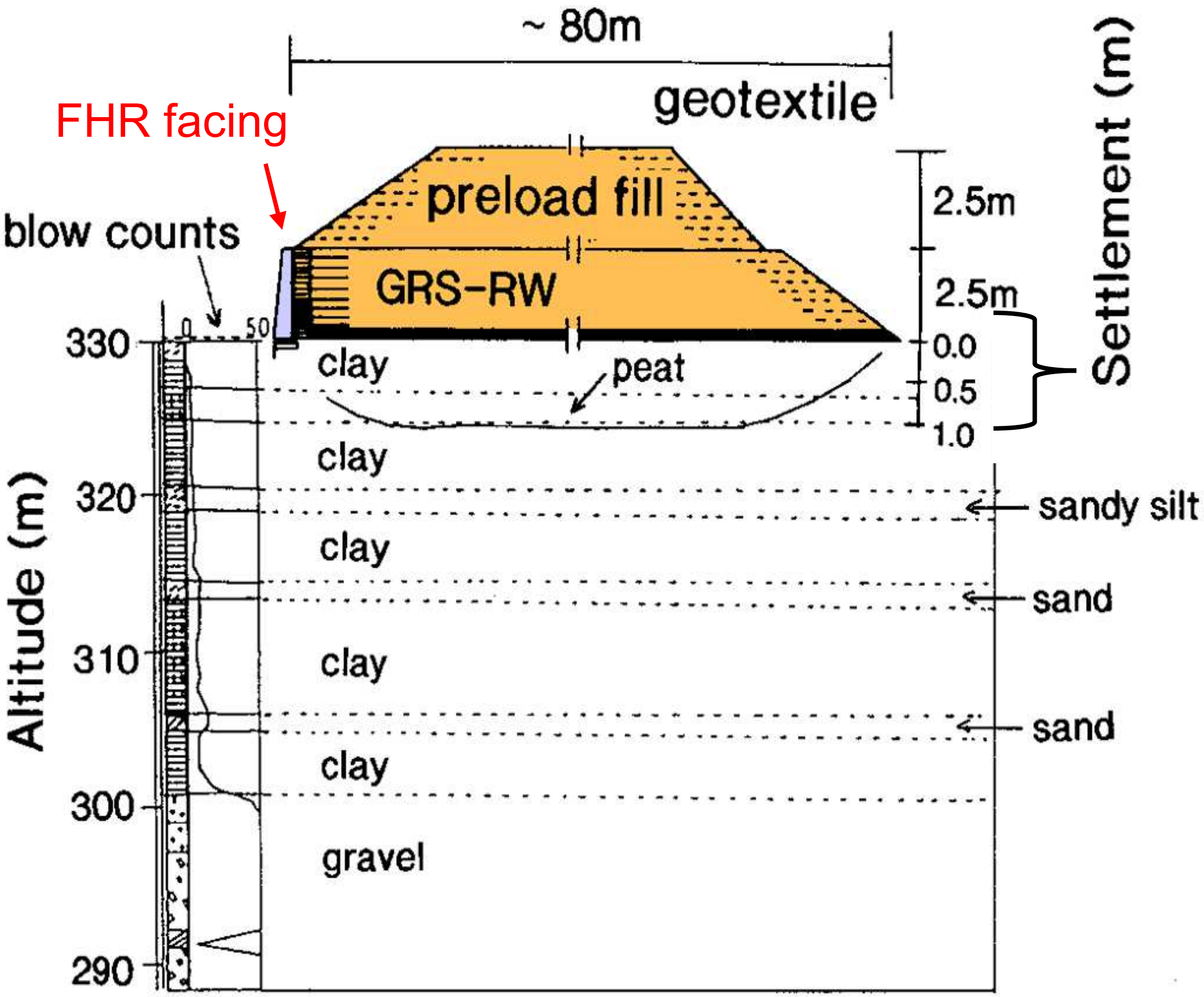
1) Very small residual differential settlements take place between the FHR facing and the backfill.
2) The gravel bags protect the facing/geogrid connection.

⇒ Essentially no damage to the facing/geogrid connection during long-term service, even when subjected to severe earthquakes.

⇒ The construction of GRS RW "using compressive backfill" and/or "on a compressive subsoil" becomes possible.

Nagano wall:
- for a depot for HSR (Shinkansen)
- 2.0 m-high & 2 km-long GRS RW
- constructed 1993 - 1994

Very difficult conditions:
a) nearly saturated soft backfill; &
b) a very thick soft clay deposit, requiring very long piles for a conventional cantilever RW



Overcome by staged construction:
1) GRS RW w/o FHR facing
2) preload fill
3) settlement (about 1 m)
4) removal of preload fill
5) construction of FHR facing

Preloading

<u>wall height</u>

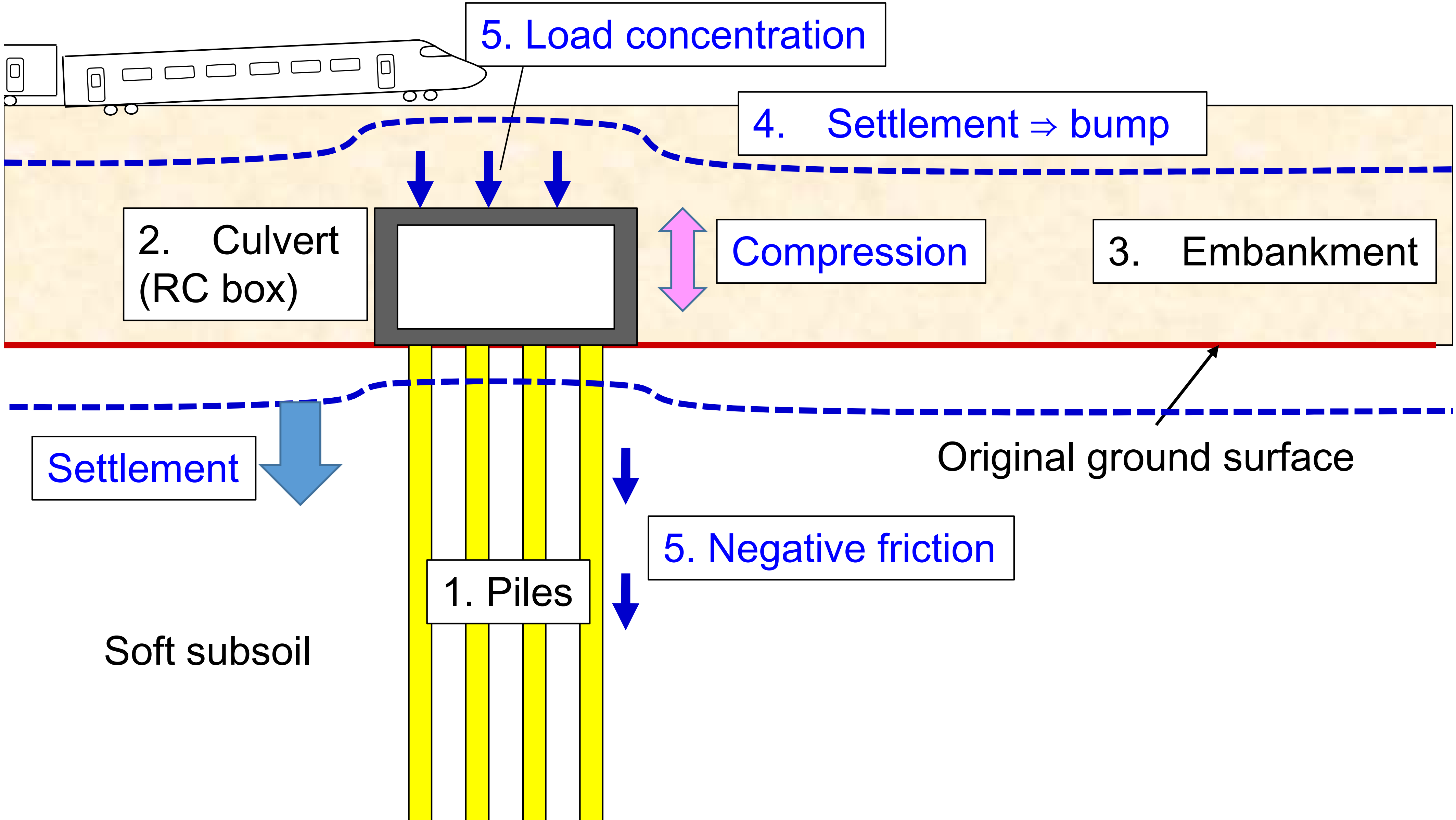
before preloading: 3.0 m

after preloading: 2.0 m

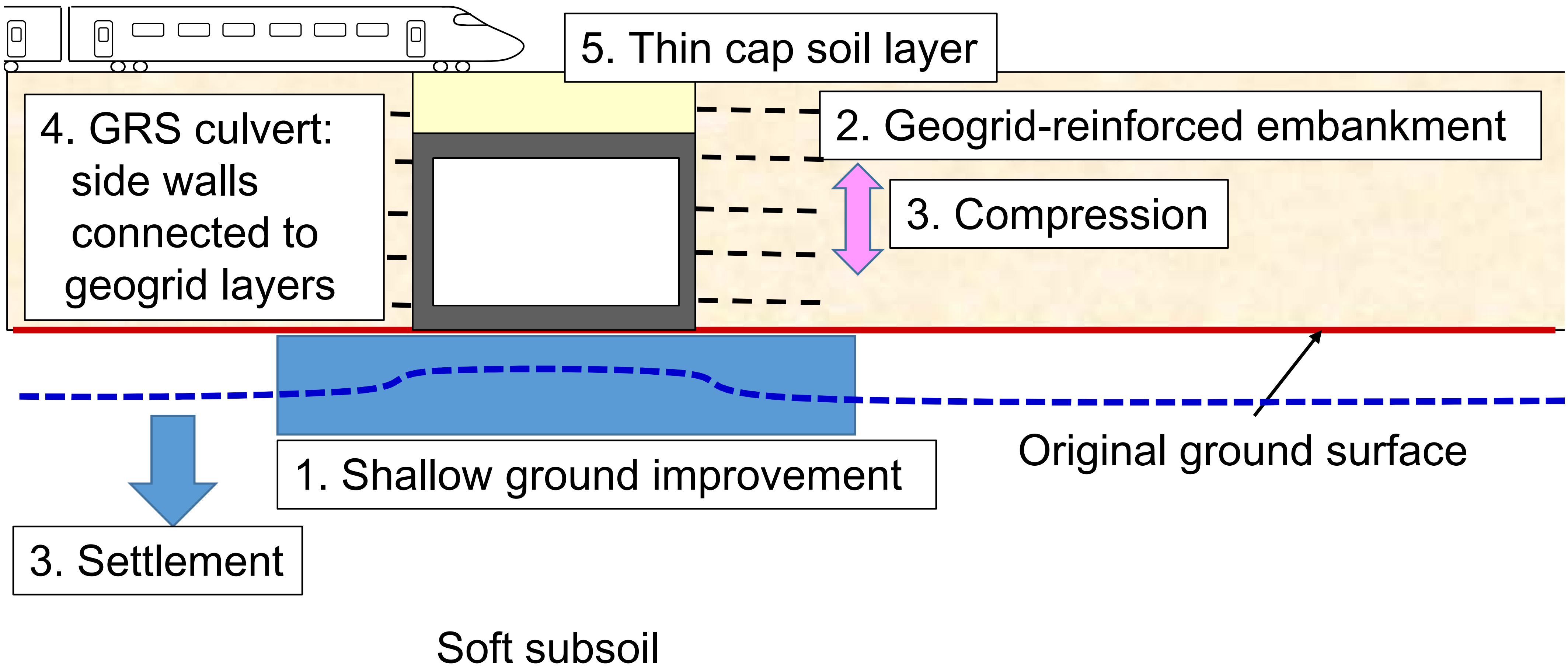
Construction of FHR facing after removing the preload fill, so FHR facing is free from large wall settlement & irregular wall face deformation

20 years after construction, 6th July 2014

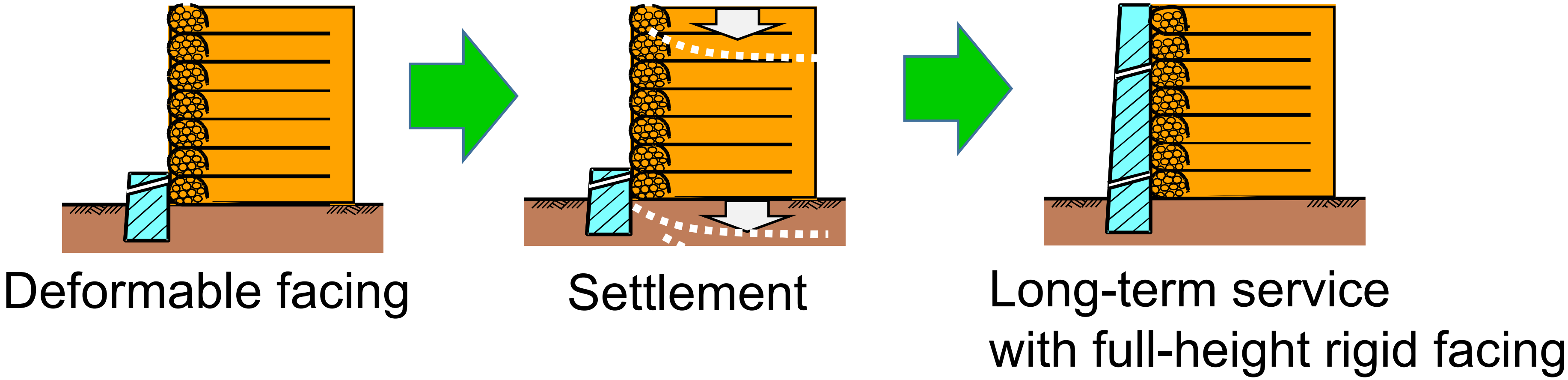
Several serious problems with the box culvert crossing road/railway embankment on soft soil when constructed by the conventional method



A solution by staged-construction of GRS box culvert



Advantages of staged construction (summary)



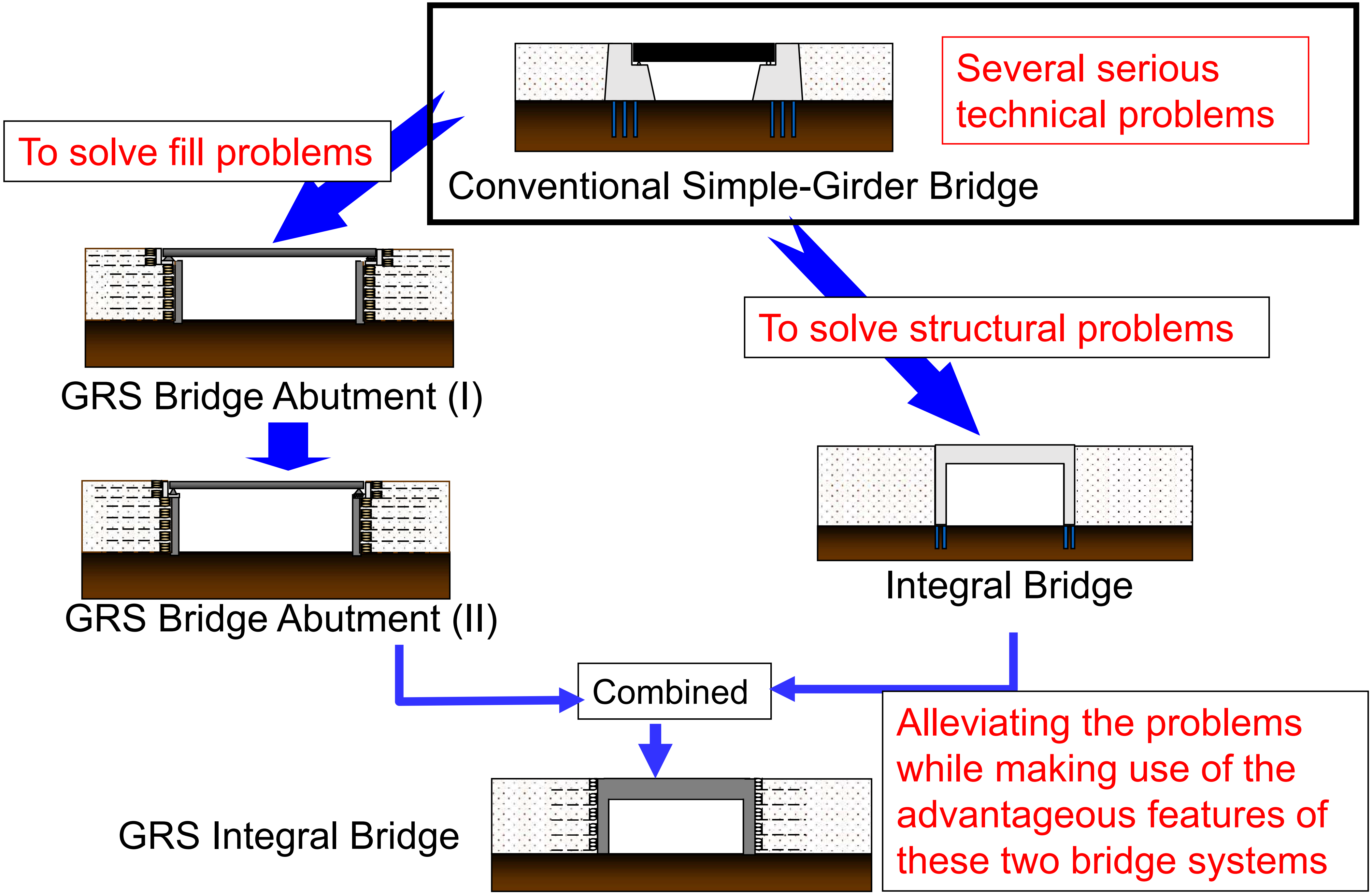
Such stage construction as shown above can alleviate the following contradiction:

1) during the construction of wrapped-around geogrid-reinforced backfill, the temporary facing should be **deformable** enough to accommodate the deformation of backfill & subsoil; whereas

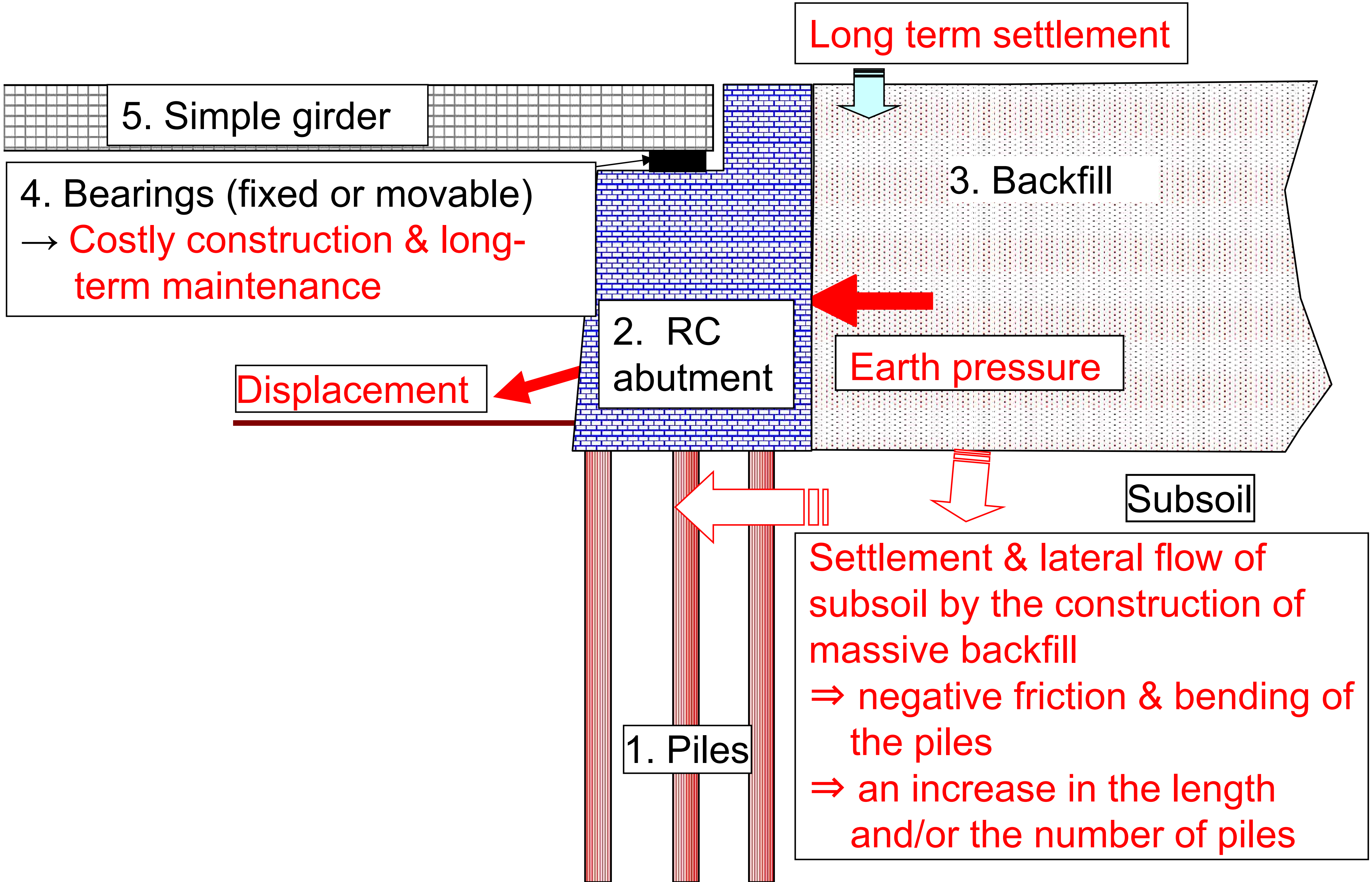
2) during long-term service, in particular when subjected to severe earthquakes, the facing should be **stiff & strong** to keep small the wall deformation ensuring high wall stability.

Contents

Developments from GRS RWs to GRS bridge structures



Serious problems with conventional simple girder bridge

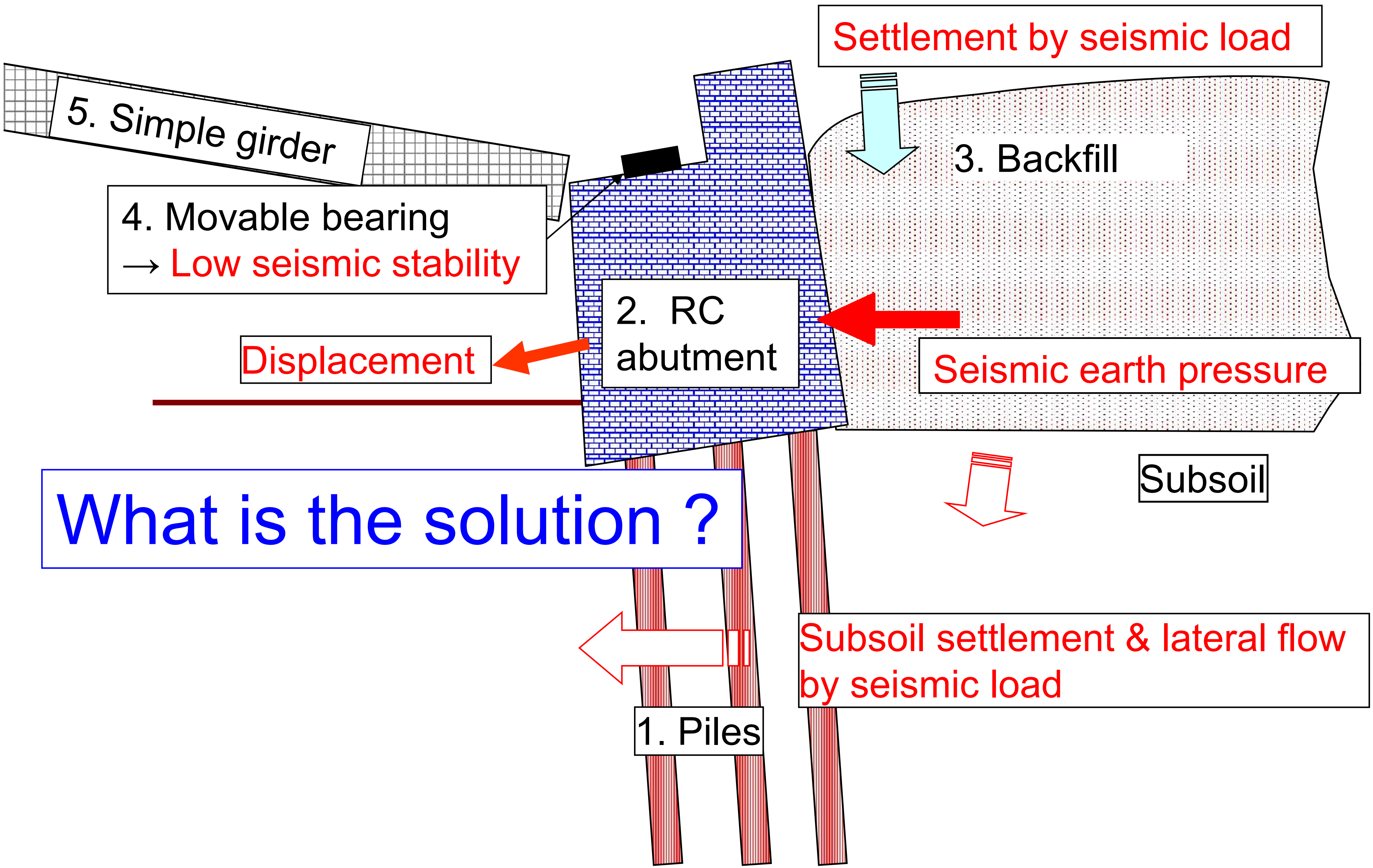


1995 Kobe Earthquake, Kobe Railway Line

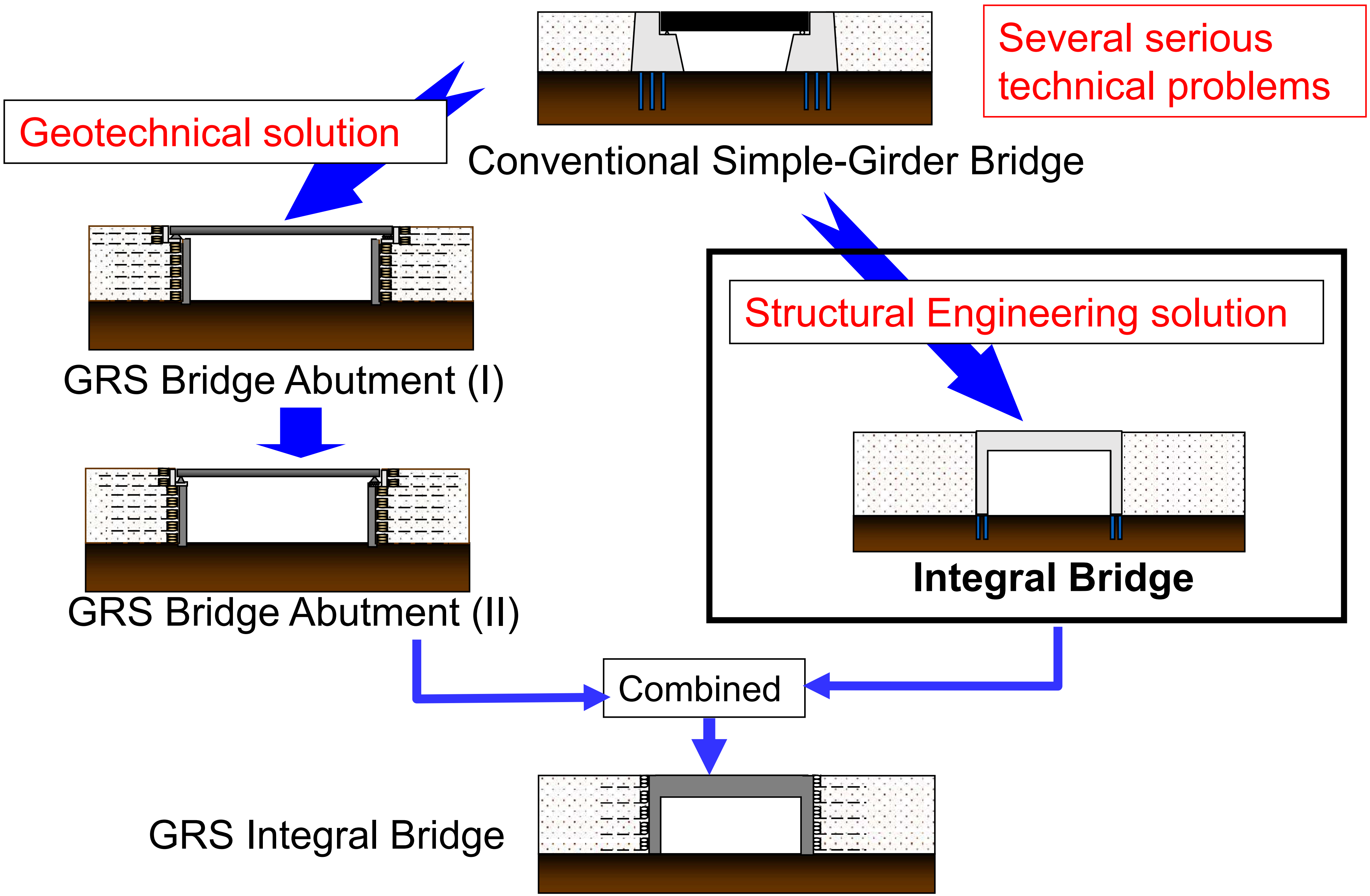
Bridge abutment

Collapse of wing wall & approach fill of a bridge abutment

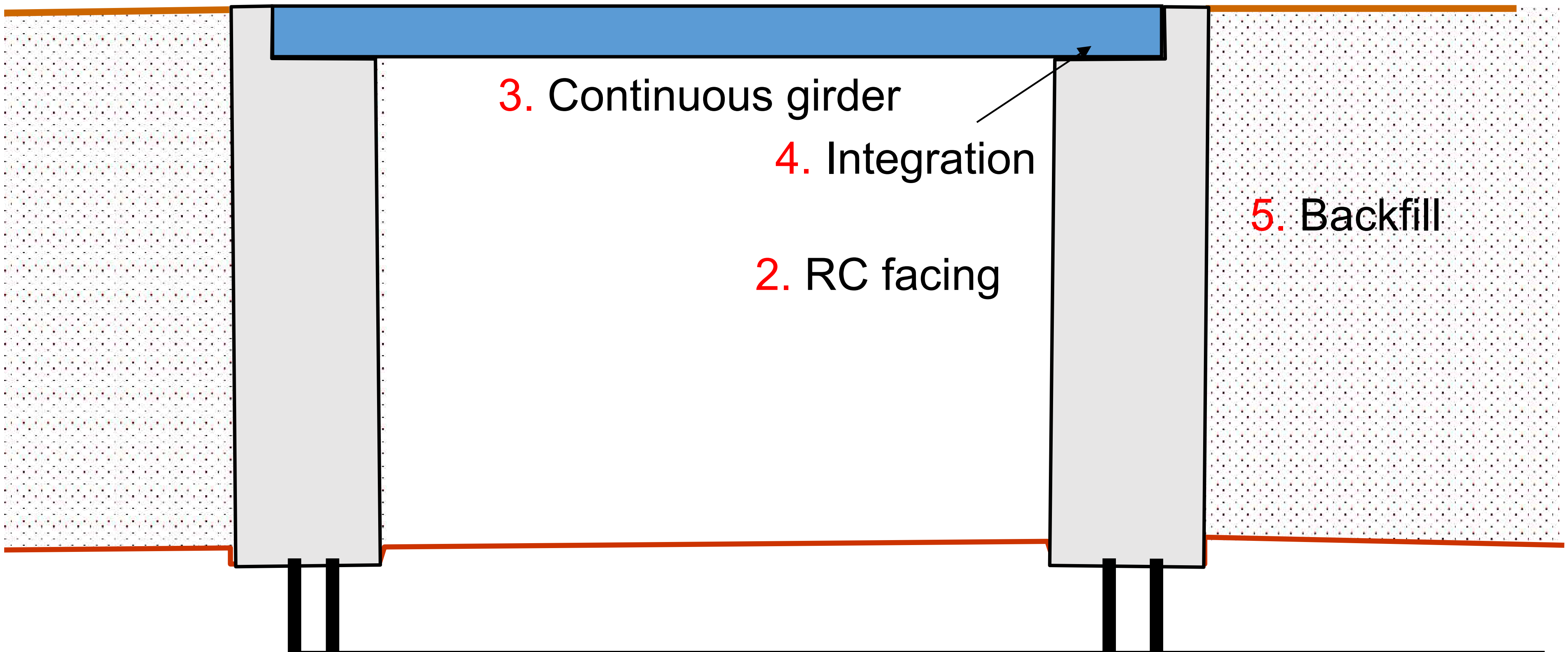
… and problems by seismic loads



Developments from GRS RWs to GRS bridge structures



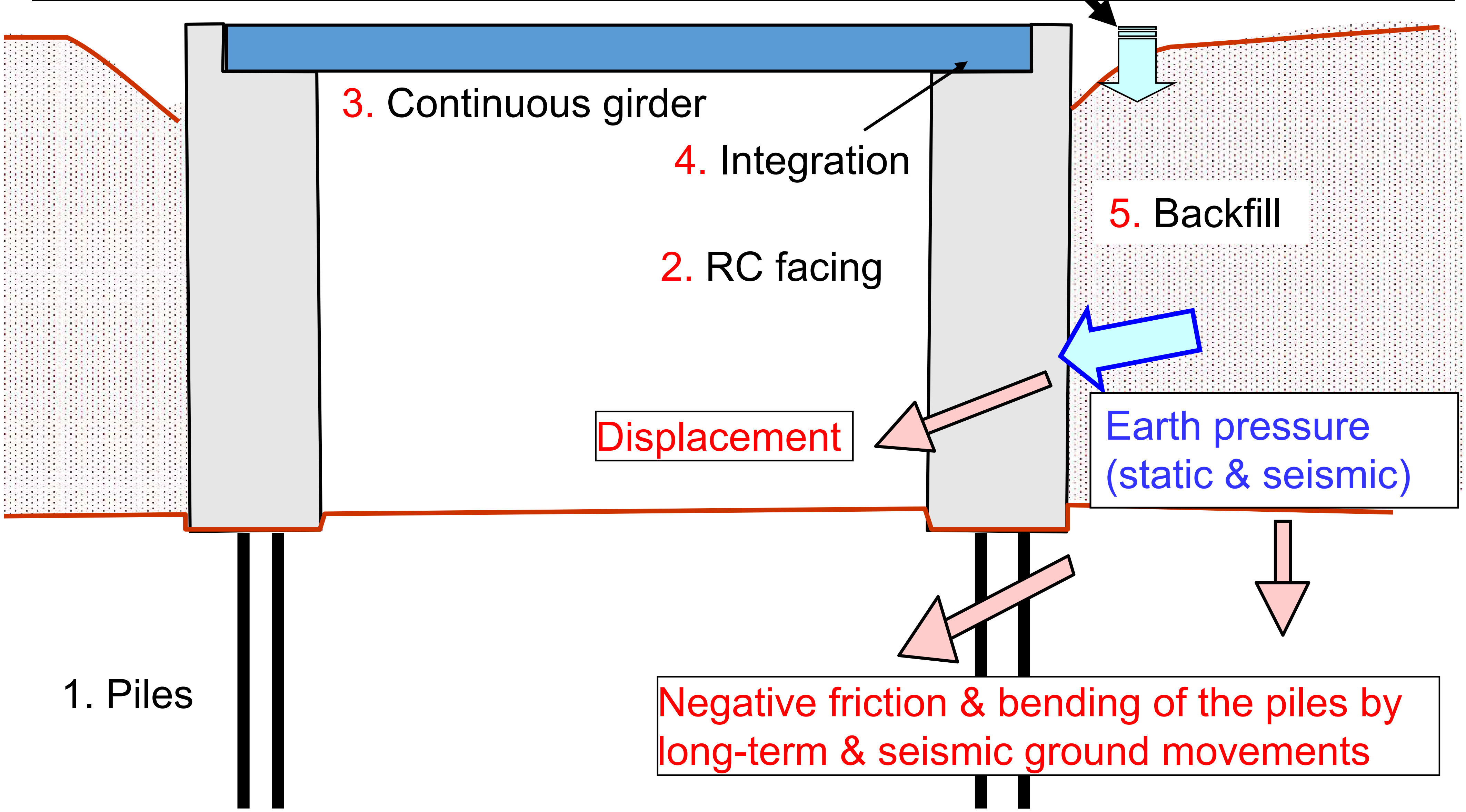
Integral Bridge



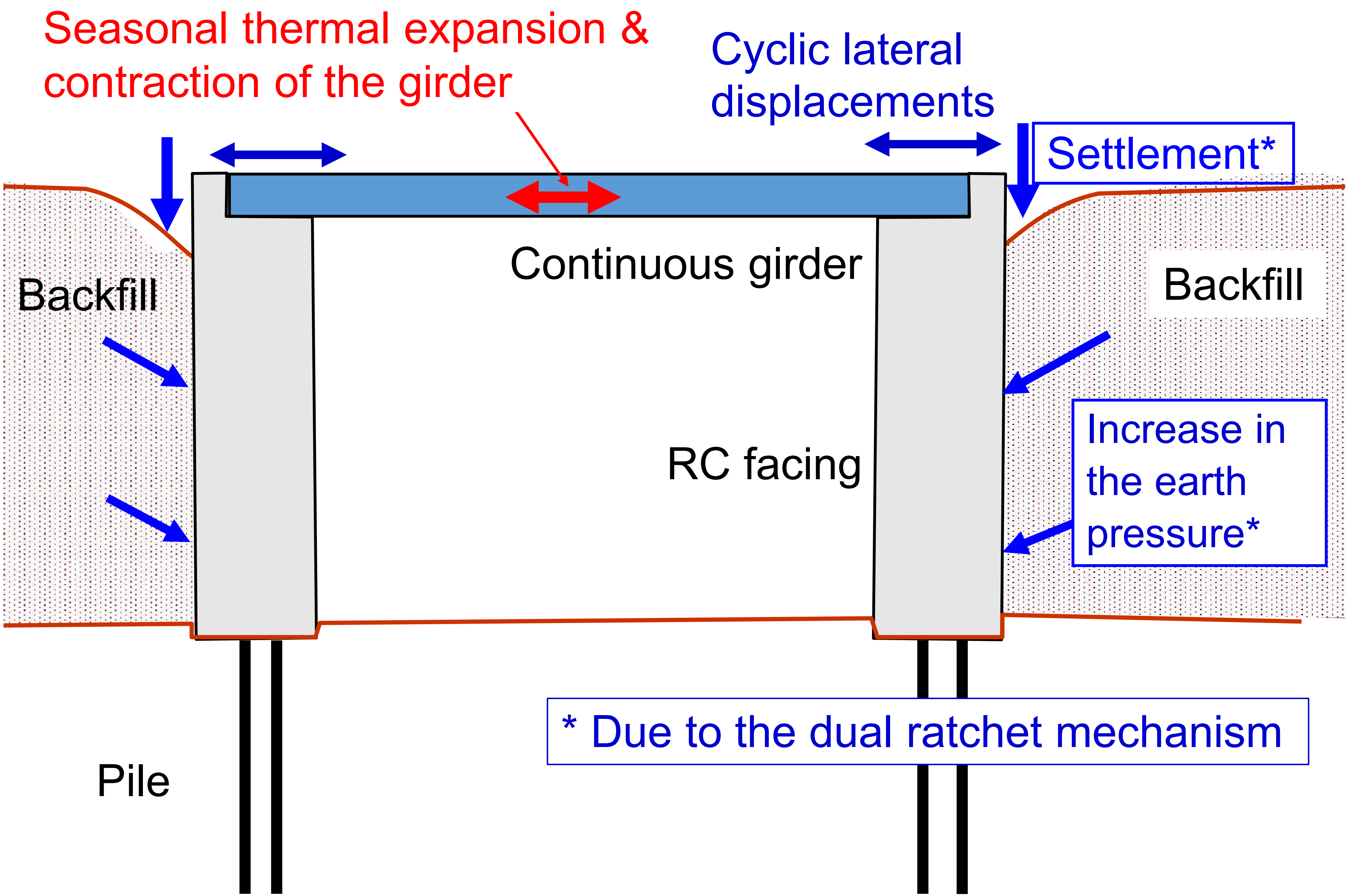
Many were constructed in the UK and the USA,
due to low cost for construction & maintenance by:
a) no use of girder bearings &
b) the use of a jointless girder

However, several unsolved old problems !

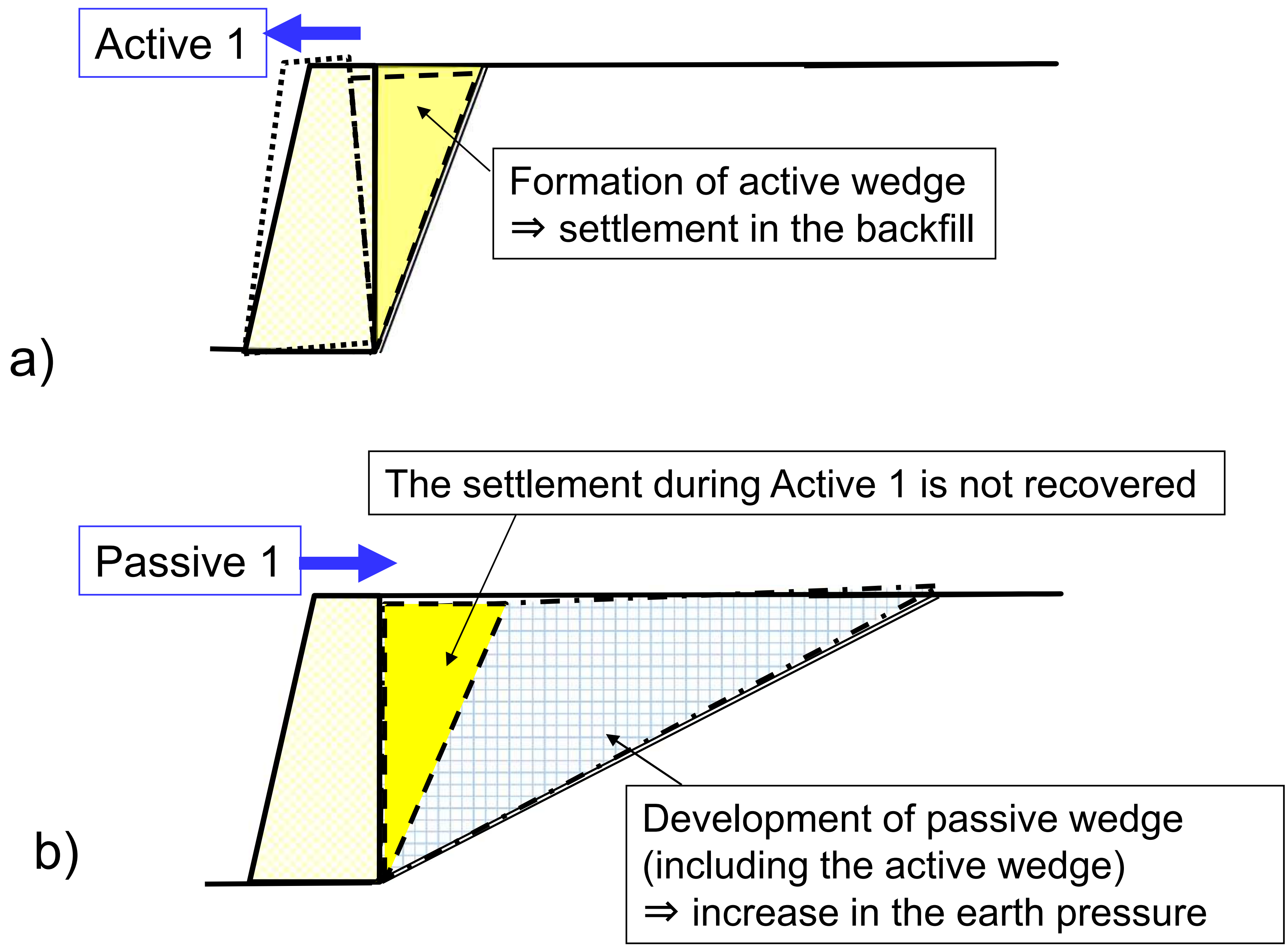
Long-term service issues: a. gradual settlement
b. sudden large settlement by seismic load



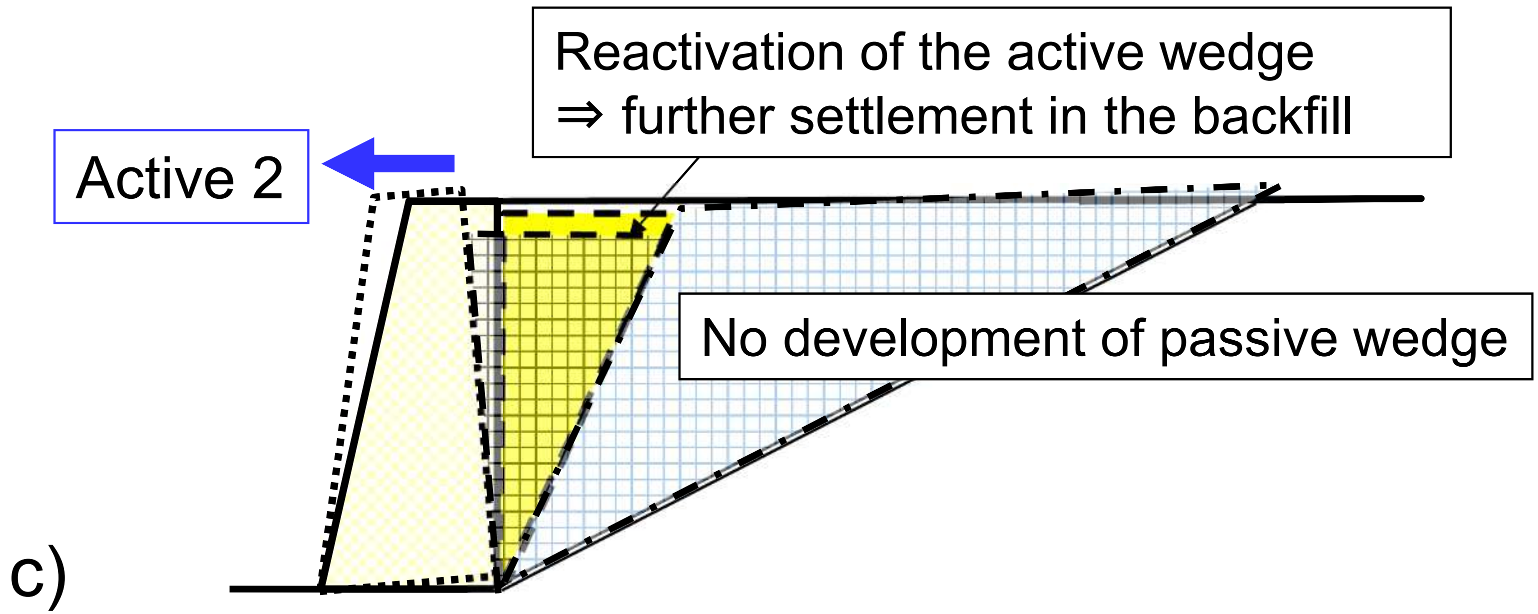
…… and new problems !

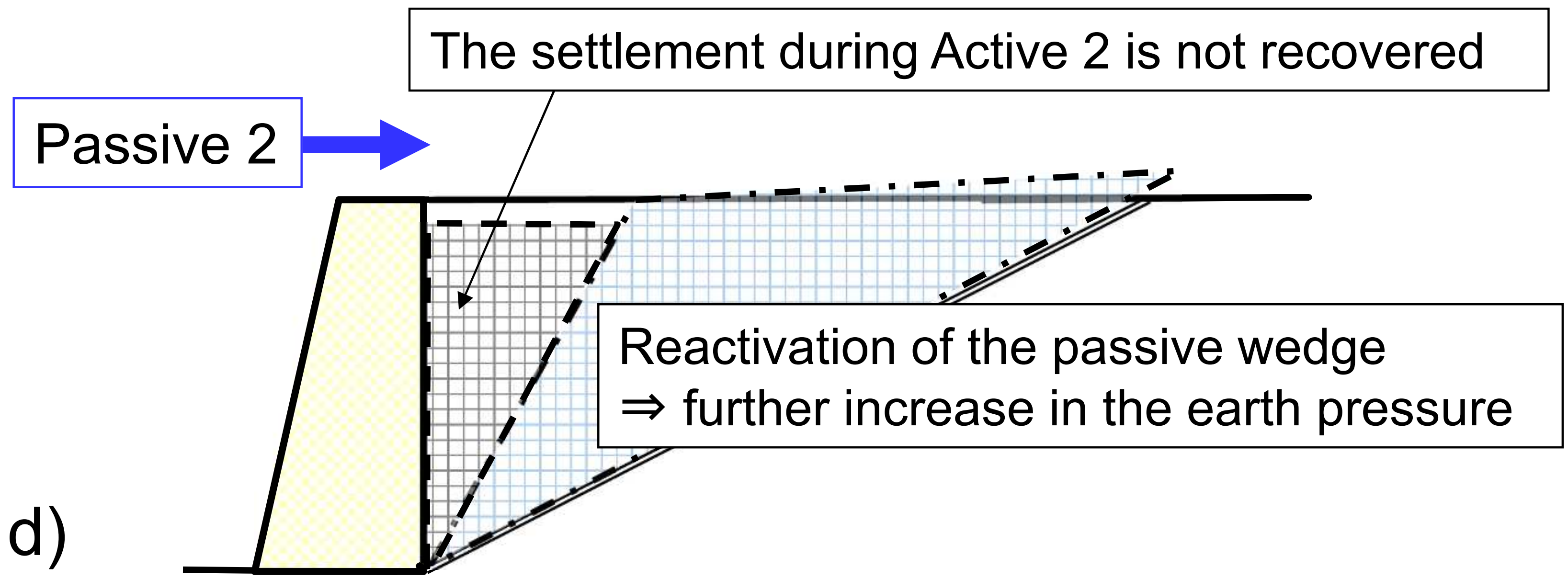


Dual ratchet mechanism – 1/2

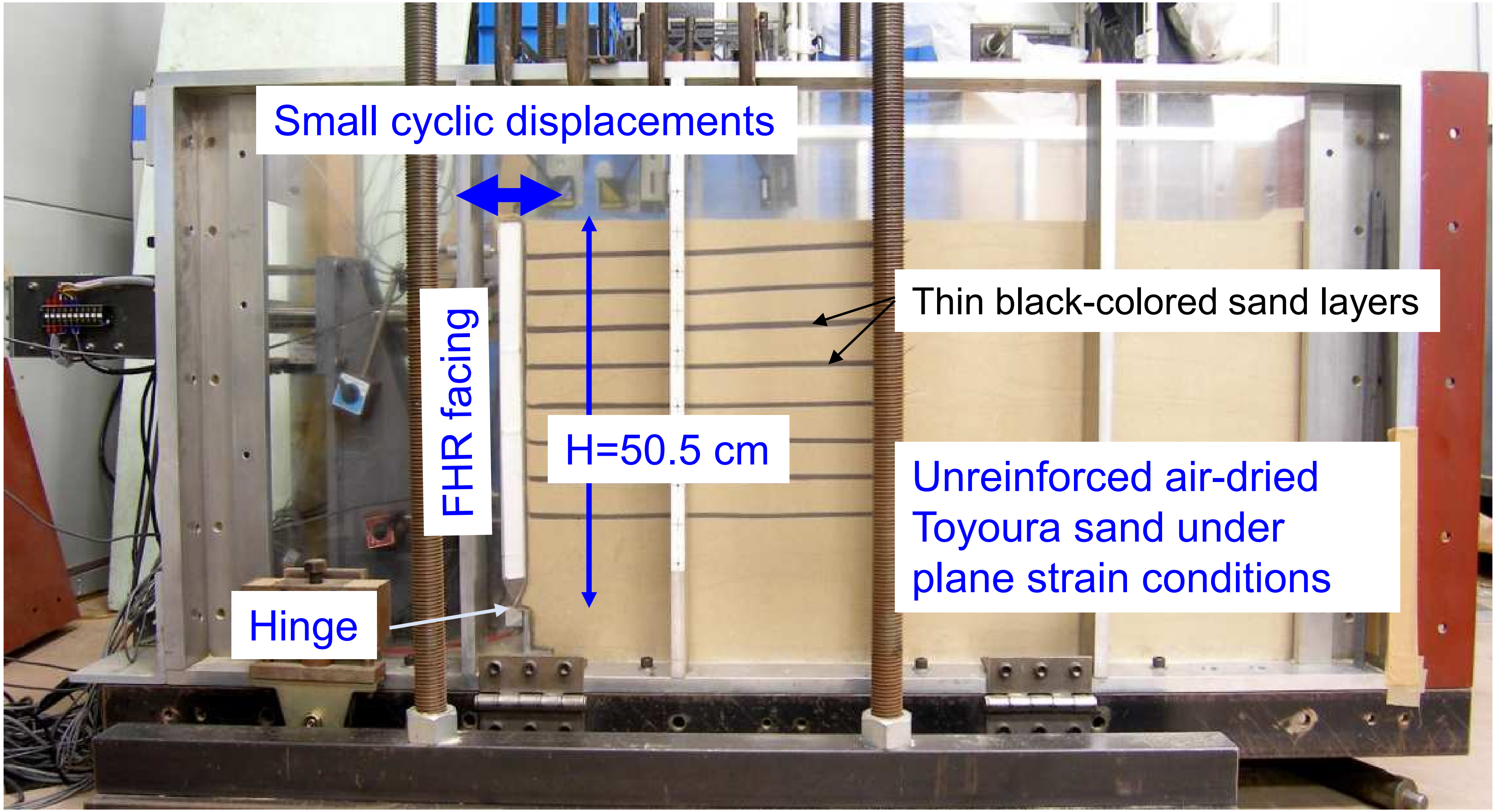


Dual ratchet mechanism – 2/2

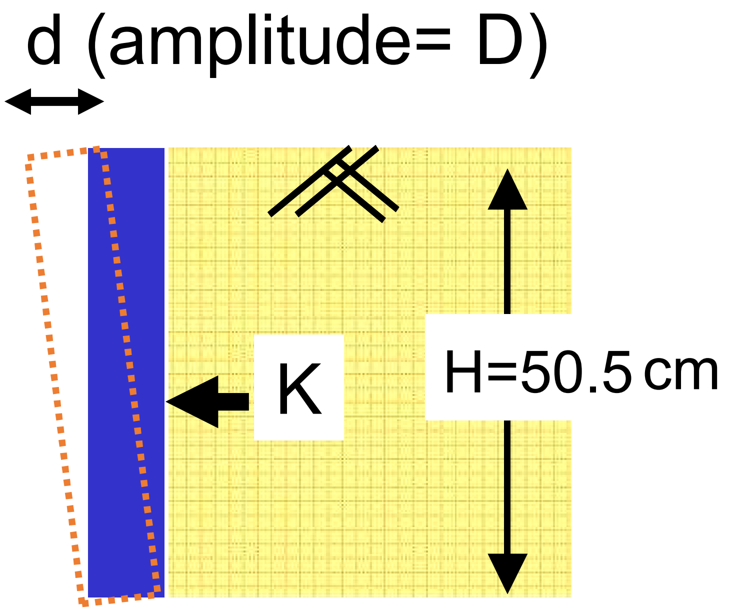




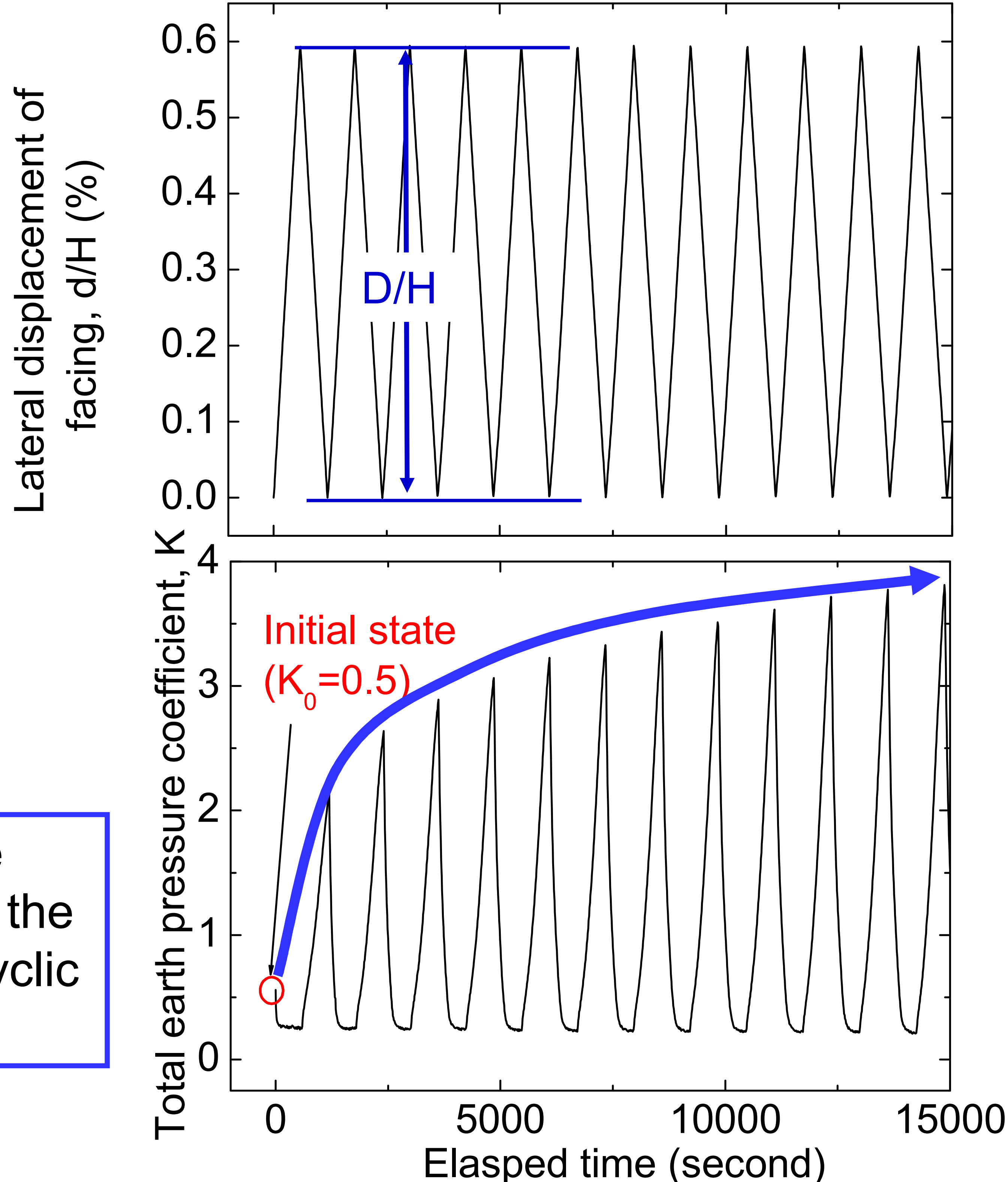
Cyclic lateral loading model test in 1g
(considered model scale: 1/10)



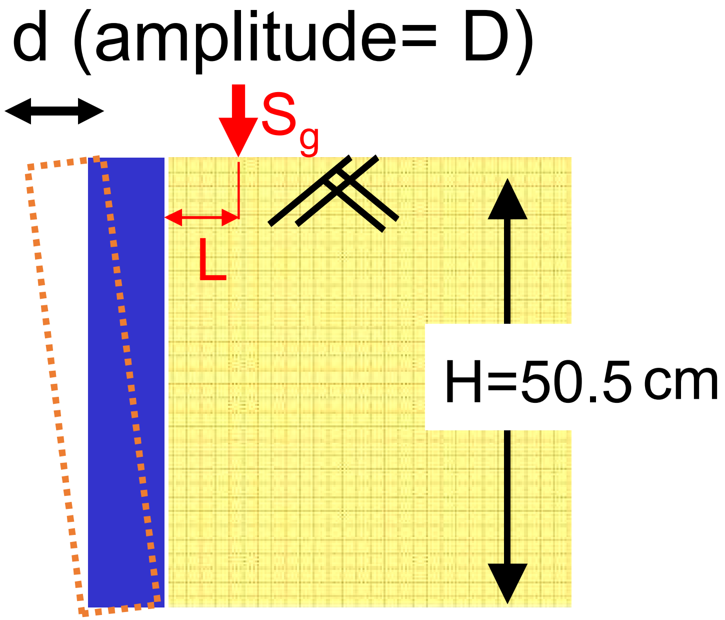
Cyclic lateral loading model test in 1g
(considered model scale: 1/10)



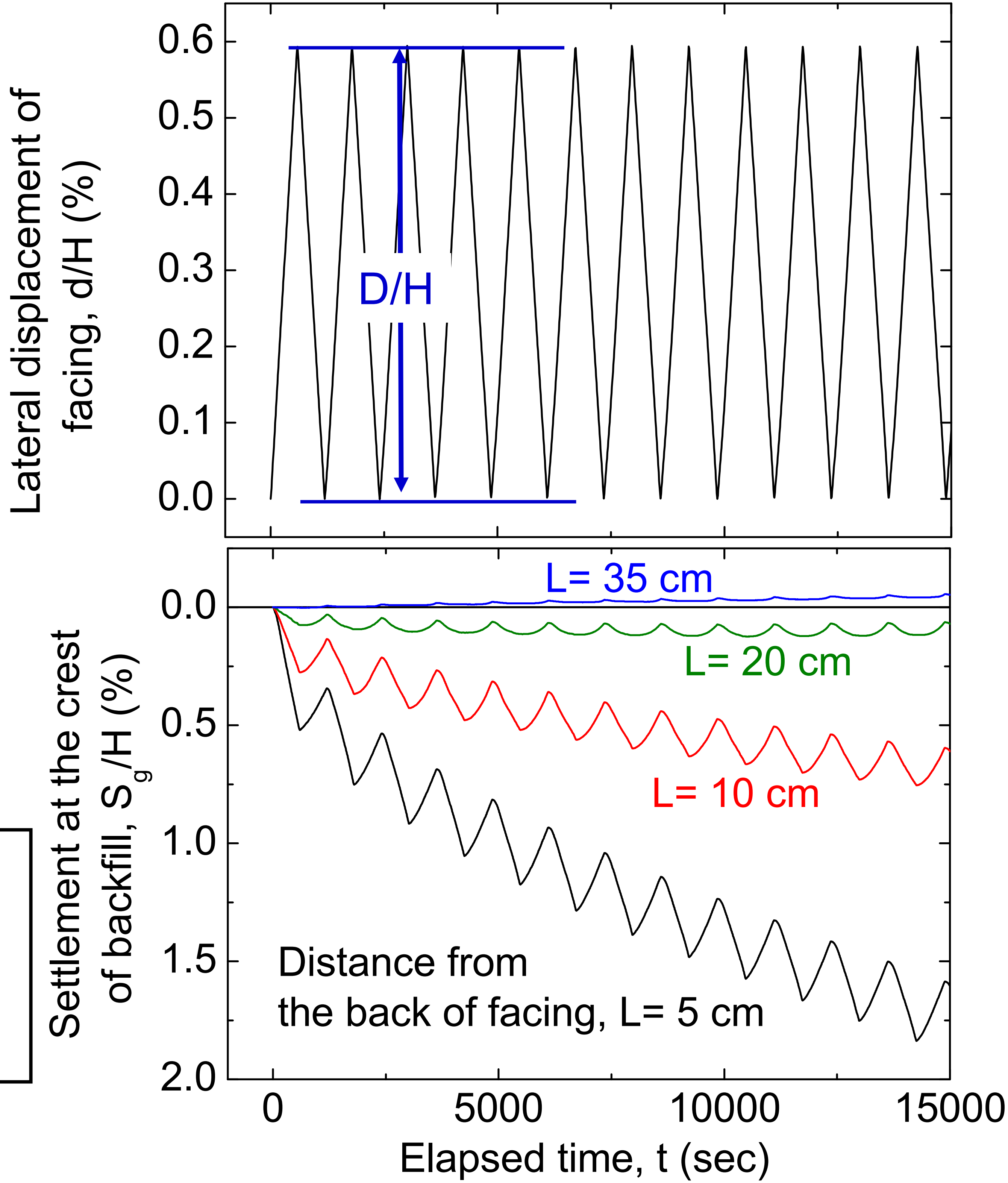
Significant increase in the passive earth pressure in the unreinforced backfill by cyclic loading



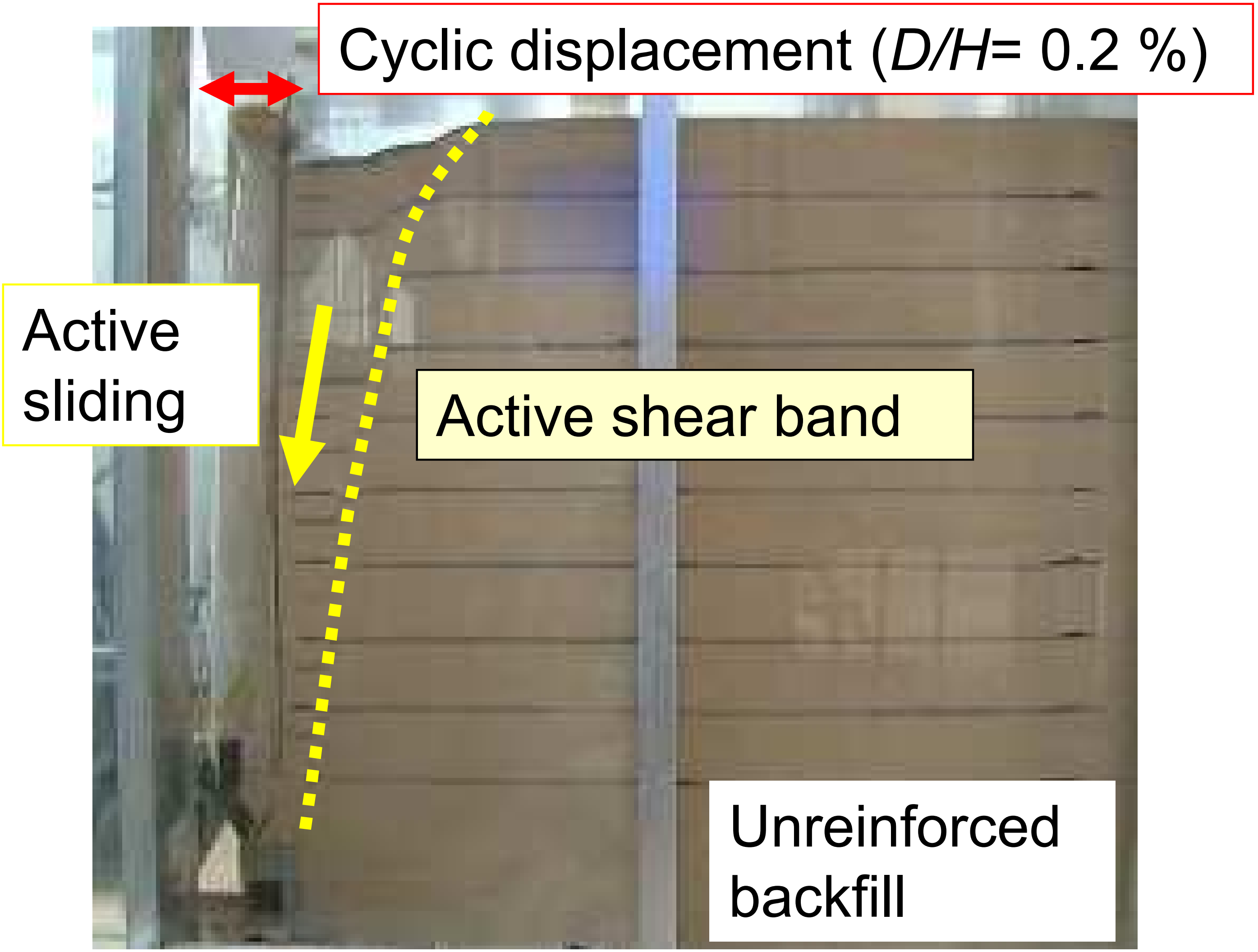
Cyclic lateral loading model test in 1g (considered model scale: 1/10)



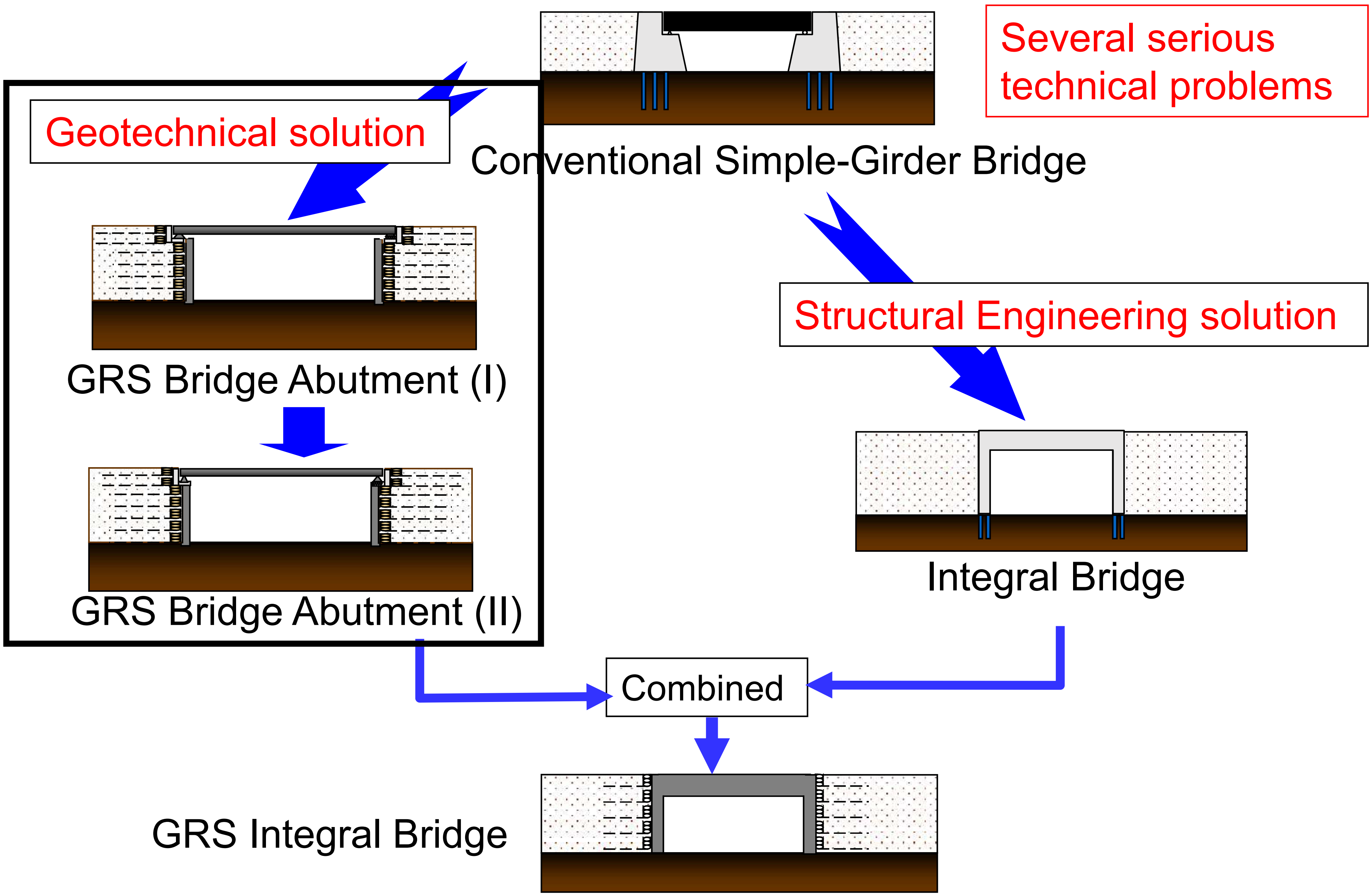
Significant settlement in the unreinforced backfill by cyclic loading, esulting into a bump



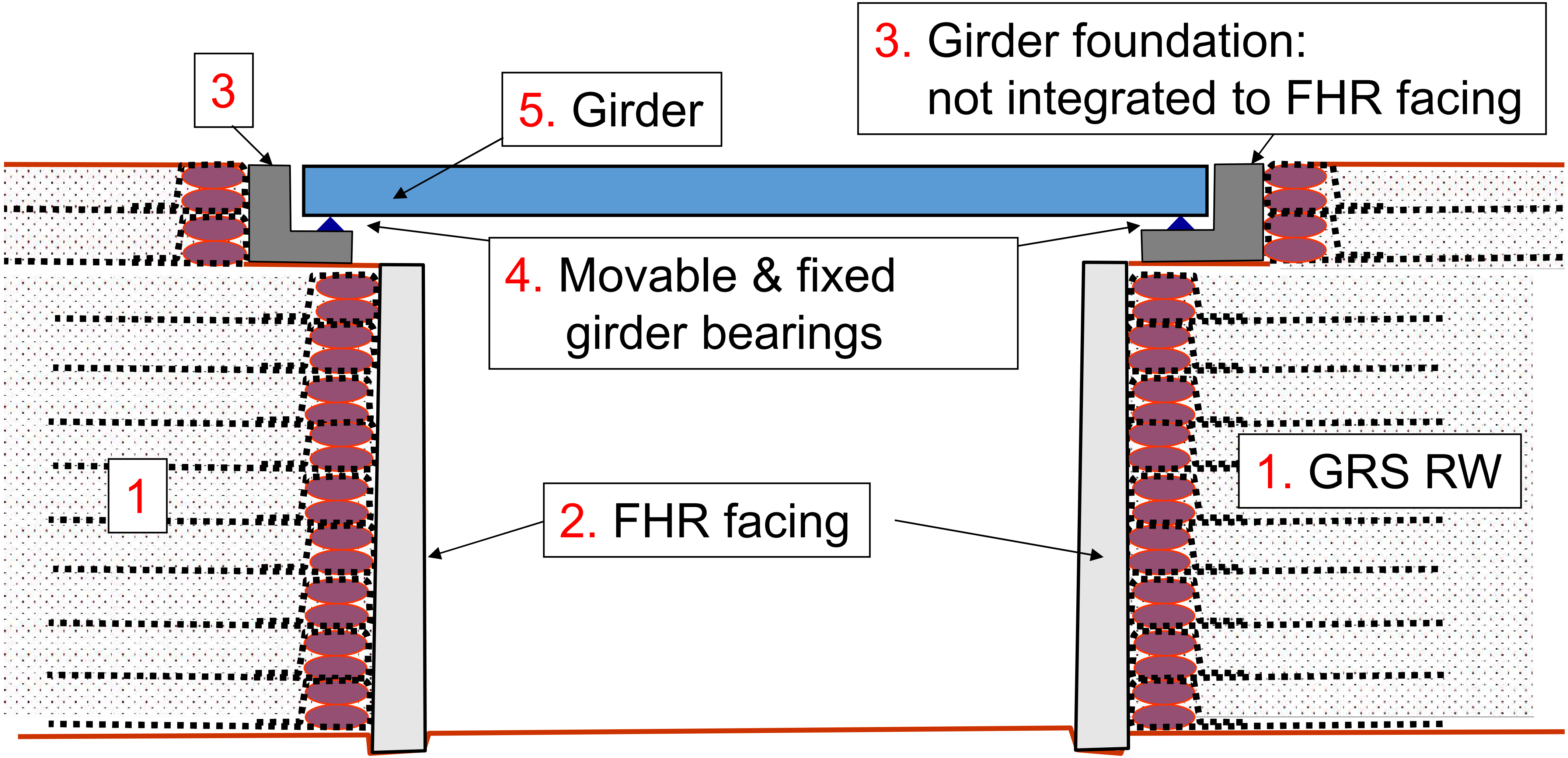
Active failure in unreinforced backfill
by small cyclic lateral displacement of the facing,
only *D/H*= 0.2 % in this case !
D/H= 0.2 % is only 1 cm for H= 5 m !



Developments from GRS RWs to GRS bridge structures



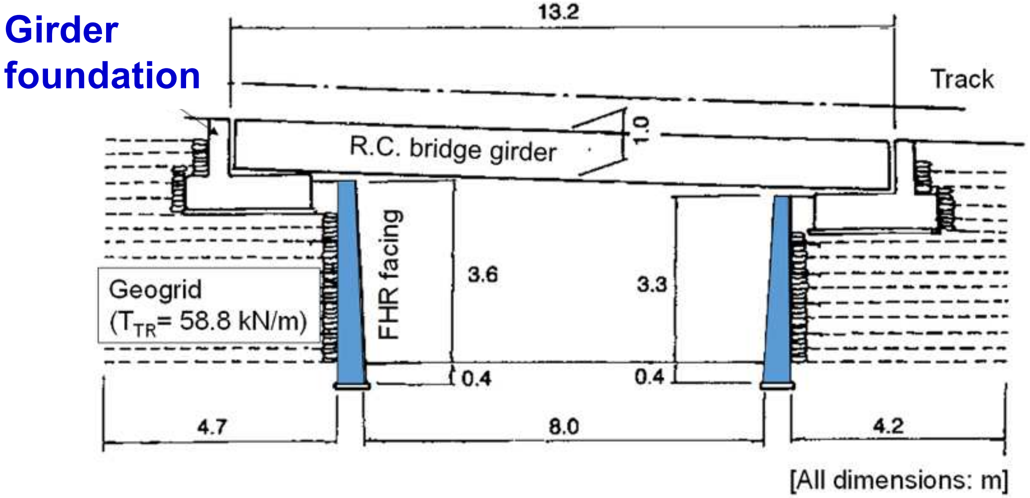
GRS Bridge Abutment – first generation

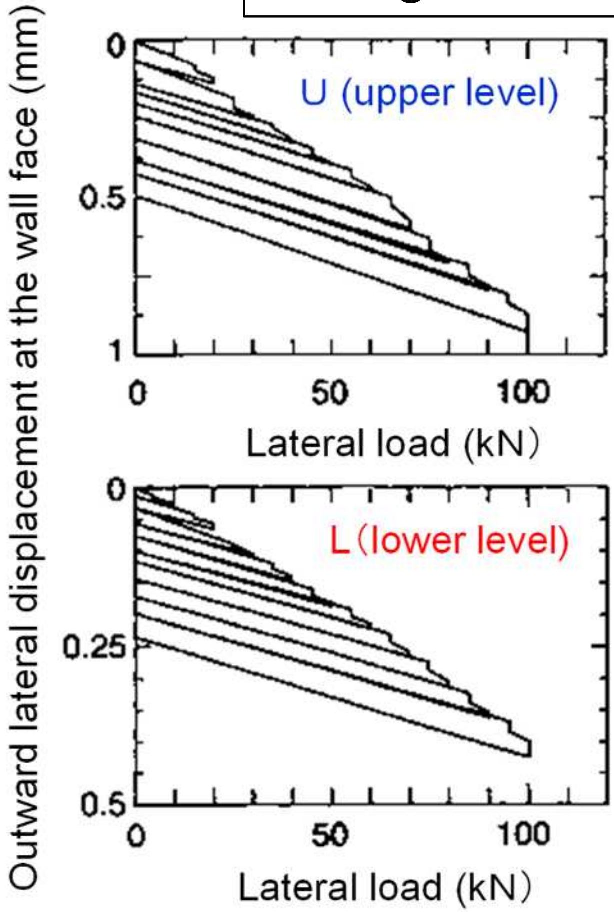


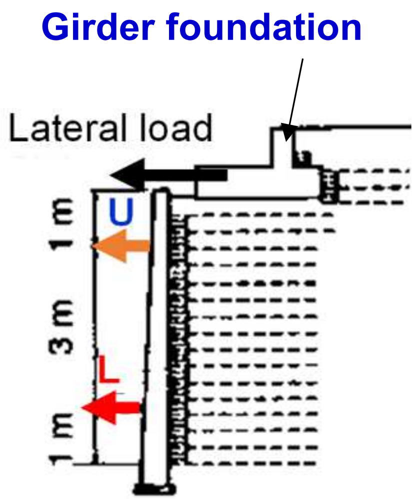
1. No bump right back of the FHR facing ⇒ low maintenance cost
2. Stable approach fills
3. Highly cost-effective

A pair of GRS Bridge Abutments (1st generation) for Seibu Ikebukuro Line, Tokyo, 1993

Stable monolithic behaviour during lateral loading test

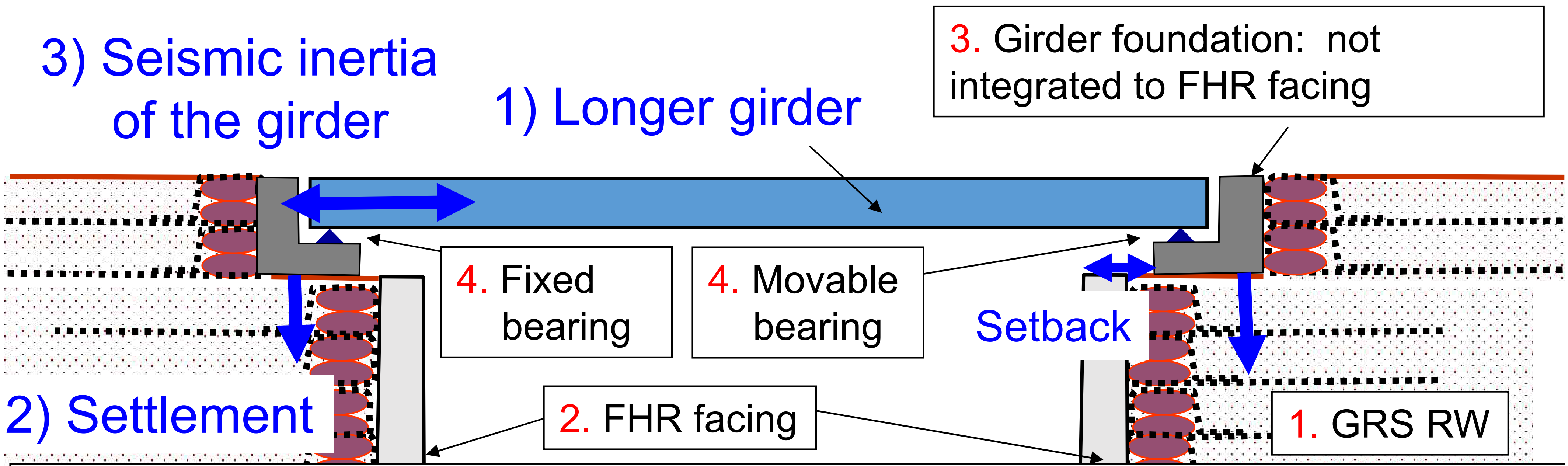






Satisfactory performance of this GRS BA led to the construction of many others!

Limitations of GRS Bridge Abutment – first generation



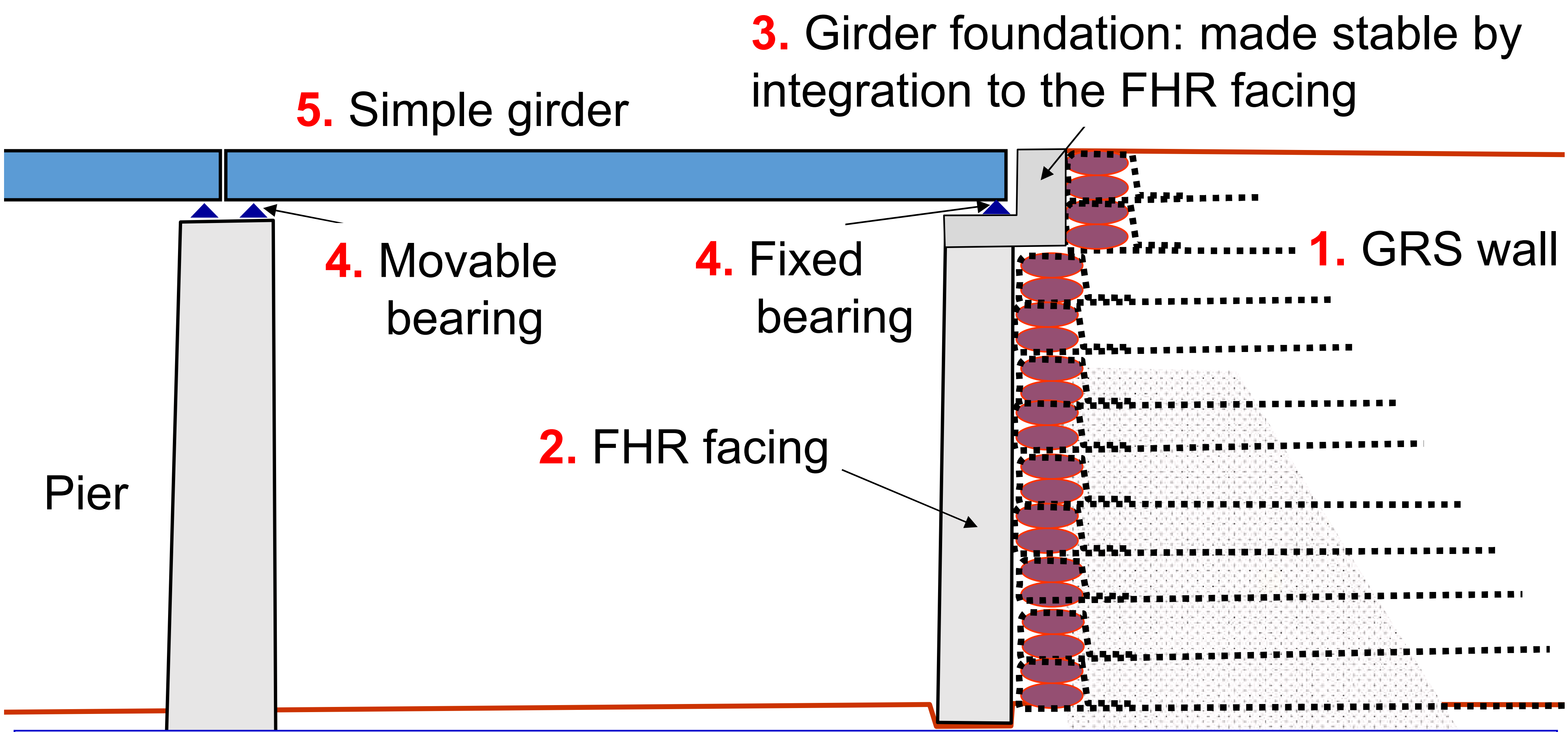
However,
1) the girder becomes longer by a setback of the girder foundation; and

when the girder becomes long and heavy,
2) the settlement of the girder foundation due to the compression of the underlying backfill may become unacceptable and

3) the girder foundation where the fixed bearing is arranged may become unstable by large seismic inertia load of the girder.

⇒ Development of GRS Bridge Abutment of second generation by solving the problems 1), 2) & 3).

GRS Bridge Abutment – second generation

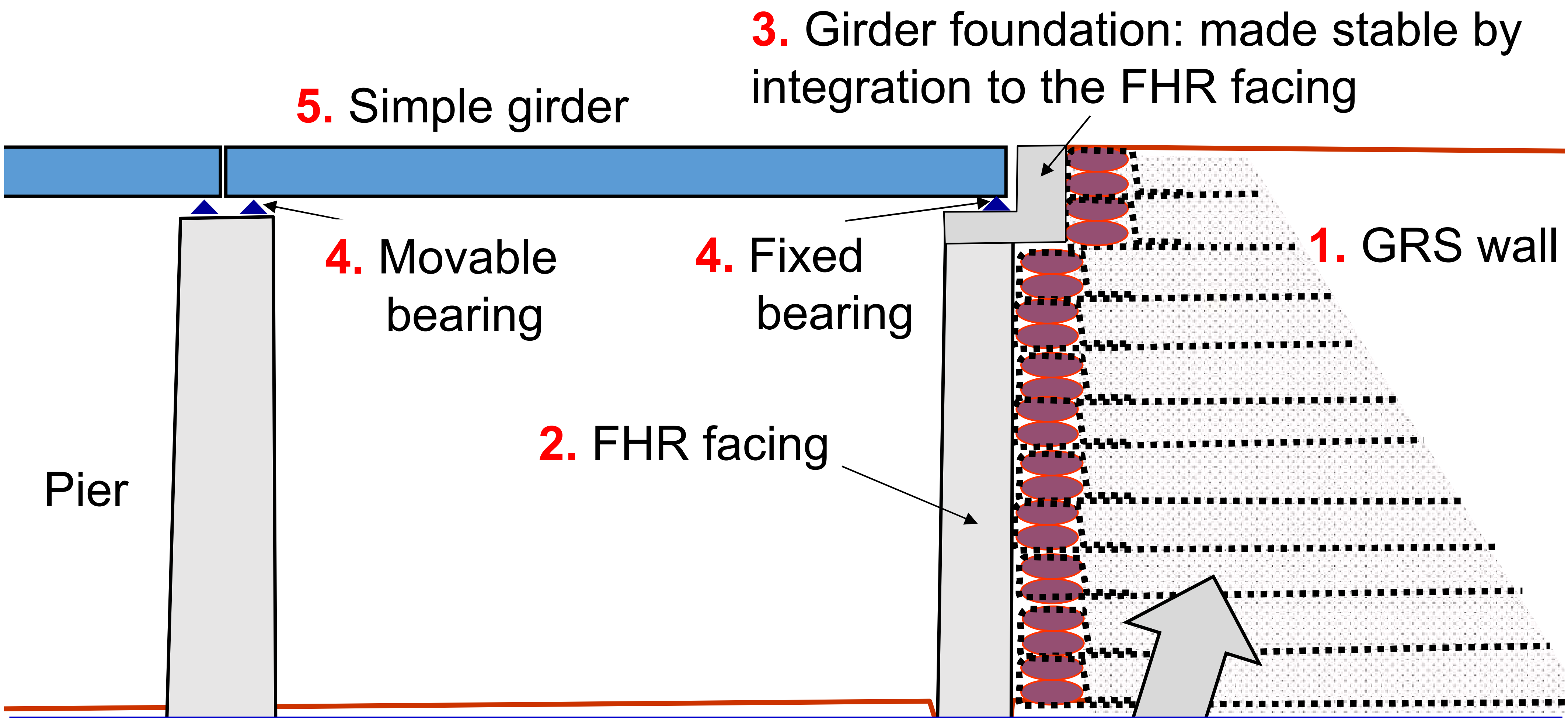


Much more stable & much more cost-effective than GRS BA of first generation, so definitely better than the conventional type bridge abutment.

Besides, GRS BA of second generation is statically determinate due to the use of a bearing. So, the internal forces in the girder & FHR facing are not sensitive to the thermal deformation of the girder and subsoil deformation.

⇒ The design of the girder & FHR facing is not sophisticated.

GRS Bridge Abutment – second generation



For railways, to minimize the deformation of the reinforced zone, particularly for the use of continuous RC slab tracks, and to ensure high stability against severe seismic loads, lightly cement-mixed well-graded gravelly soil is well compacted & reinforced with geogrid layers firmly connected to the FHR facing. ⇒ The geogrid should have very high long-term resistance against high pH of concrete (e.g., PVA)

GRS Bridge Abutment (2nd generation), completed 2020 Shimo-shinjo No. 1, Hokuriku Shinkansen

By the courtesy of Mr. Yonezawa, T., JRTT

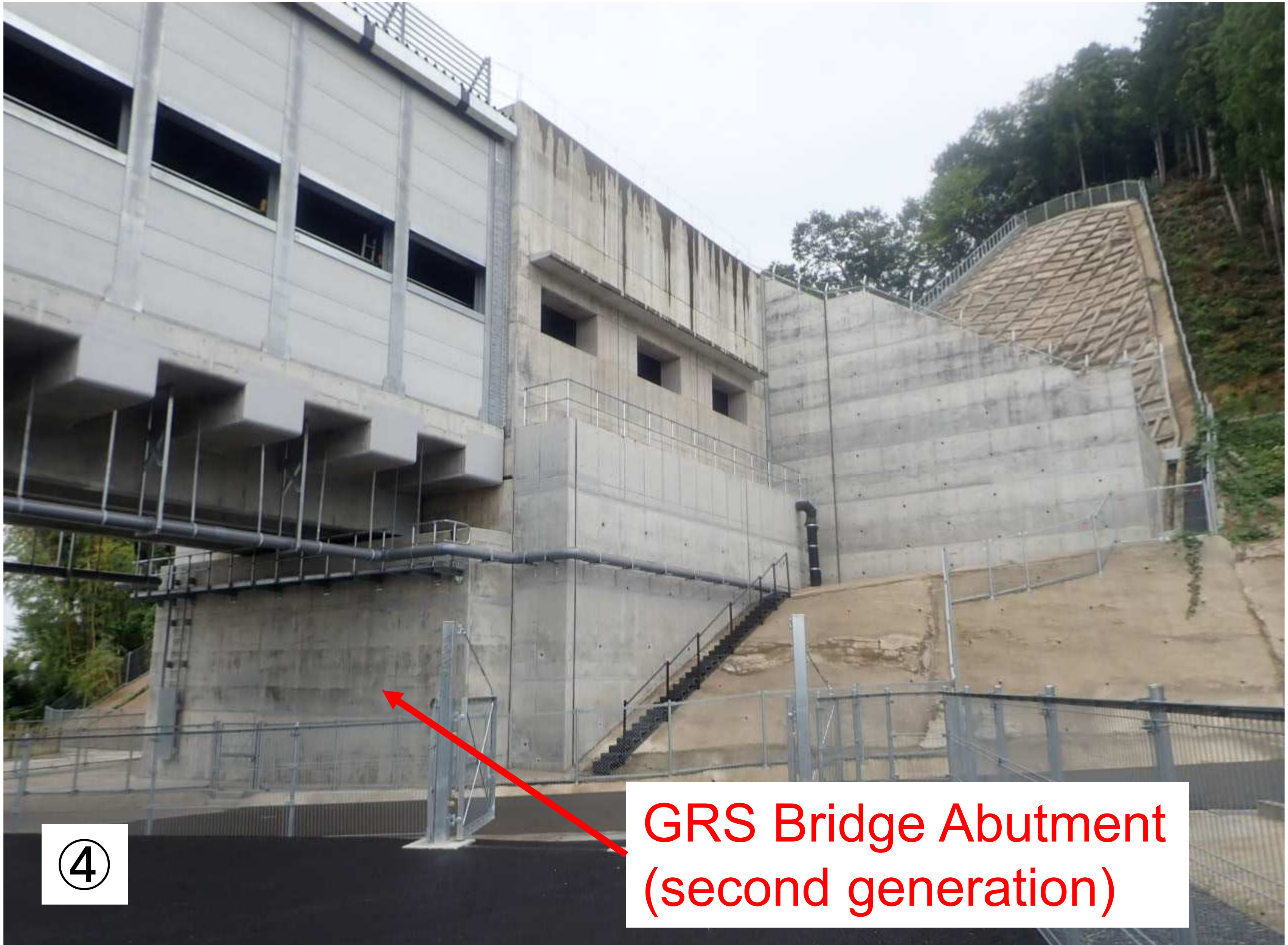
①

②

③

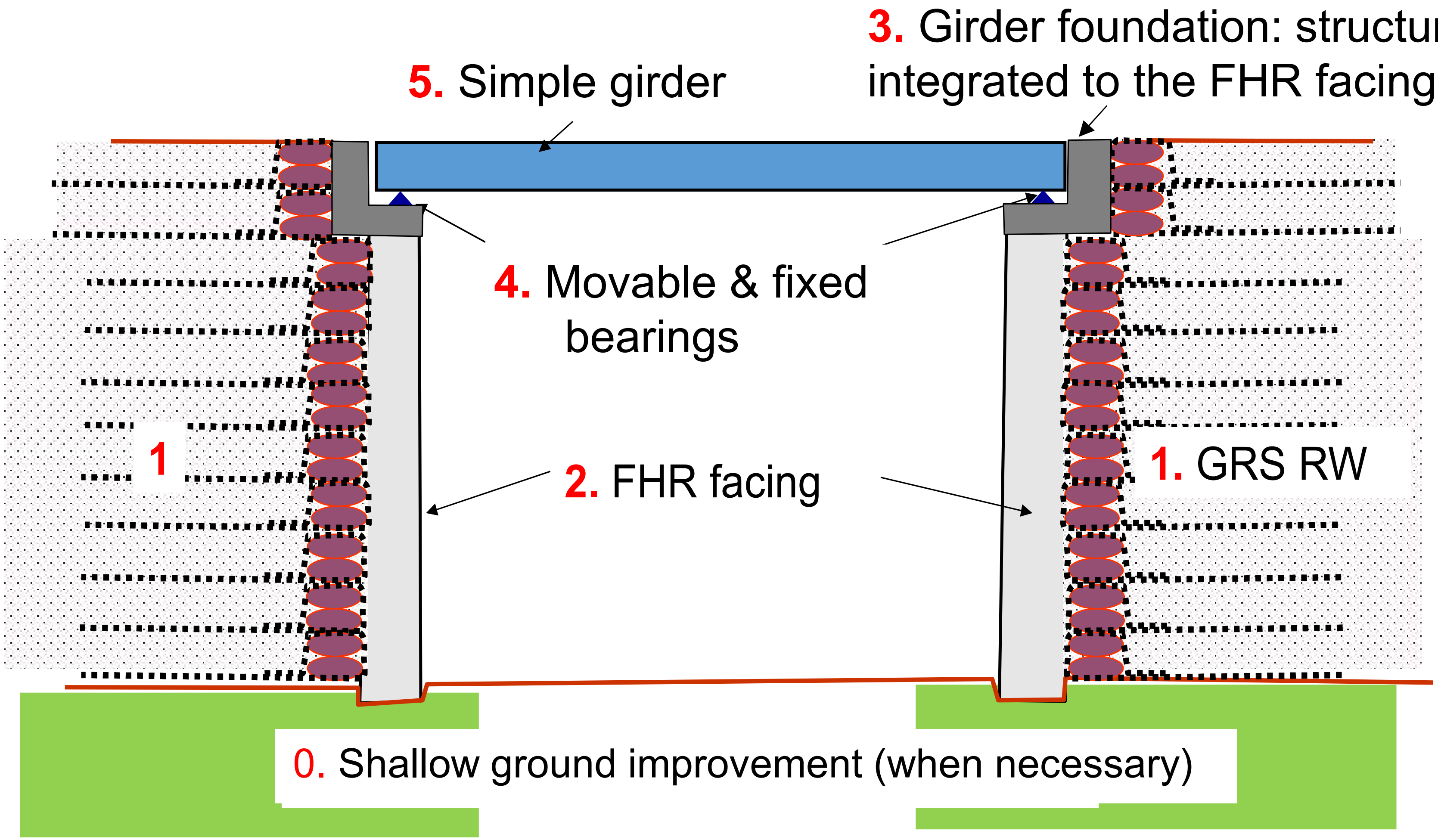
GRS Bridge Abutment (2nd generation), completed 2020
Shimo-shinjo No. 1, Hokuriku Shinkansen

By the courtesy of JRTT



A pair of GRS Bridge Abutments (2nd generation) supporting a simple girder via bearings:

Much better performance & much higher cost-effectiveness than GRS BA (1st generation), so definitely better than the conventional simple girder bridge ⇒ constructed at many places



A pair of GRS Bridge Abutments (2nd generation) supporting a simple girder, Kyushu Shinkansen, Nishi-Nihon Route, 28 October, 2022

GRS Bridge Abutment

GRS Bridge Abutment

Summary of GRS Bridge Abutment – Second generation

First GRS Bridge Abutment,
at Takada for Kyushu Shinkansen

GRS Bridge Abutment at Mantaro
for Hokkaido Shinkansen

- First one at Takada in 2003
- By 2022, in total 185, including:
  - 41 for Hokkaido High Speed Railway (Shinkansen);
  - 79 for Kyushu HSR; and
  - 49 for Hokuriku HSR

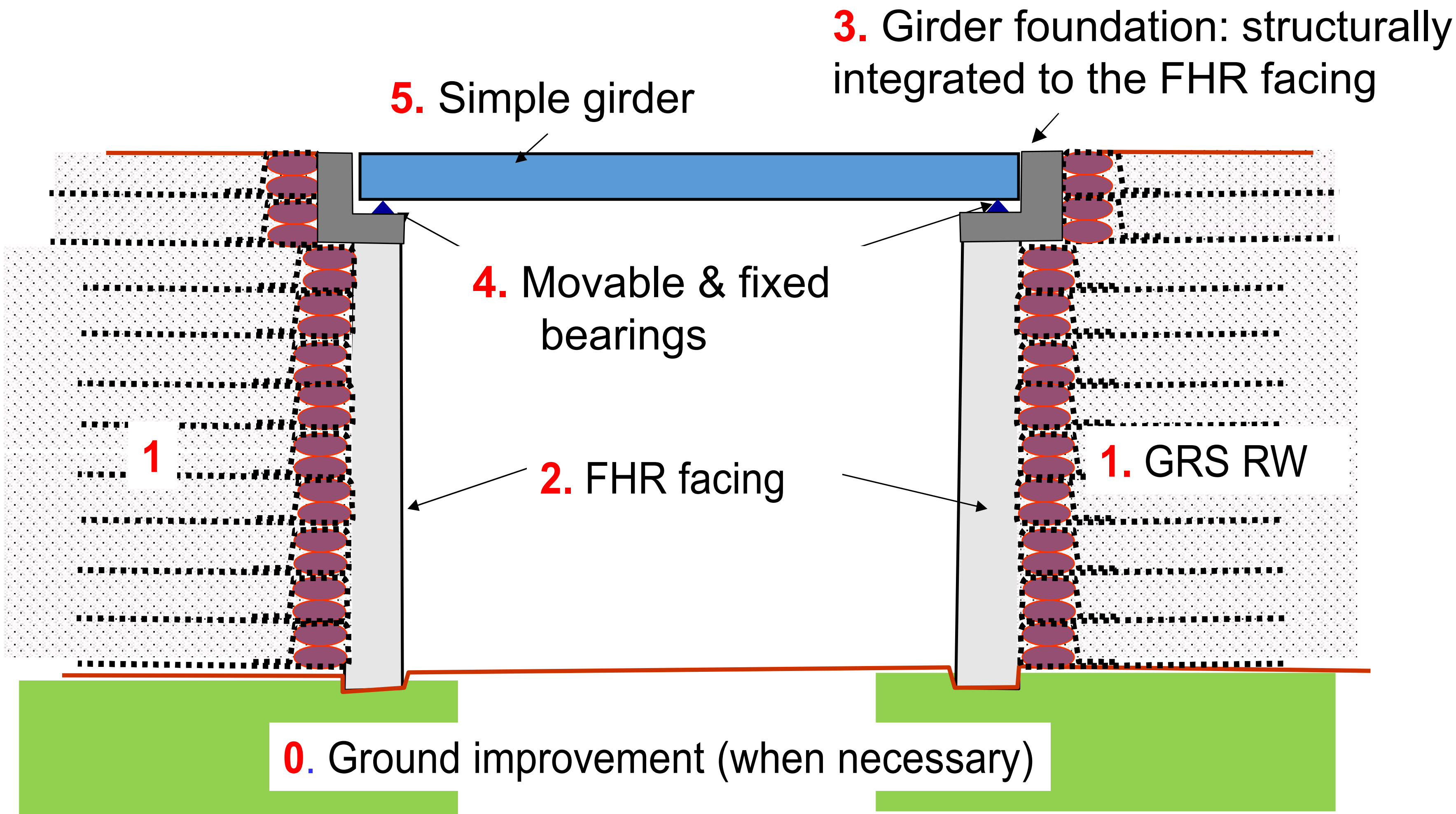
A pair of GRS Bridge Abutments (2nd generation) supporting a simple girder via bearings: - generally good performance.

However, the following two problems remain:

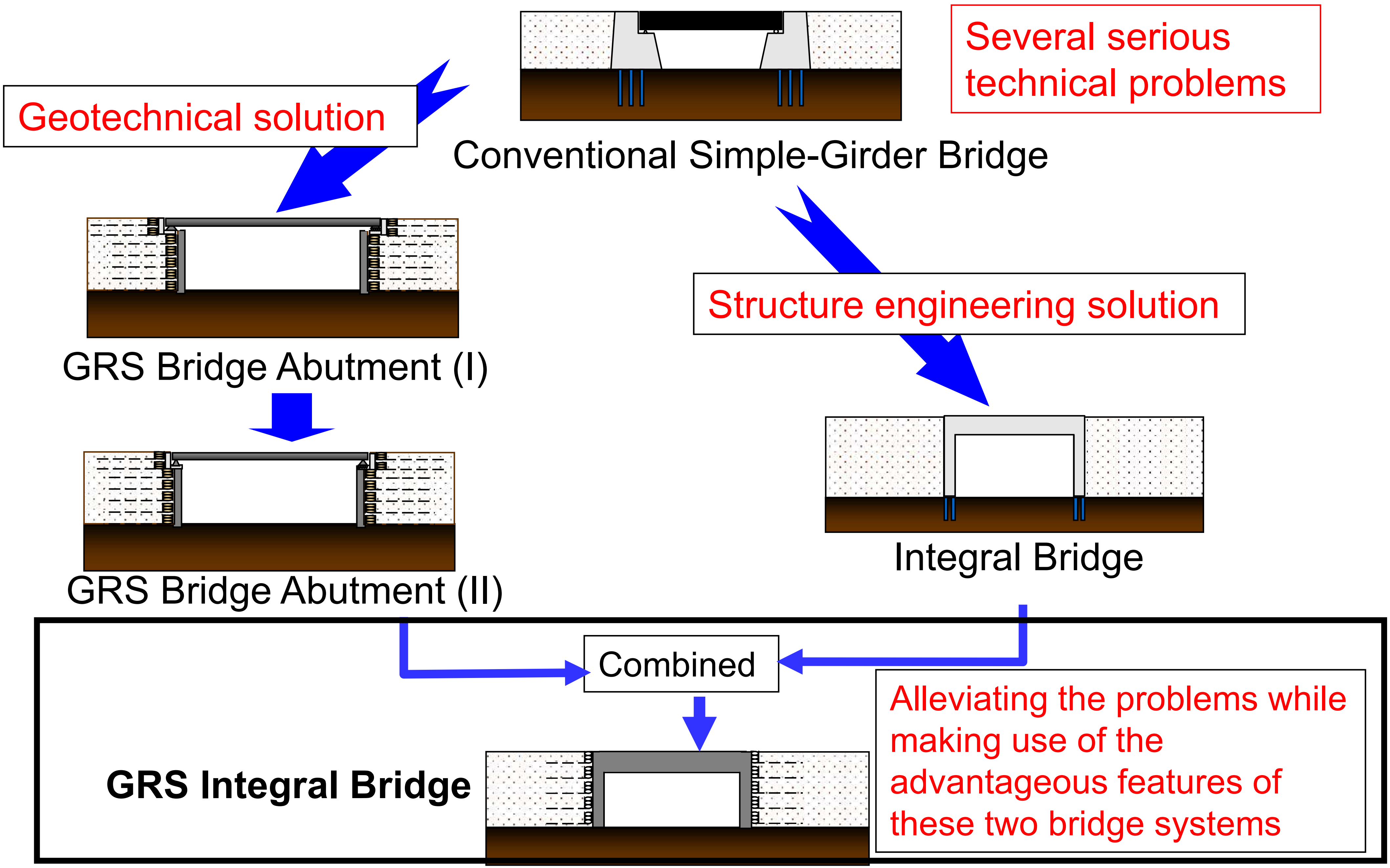
1) costly construction & maintenance of the bearings; and

2) low seismic stability of the girder at the movable bearing.

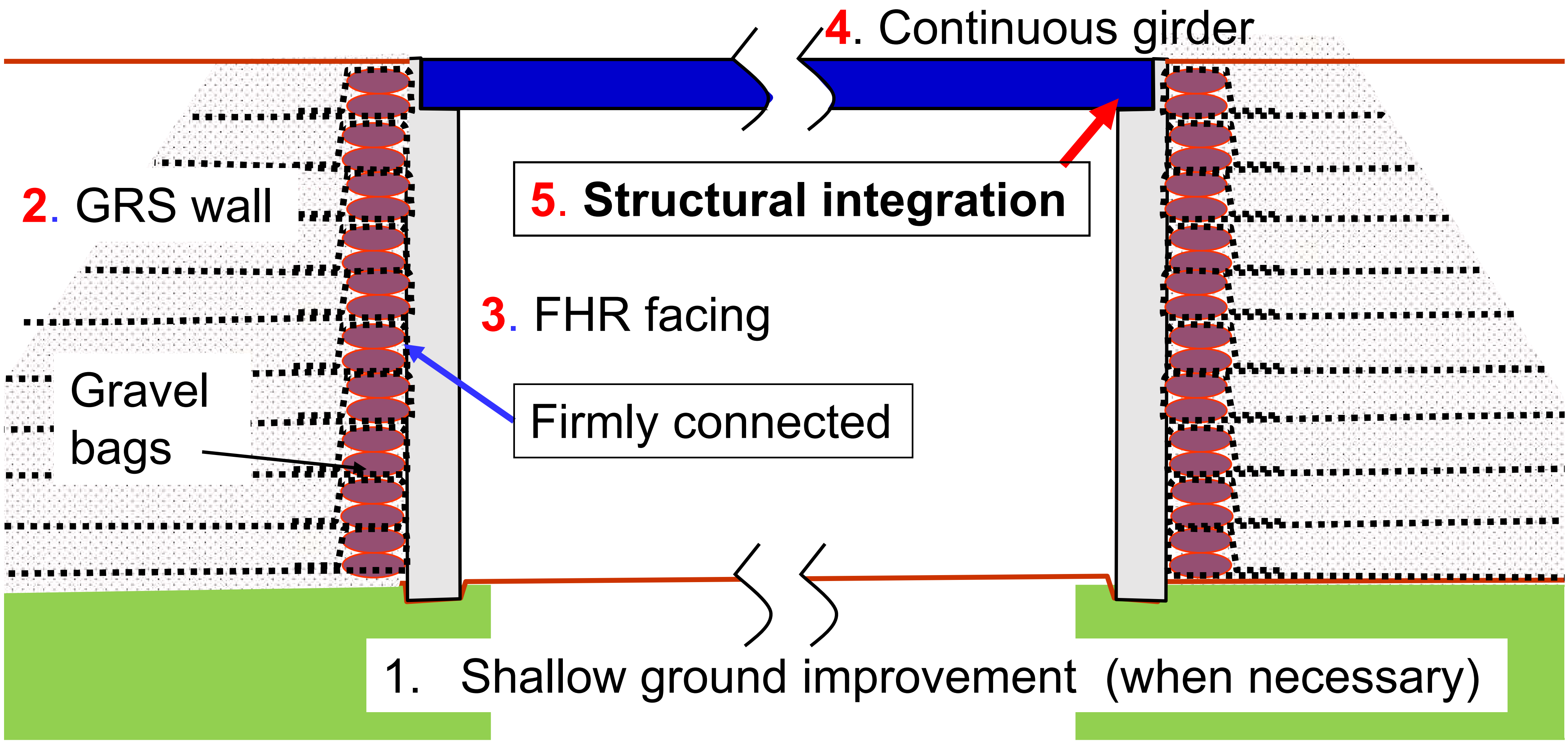
⇒ GRS Integral Bridge, alleviating these two problems



Developments from GRS RWs to GRS bridge structures



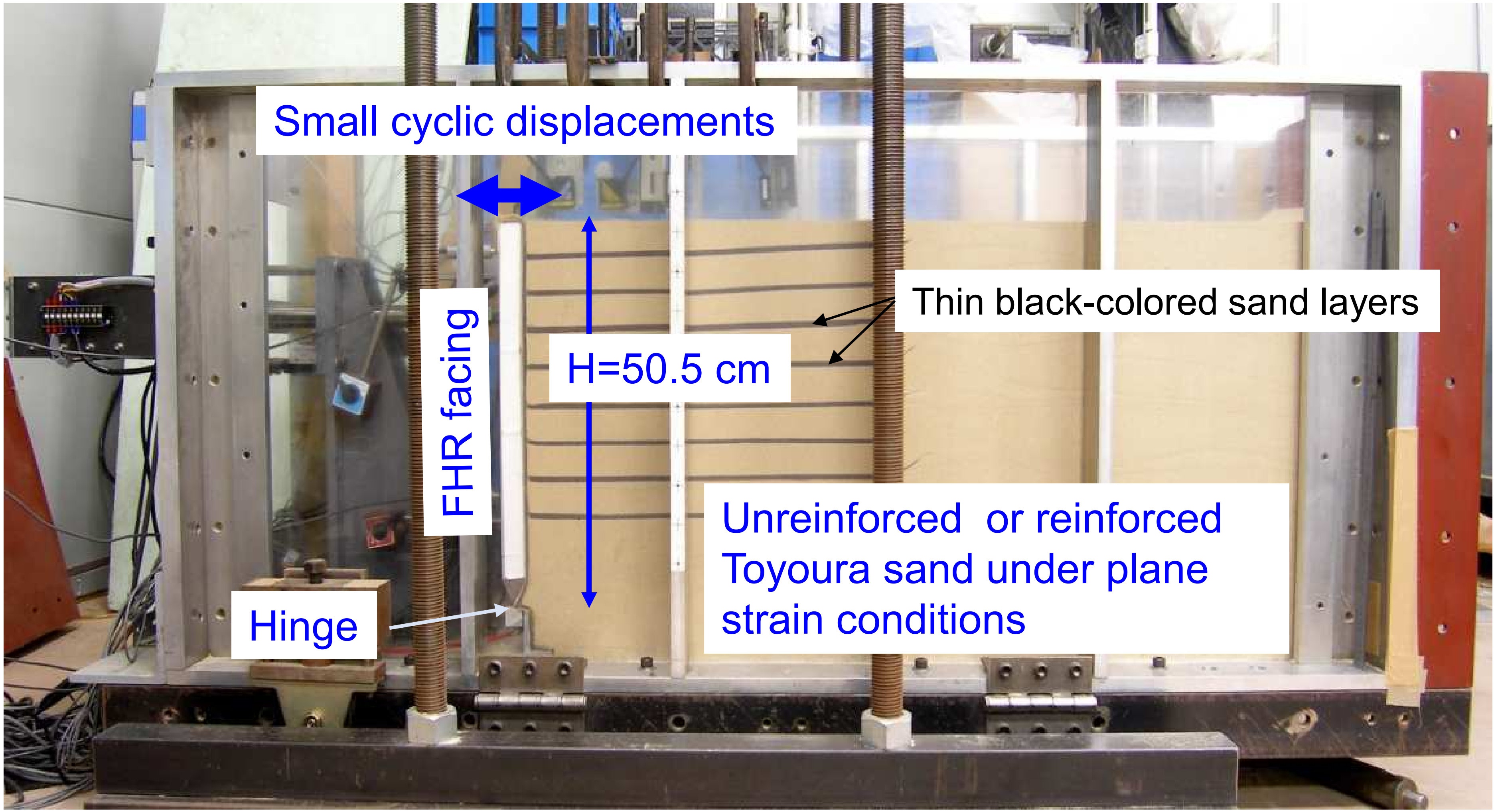
GRS Integral Bridge



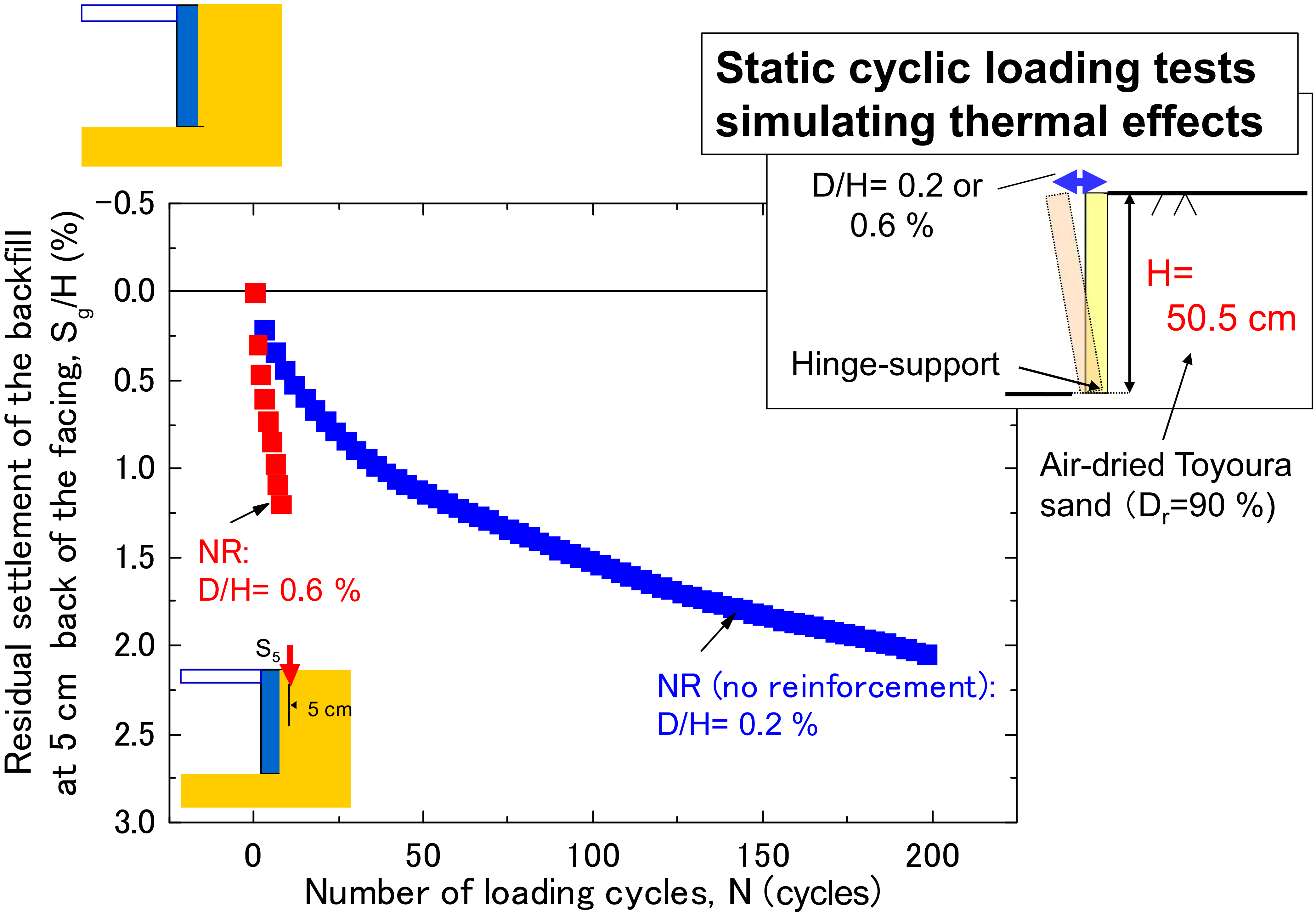
⇒ A series of static & dynamic model tests to evaluate the performance of GRS Integral Bridge

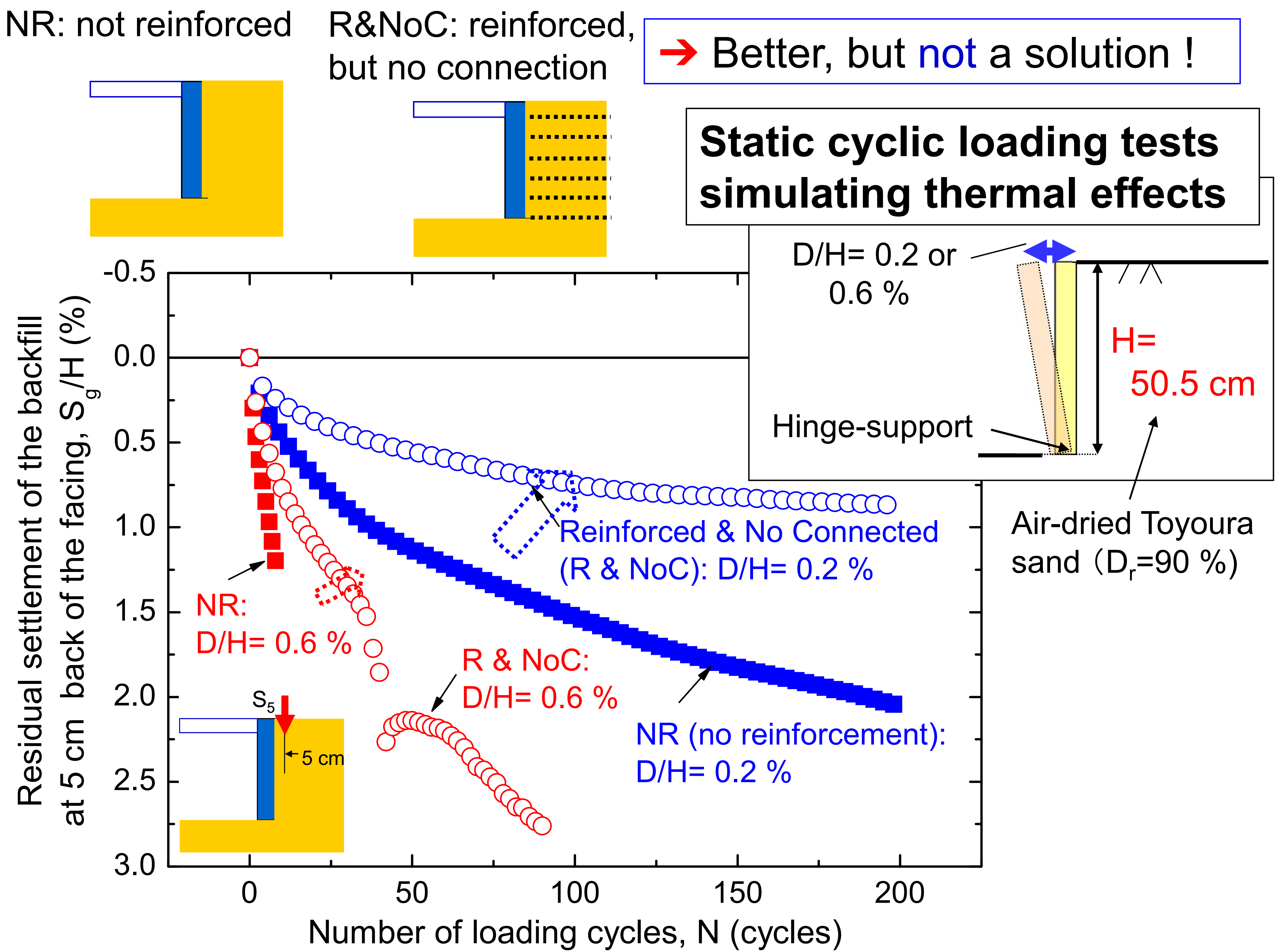
Cyclic lateral loading model test in 1g

(considered model scale: 1/10)

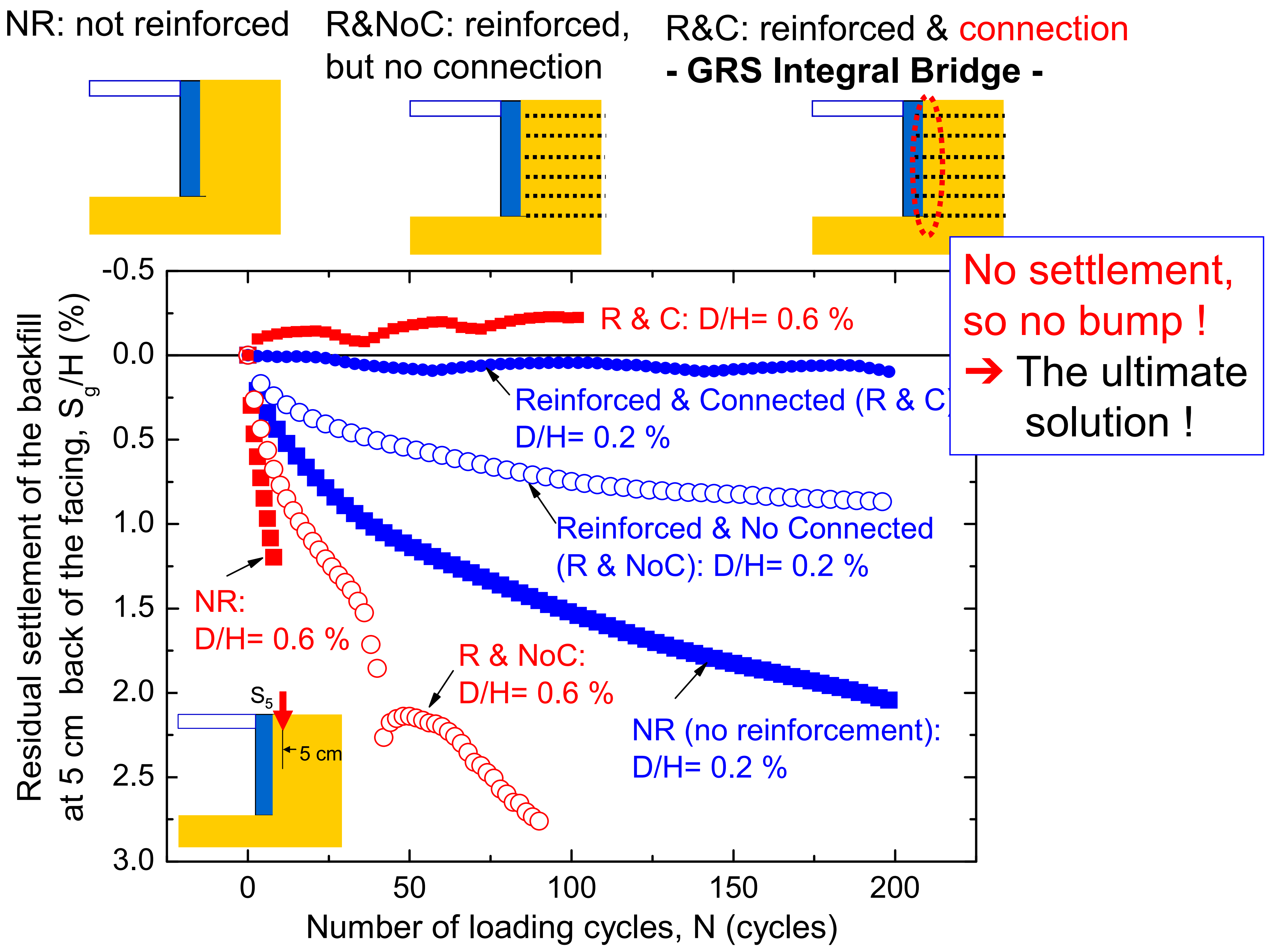


NR: not reinforced





NR: not reinforced
R&NoC: reinforced, but no connection
Better, but not a solution !
Static cyclic loading tests simulating thermal effects
D/H= 0.2 or 0.6 %
H= 50.5 cm
Hinge-support
Air-dried Toyoura sand (Dr=90 %)
Reinforced & No Connected (R & NoC): D/H= 0.2 %
NR: D/H= 0.6 %
R & NoC: D/H= 0.6 %
NR (no reinforcement): D/H= 0.2 %
S5
5 cm
Residual settlement of the backfill at 5 cm back of the facing, Sg/H (%)
Number of loading cycles, N (cycles)
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
50
100
150
200



NR: not reinforced
R&NoC: reinforced, but no connection
R&C: reinforced & connection
- GRS Integral Bridge -
No settlement, so no bump !
➔ The ultimate solution !
R & C: D/H= 0.6 %
Reinforced & Connected (R & C)
D/H= 0.2 %
Reinforced & No Connected
(R & NoC): D/H= 0.2 %
NR:
D/H= 0.6 %
R & NoC:
D/H= 0.6 %
NR (no reinforcement):
D/H= 0.2 %
S5
5 cm
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
50
100
150
200
Residual settlement of the backfill at 5 cm back of the facing, Sg/H (%)
Number of loading cycles, N (cycles)

GRS Integral Bridge model for shaking table tests

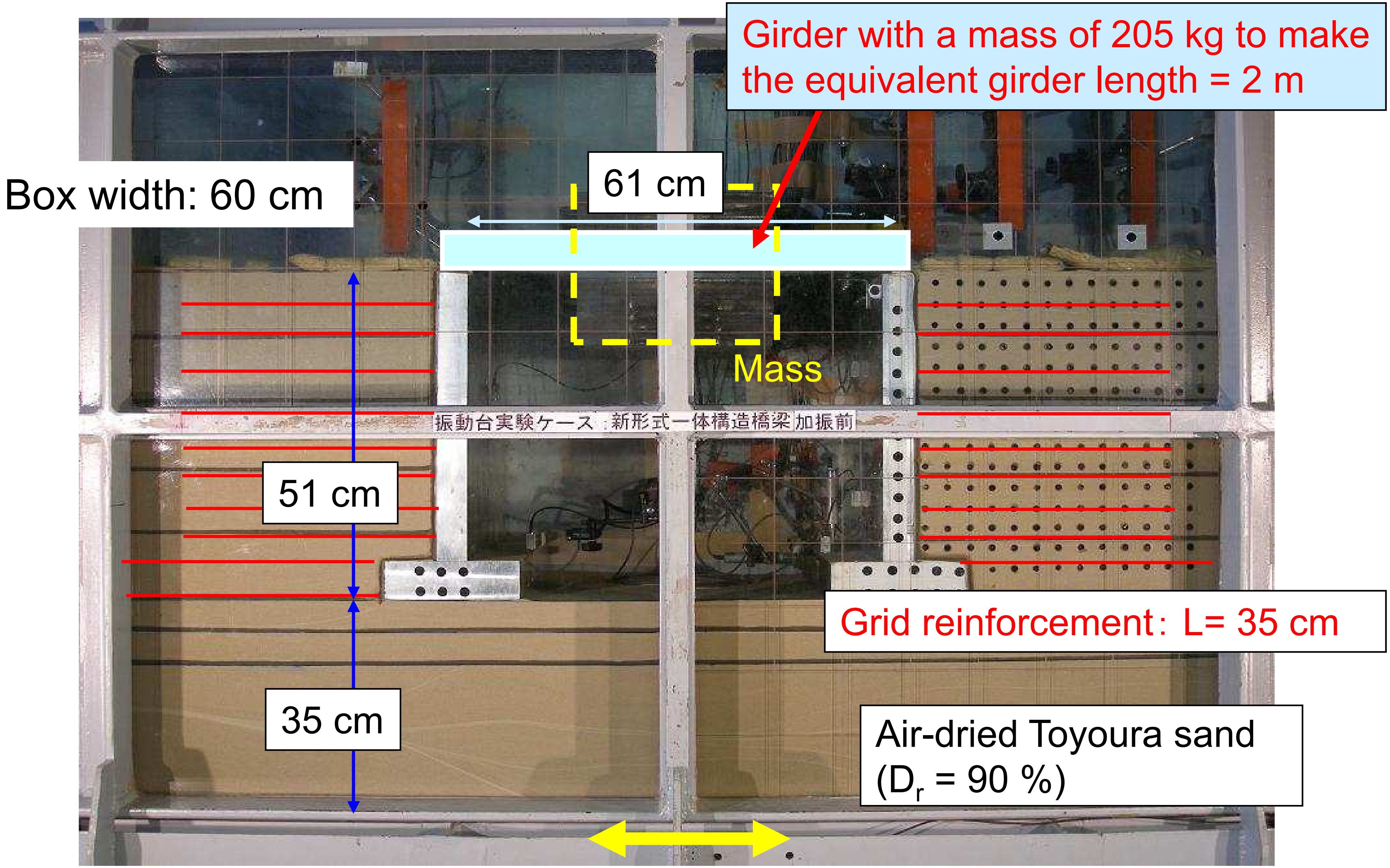
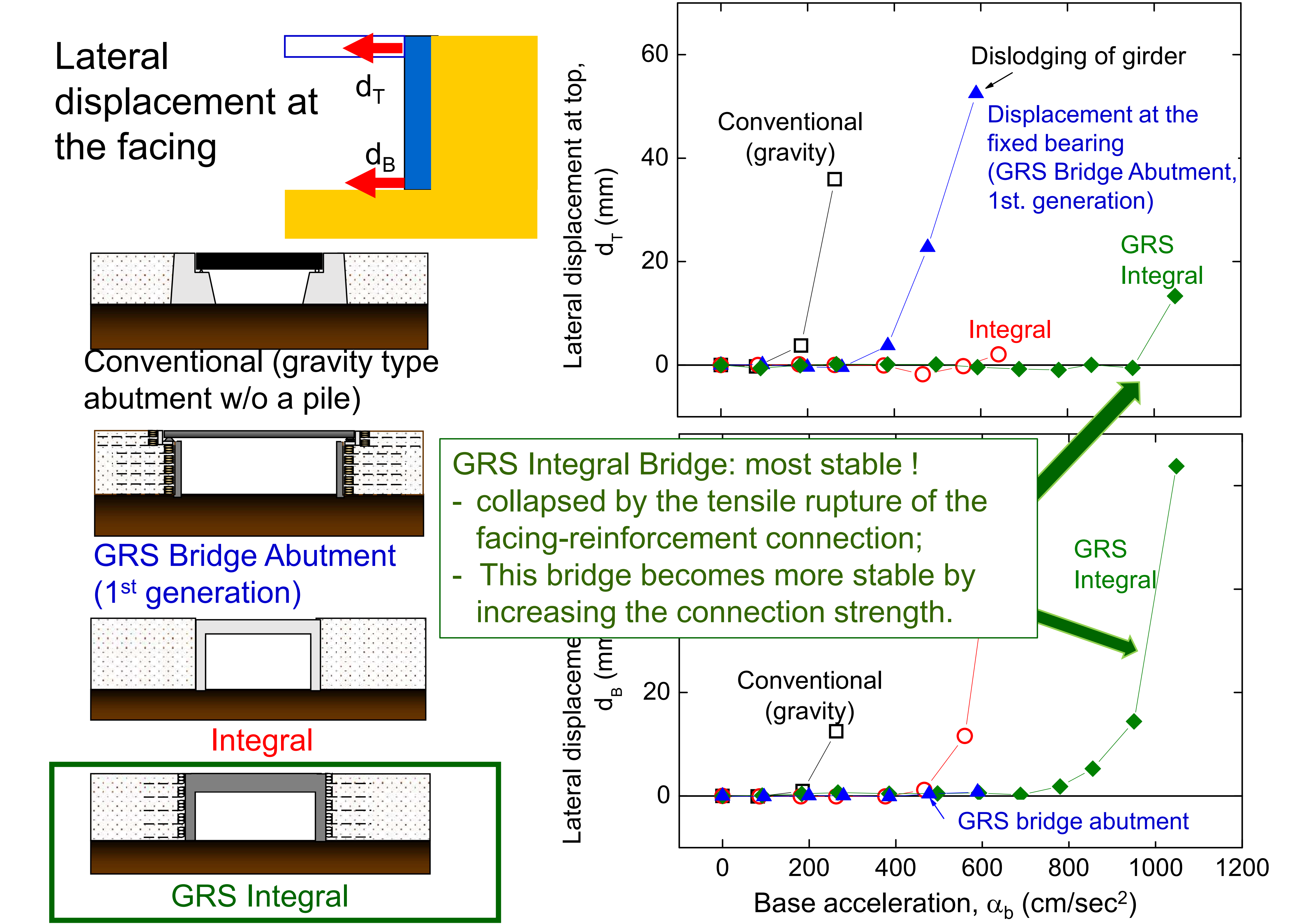
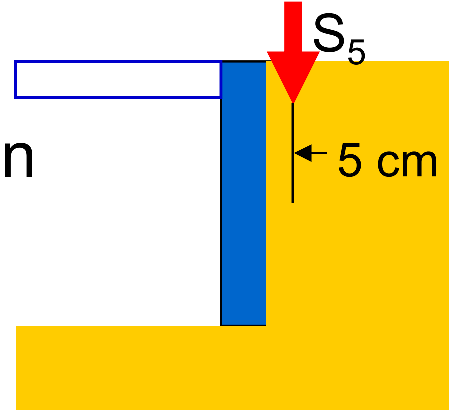


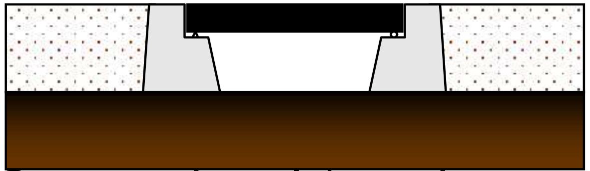
Table acceleration: uniform 20 waves (f_i= 5 Hz) at each step, increasing the amplitude, α_b, by an increment of 100 cm/sec^2/step


Lateral displacement at the facing
d_T
d_B
Conventional (gravity type abutment w/o a pile)
GRS Bridge Abutment (1st generation)
Integral
GRS Integral
Lateral displacement at top, d_T (mm)
60
40
20
0
Dislodging of girder
Conventional (gravity)
Displacement at the fixed bearing (GRS Bridge Abutment, 1st. generation)
GRS Integral
Integral
GRS Integral Bridge: most stable !
- collapsed by the tensile rupture of the facing-reinforcement connection;
- This bridge becomes more stable by increasing the connection strength.
GRS Integral
Lateral displaceme
d_B (mm
Conventional (gravity)
GRS bridge abutment
0
200
400
600
800
1000
1200
Base acceleration, α_b (cm/sec^2)

Residual settlement in the backfill

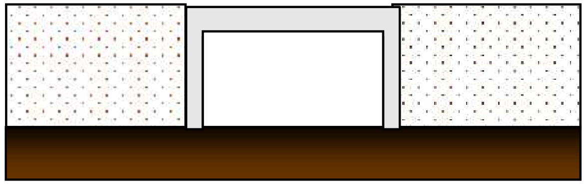


GRS Integral Bridge:
essentially no settlement in the backfill right behind the FHR facing

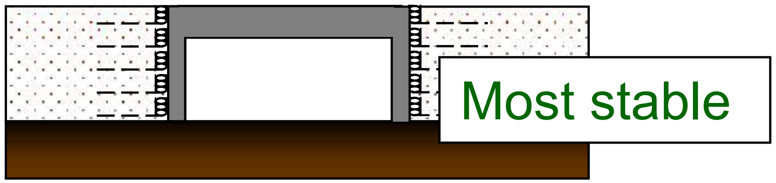


Conventional (gravity type abutment w/o a pile)

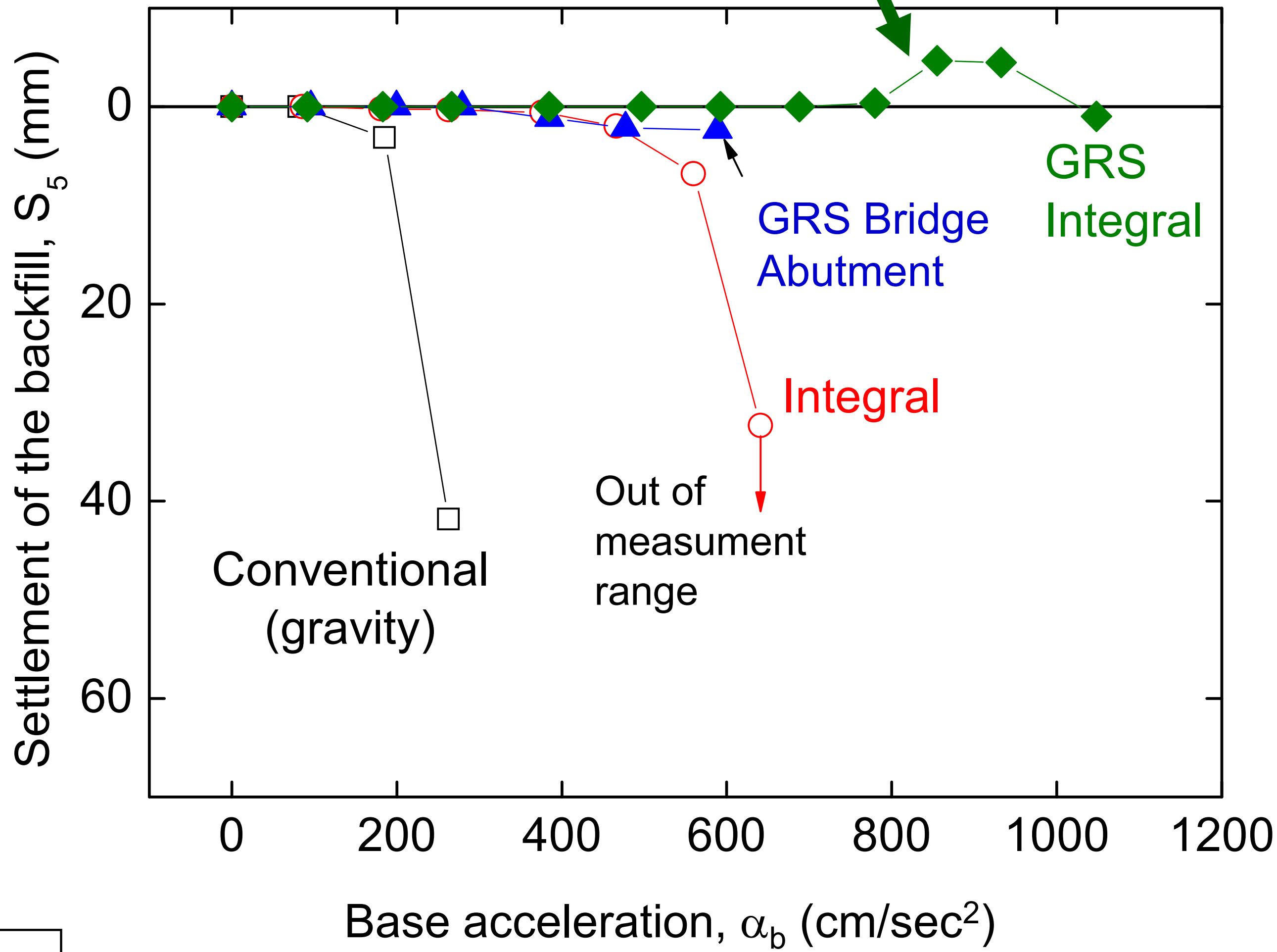
GRS Bridge Abutment (1^{st} generation)



Integral

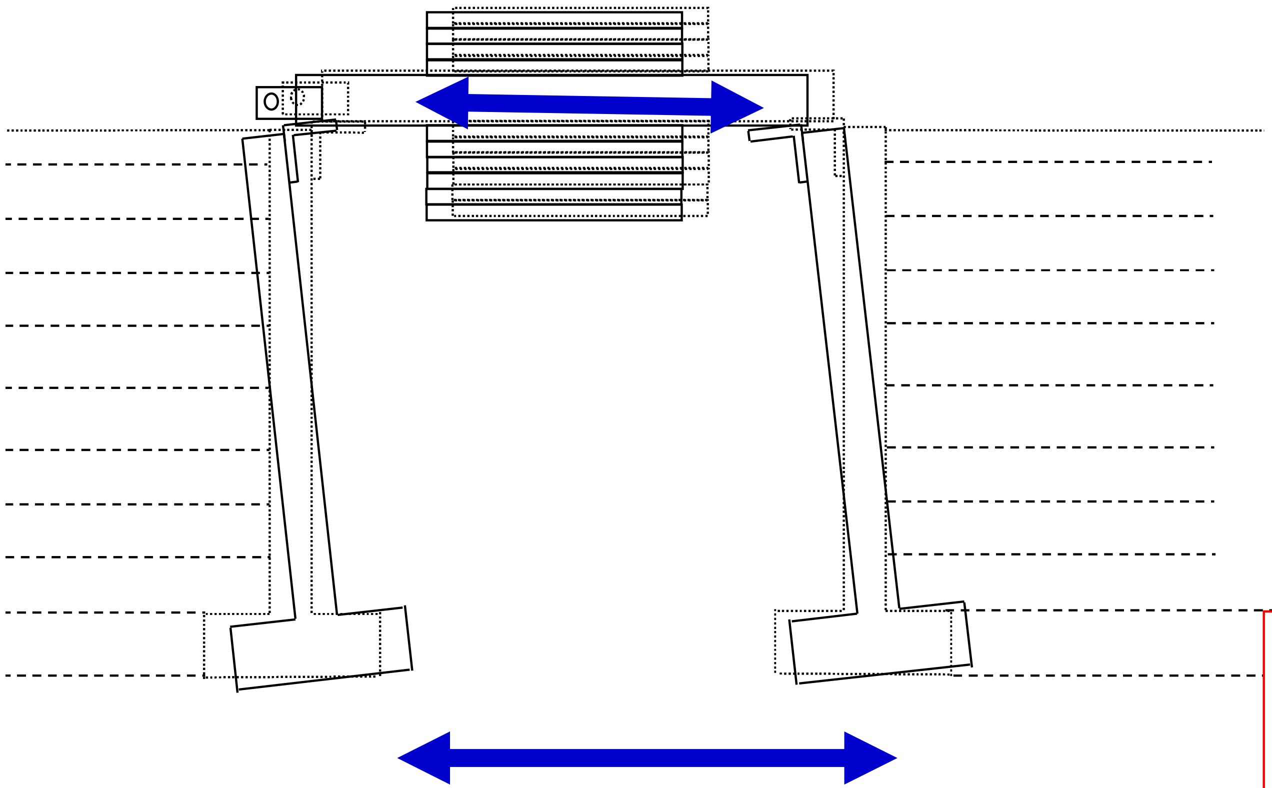


GRS Integral



The first mode of dynamic deformation,
modeled by a damped single-degree-of-freedom system

Response acceleration (amplitude: α_t)



Measured

Acceleration magnification ratio:

$$M = \alpha_t/\alpha_b$$

Phase difference: φ

Back-cacluated

Natural frequency; f_0

→Tuning ratio: $\beta = f_i/f_0$

Damping ratio: ξ

Sinusoidal input acceleration
(amplitude: α_b, input frequency: f_i)

Four factors for very high seismic stability of GRS Integral Bridge

1) A high initial natural frequency f_0, usually much higher than the predominant frequency f_p of major seismic loads → a low response acceleration

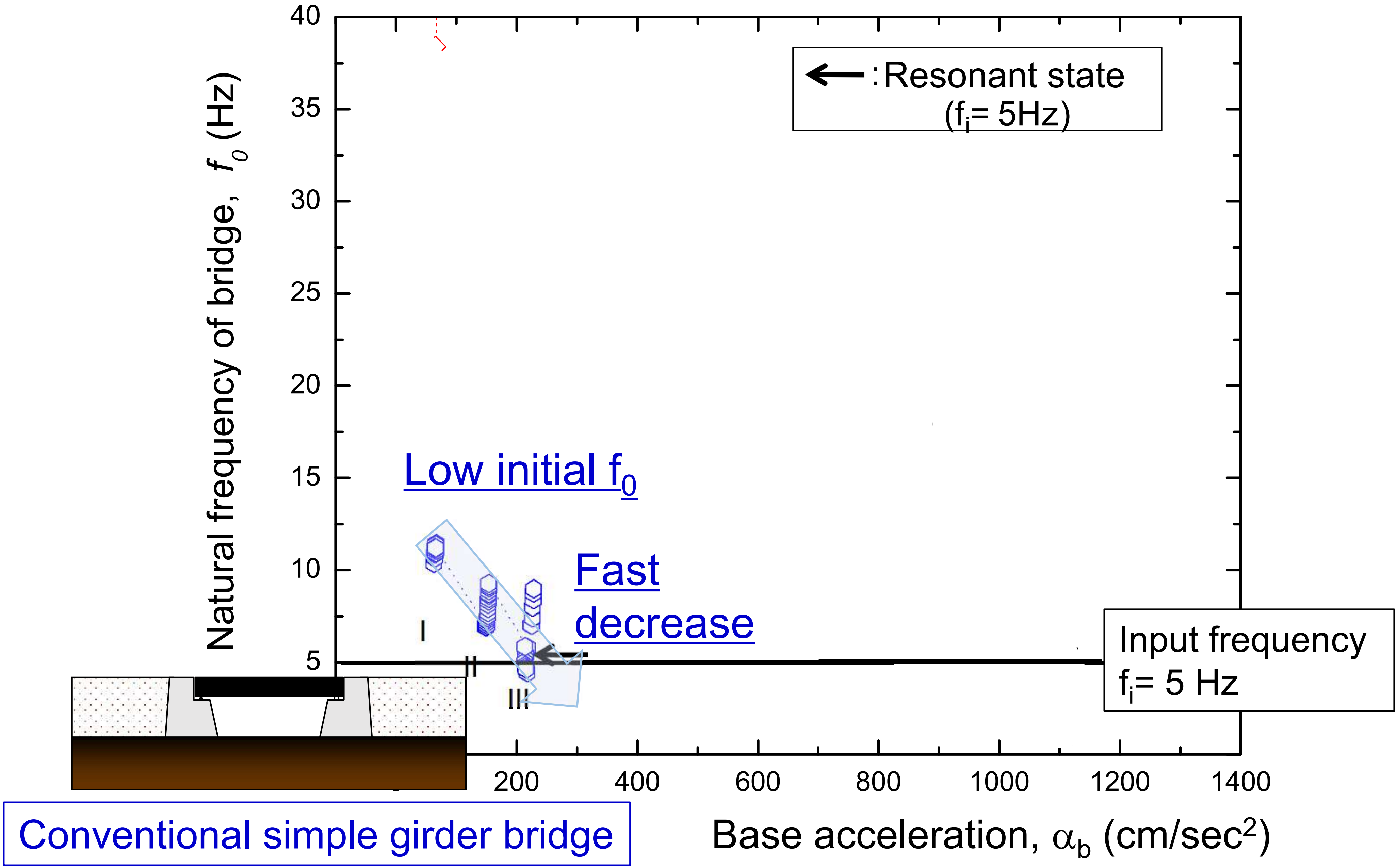
2) A slow decrease in f_0 by seismic loading (i.e., high ductility) → very slow approaching to the resonant state (where $f_0 = f_p$)

3) A large damping ratio due to efficient dissipation of the dynamic energy of the girder & facing to the backfill and subsoil → a low response acceleration

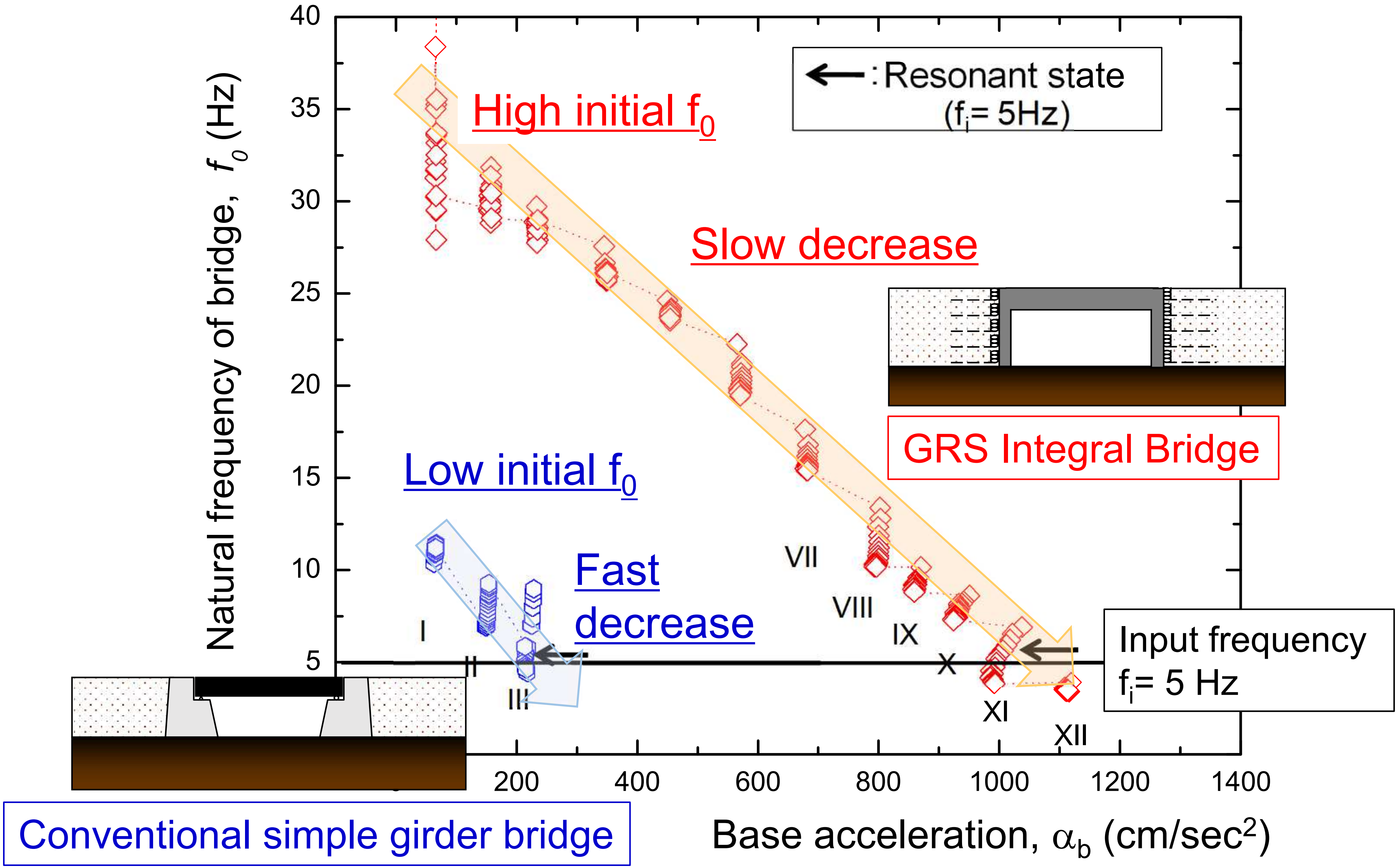
4) A high structural strength

All these features are the result from structural integration of girder, FHR facing and reinforced backfill.

Initial f_0 and a decrease in f_0 with an increase in the base acceleration in model shaking table tests



Initial f_0 and a decrease in f_0 with an increase in the base acceleration in model shaking table tests



Four factors for very high seismic stability of GRS Integral Bridge

1) A high initial natural frequency f_0
→ a low initial response acceleration

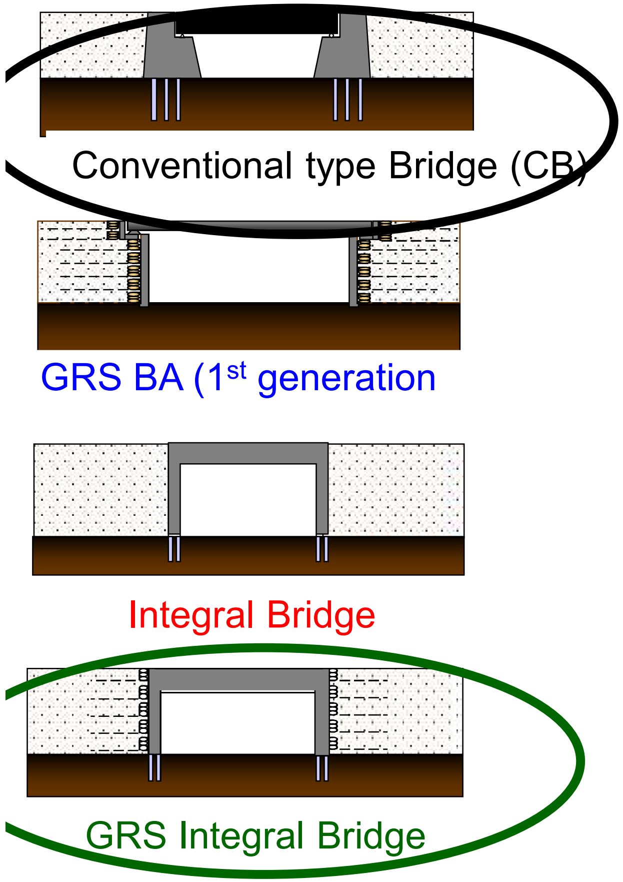
2) A slow decrease of f_0 by seismic loading
→ very slow to reach the resonant state

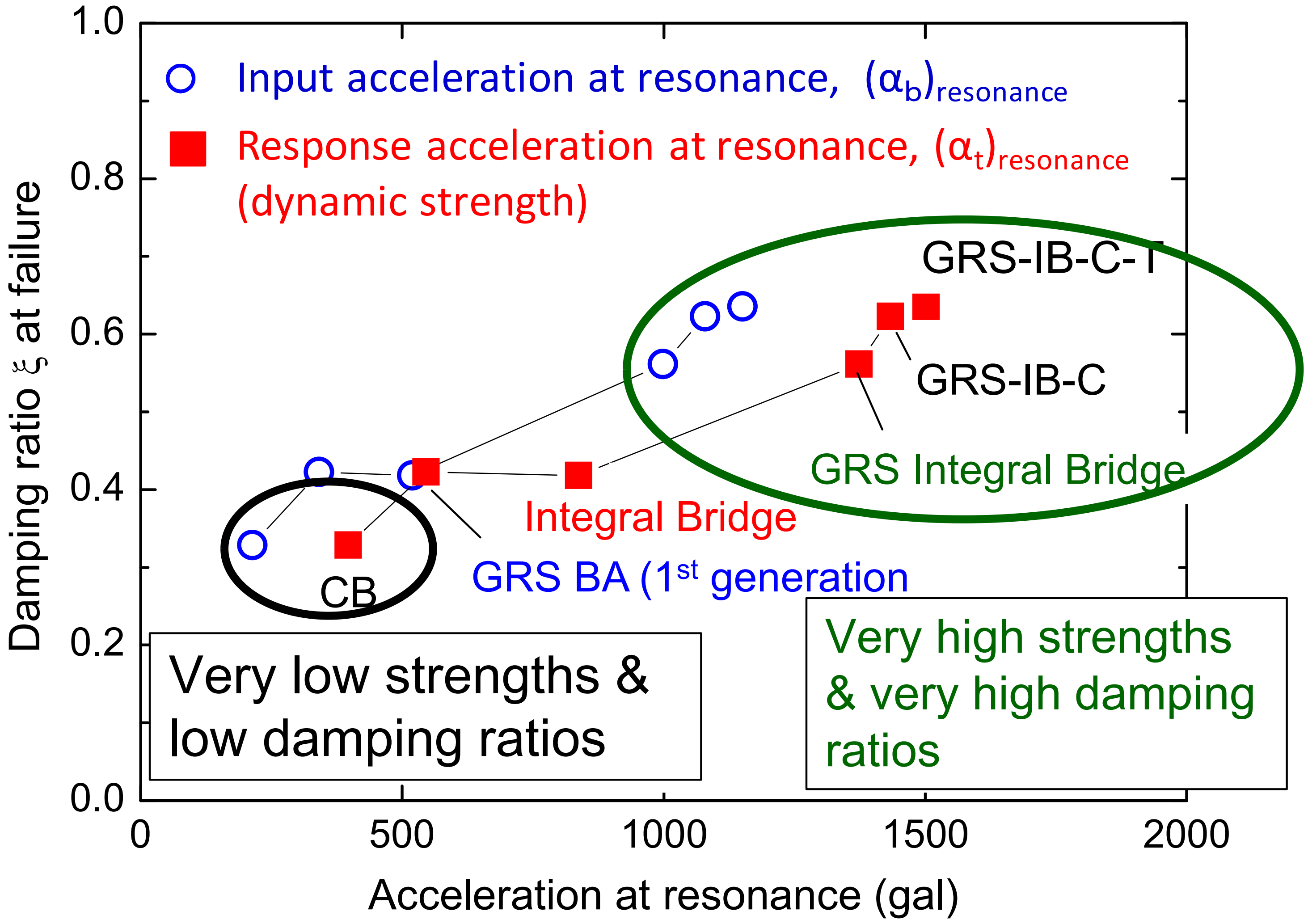
3) A large damping ratio
→ a small response acceleration

4) A high structural strength

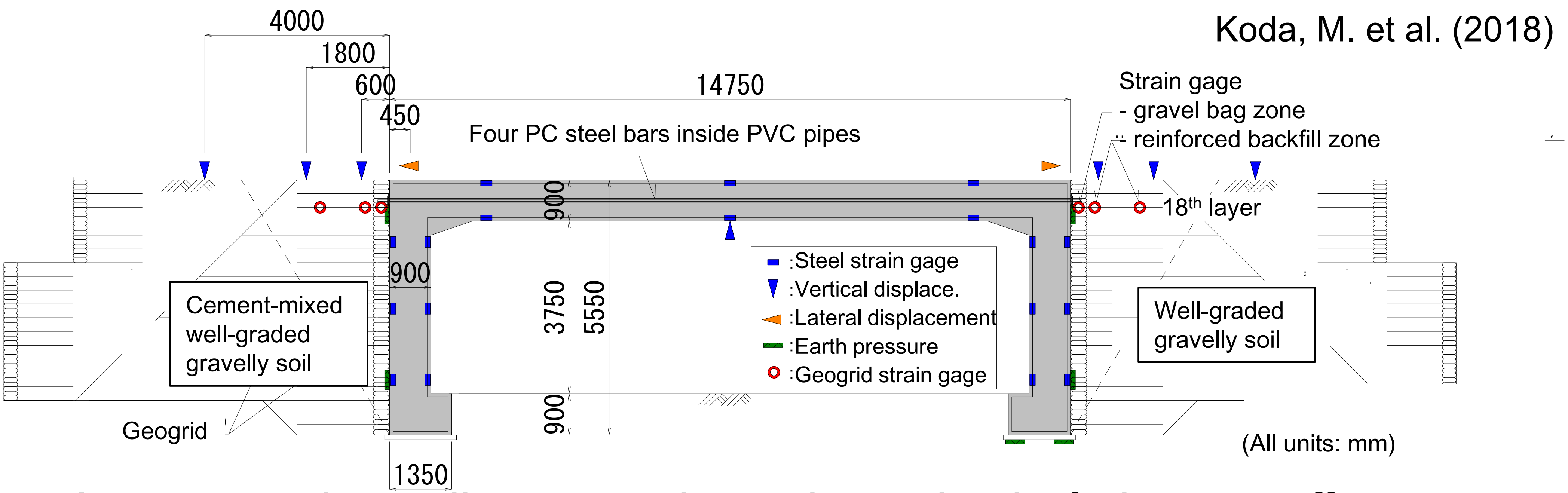
All these are by structural integration of girder, FHR facing and reinforced backfill.

Acceleration and damping ratio at the start of failure (i.e., at resonance for an input motion with f_i= 5 Hz) in model shaking table tests

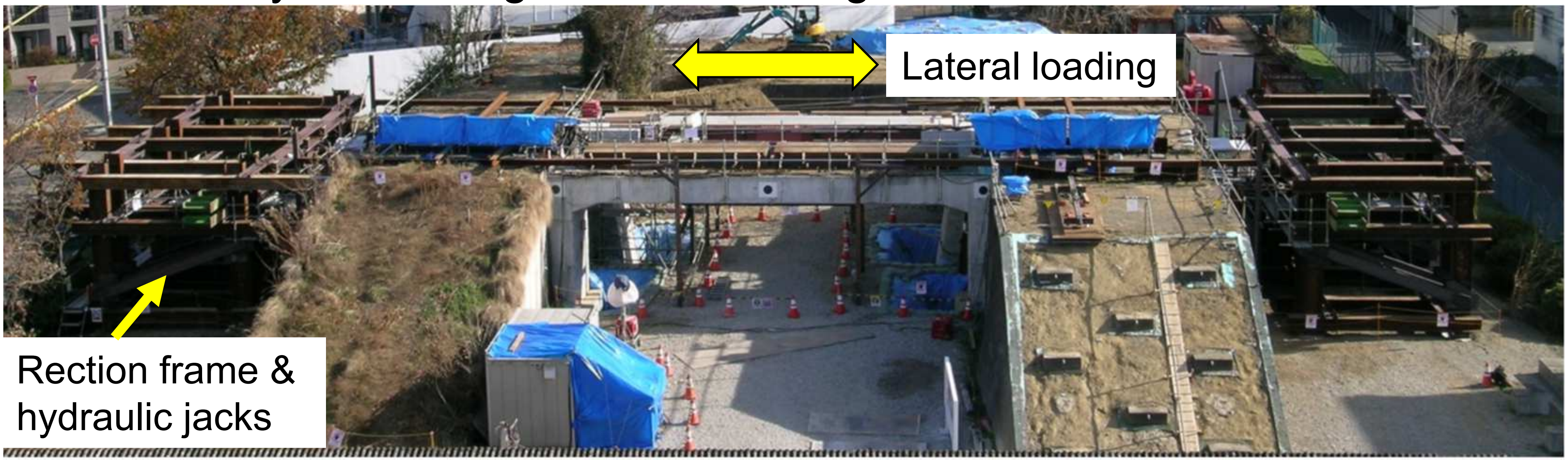




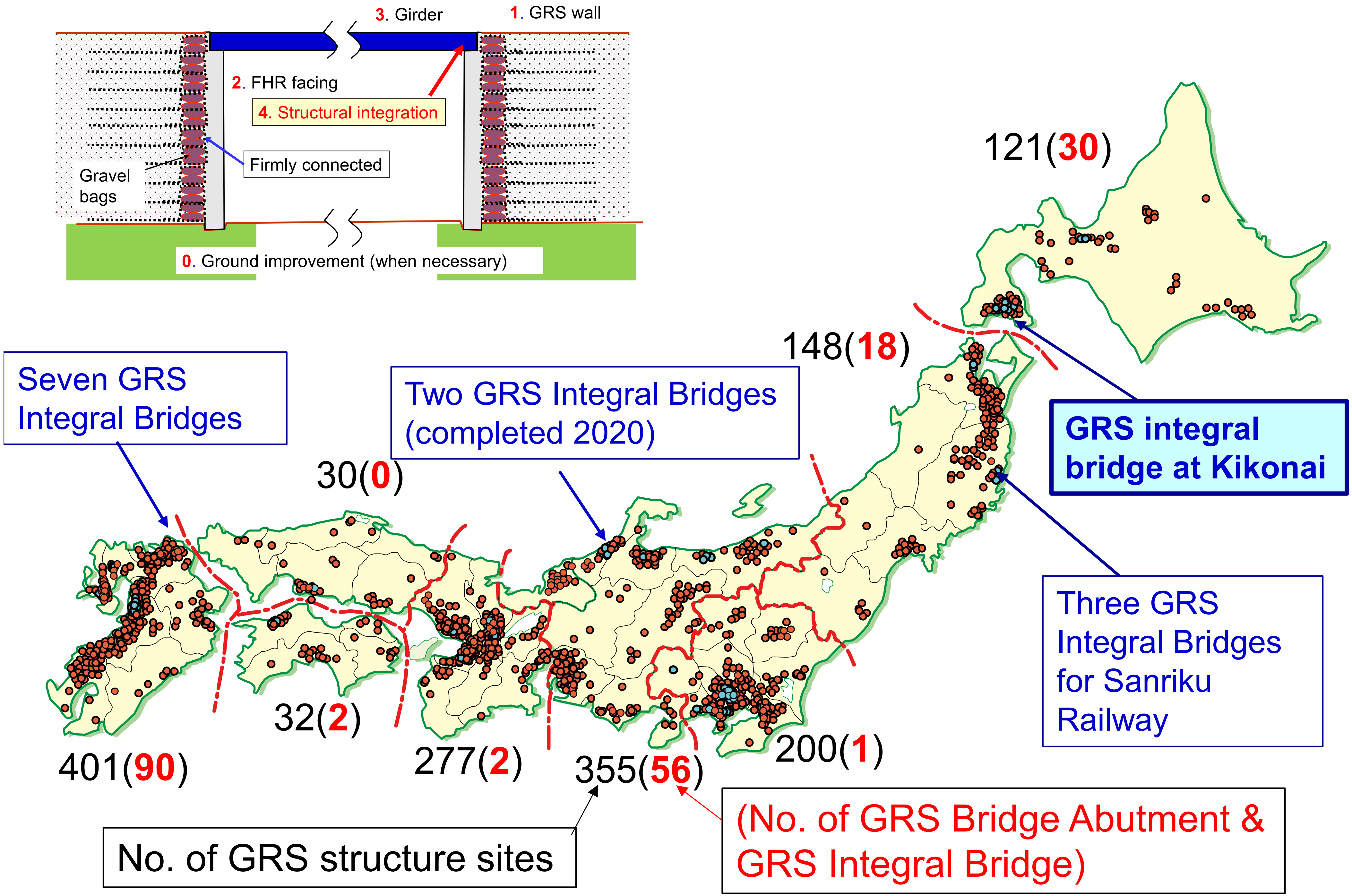
Full-scale model of GRS Integral Bridge completed Feb. 2009 at Railway Technical Research Institute, Japan



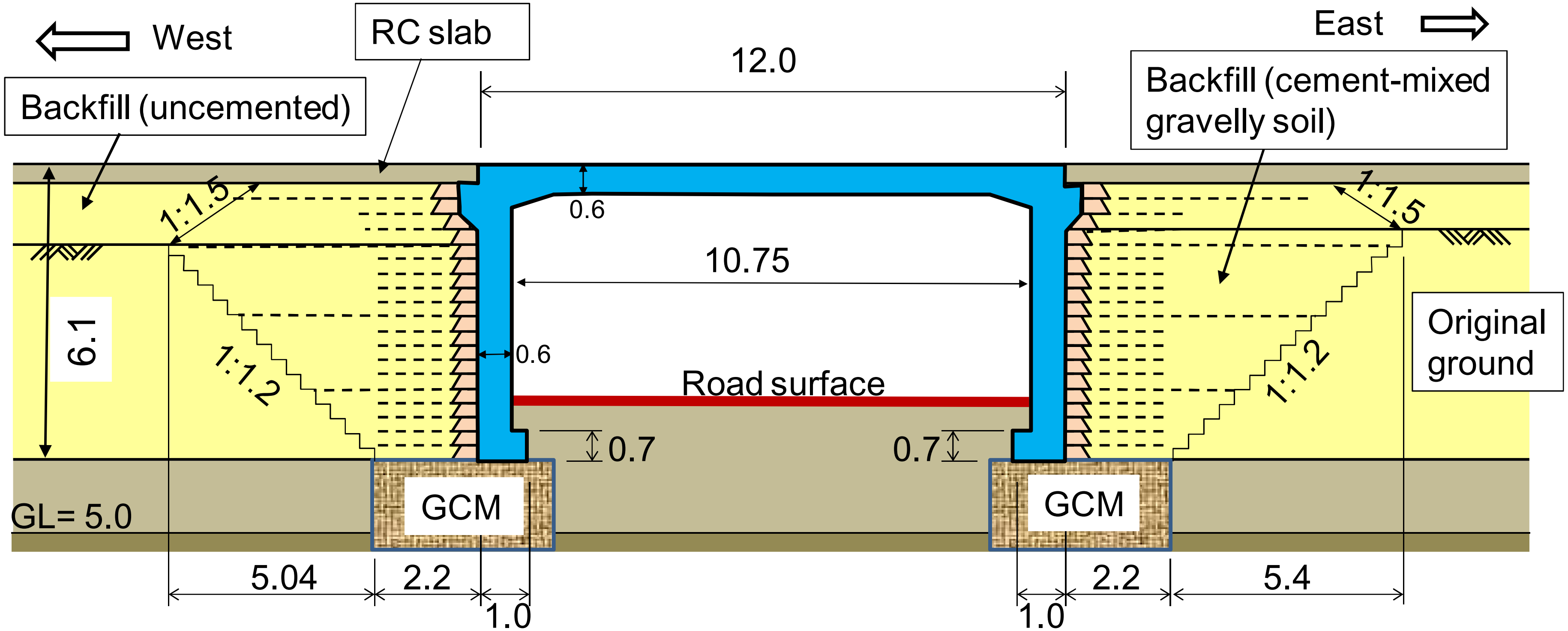
Lateral cyclic loading tests simulating seismic & thermal effects



GRS Integral Bridges for railways



First GRS Integral Bridge at Kikonai for Hokkaido Shinkansen (completed 2012)



[All units in m]

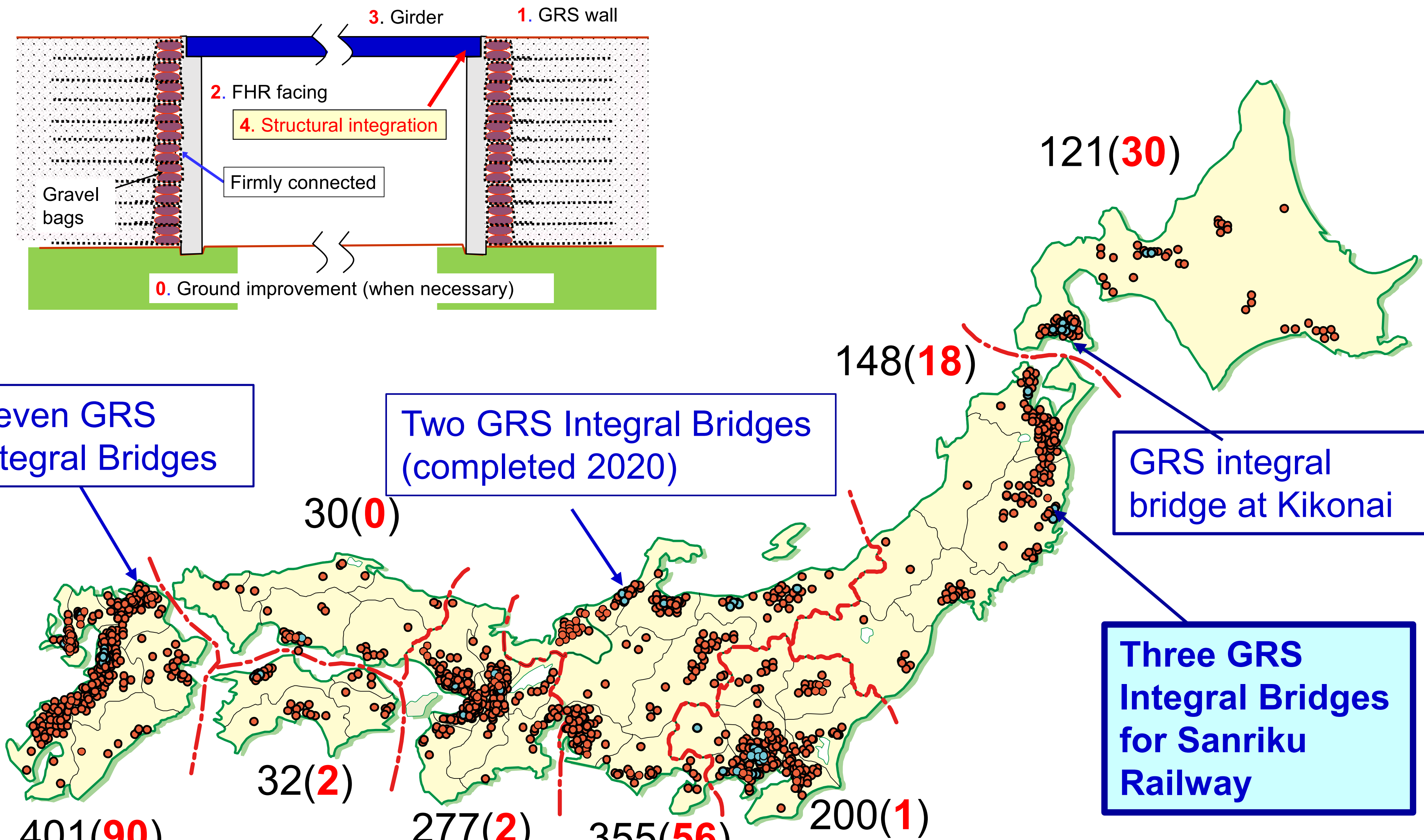
GCM: Ground improvement by cement-mixing

- Slender girder & FHR facing, resulting from structural integration of the girder to the FHR facing that are connected to the reinforcement layers
- No bump right behind the facing

⇒ A large cost reduction in construction & maintenance

(31 July 2012).

GRS Integral Bridges for railways



Seven GRS Integral Bridges

Two GRS Integral Bridges (completed 2020)

GRS integral bridge at Kikonai

Three GRS Integral Bridges for Sanriku Railway

No. of GRS structure sites

(No. of GRS Bridge Abutment & GRS Integral Bridge)

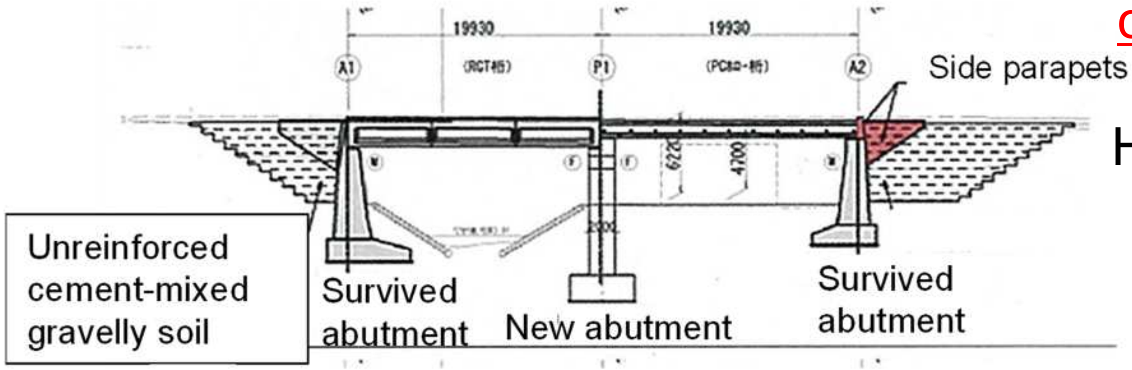
20 days after the 2011 Great East Japan E.Q. (11 March 2011), Koikoreobe, Sanriku Railway

Two simple girders had been washed away towards the inland by a great tsunami from Pacific Ocean

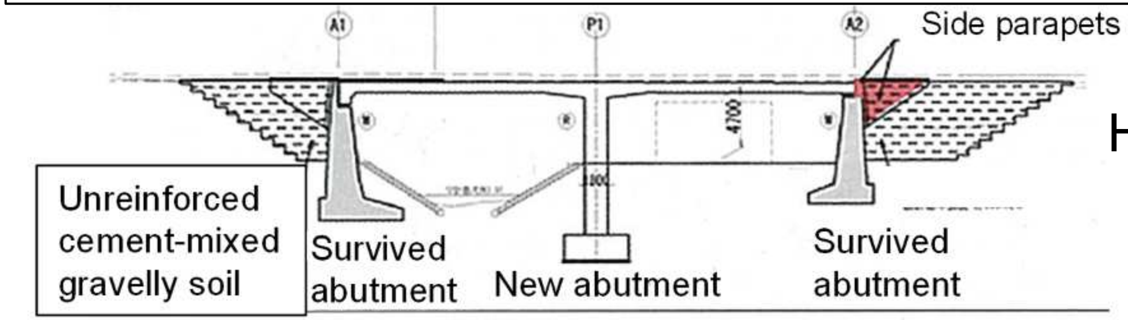
Three candidates for restoration

Candidate	Construction cost	Seismic stability	Anti-tsunami stability	Need for maintenance work
Two-span simple girders with two pairs of bearing (i.e., the collapsed bridge type)	High	Low	Low	High
Single continuous girder with a pair of bearing	High	Inter-mediate	Low	High
GRS Integral Bridge without using bearings	Low	High	High	Very low

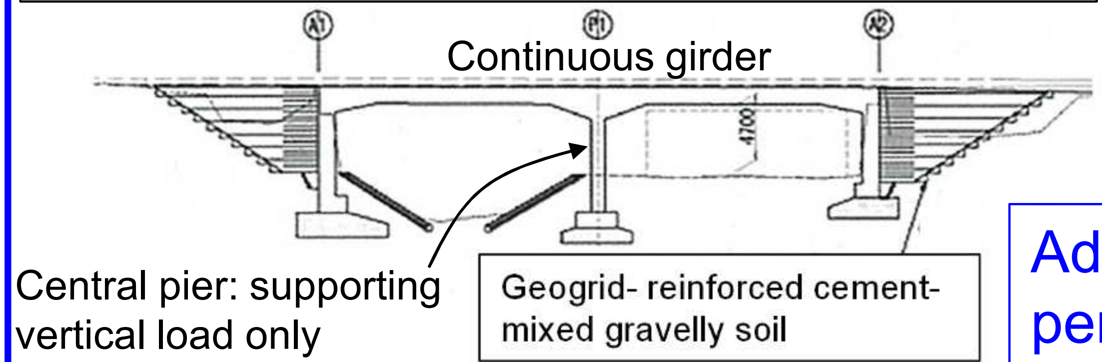
Two-span simple girders with two pairs of bearing (i.e., the collapsed bridge type)



Single continuous girder with a pair of bearing

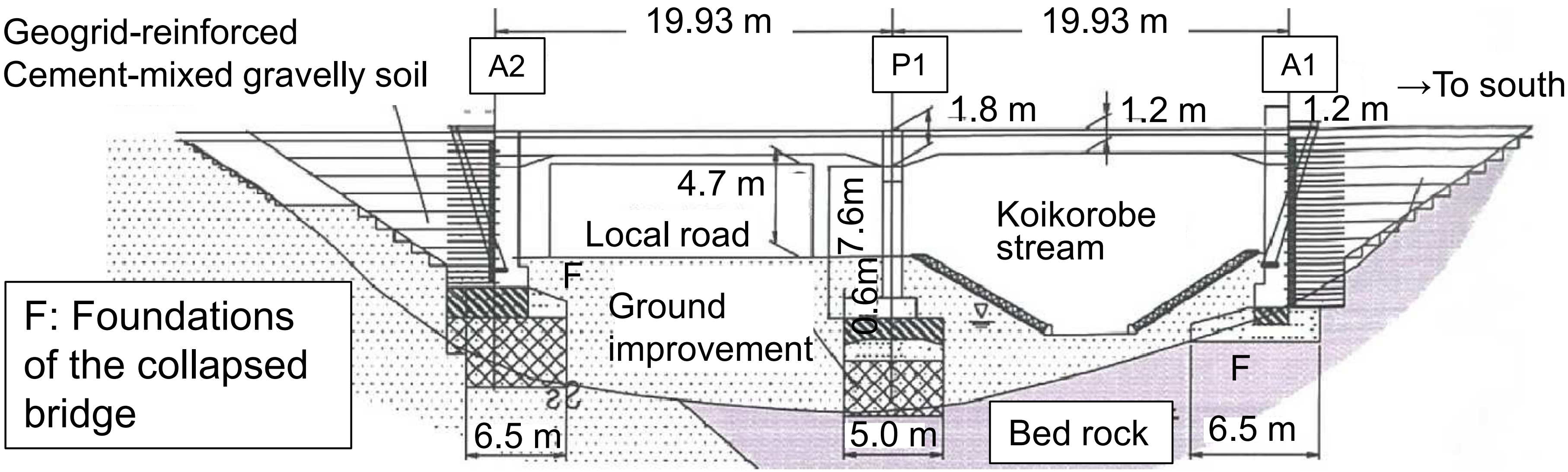


GRS Integral Bridge without using bearings



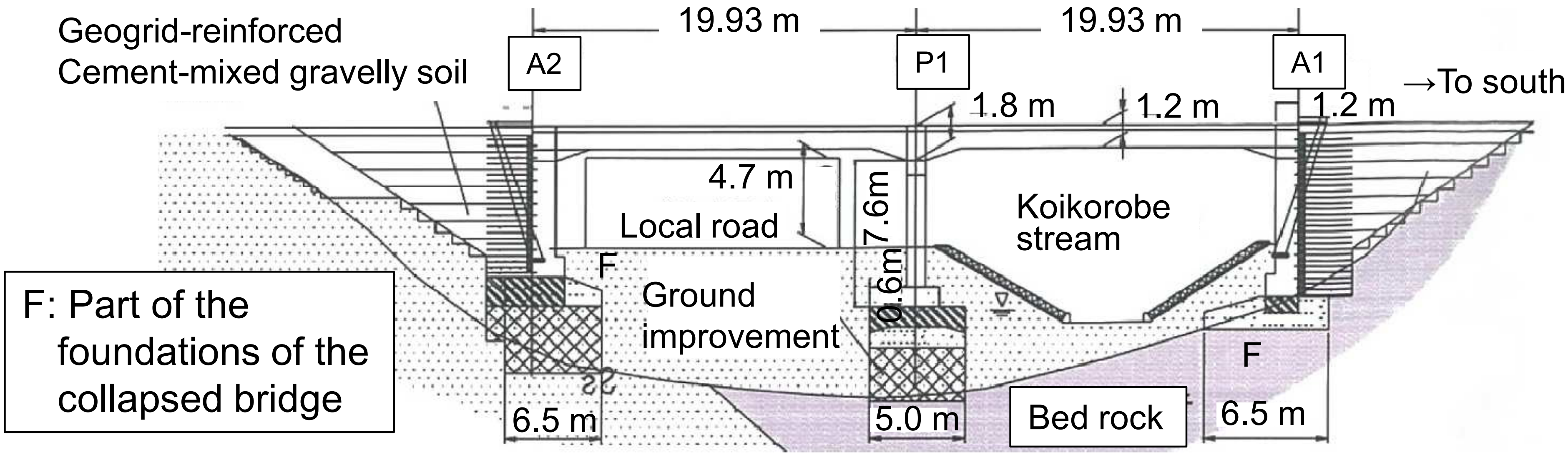
Adopted because of best expected performance & best cost-effectiveness

GRS Integral Bridge at Koikorobe, Sanriku Railway



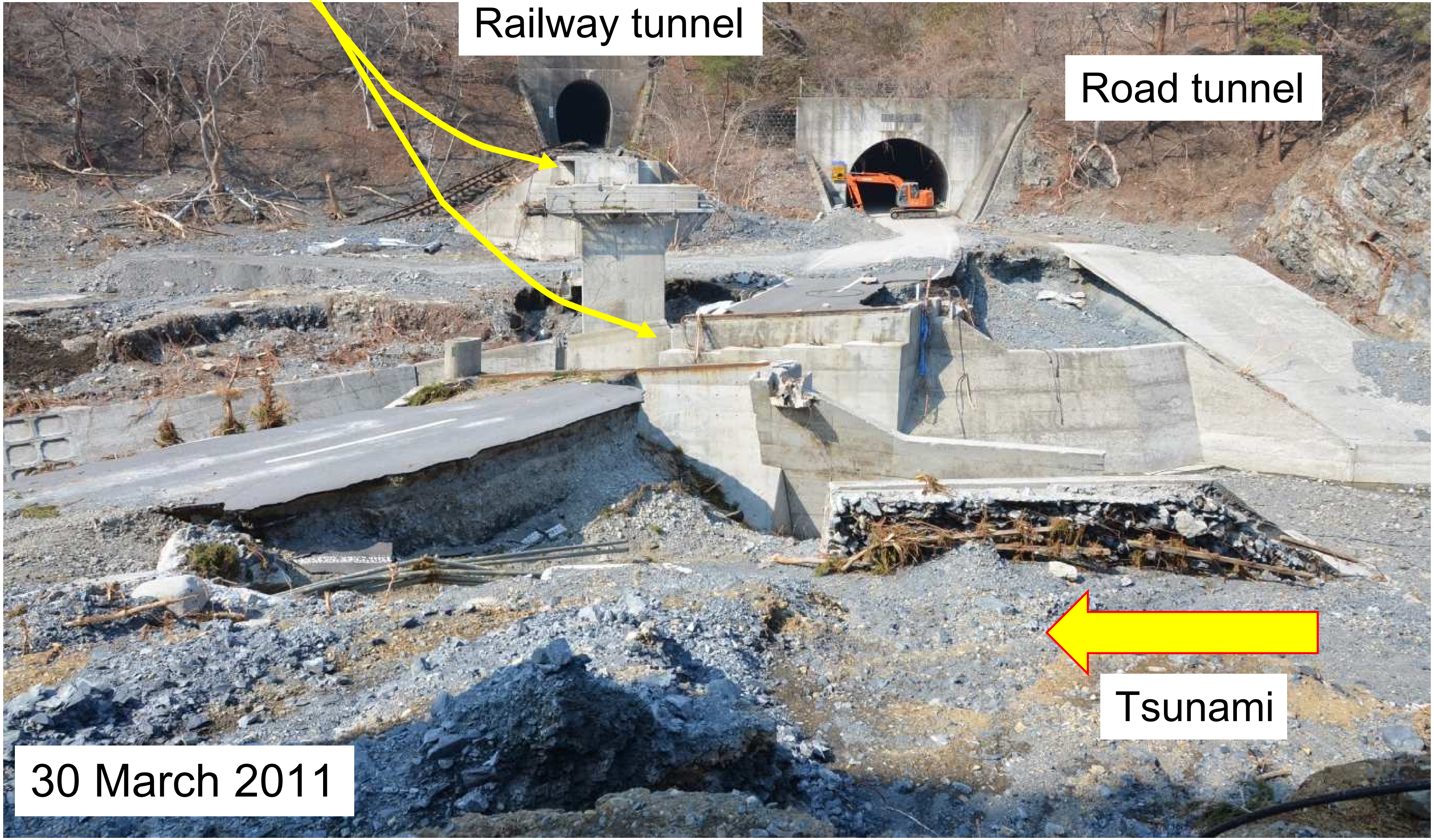
3 November 2013

GRS Integral Bridge at Koikorobe, Sanriku Railway

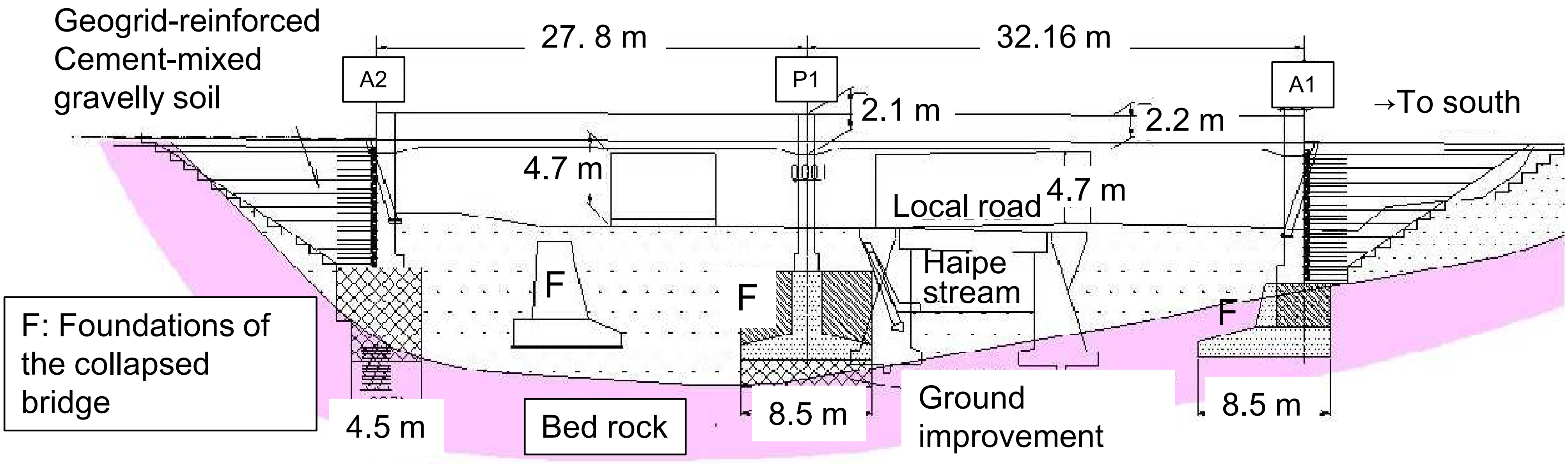


20 days after the E.Q. at Haipe, Sanriku Railway

Two simple girders had been washed away towards the inland by a great tsunami from Pacific Ocean (11 March 2011)



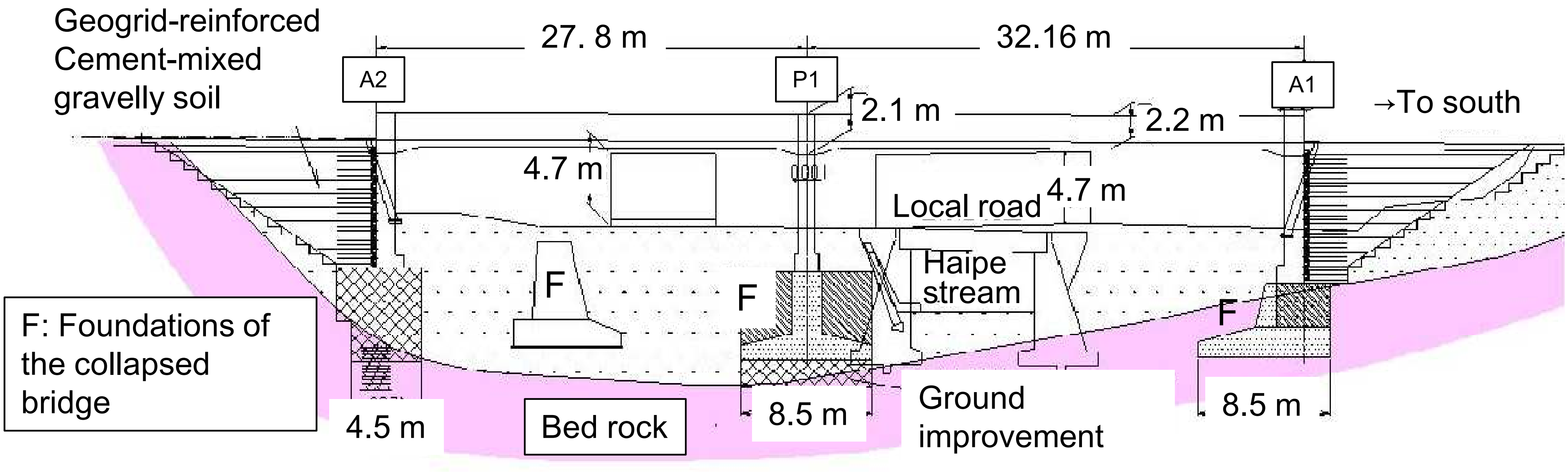
GRS Integral Bridge at Haipe, Sanriku Railway



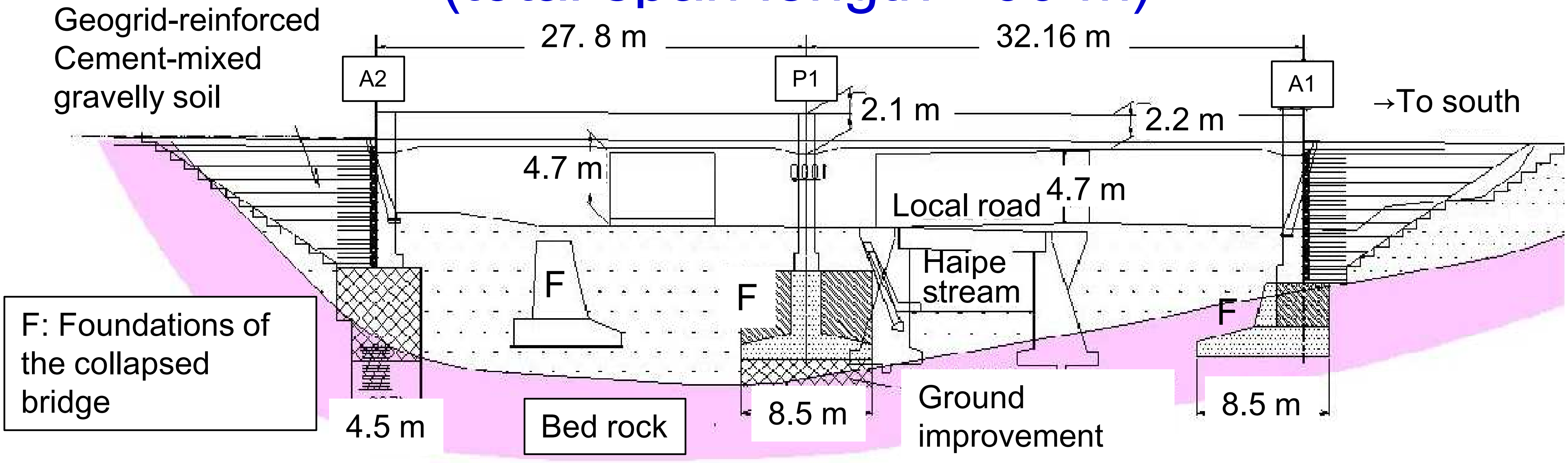
GRS Abutment
(before the
construction of FHR
facing)

22 May 2013

GRS Integral Bridge at Haipe, Sanriku Railway



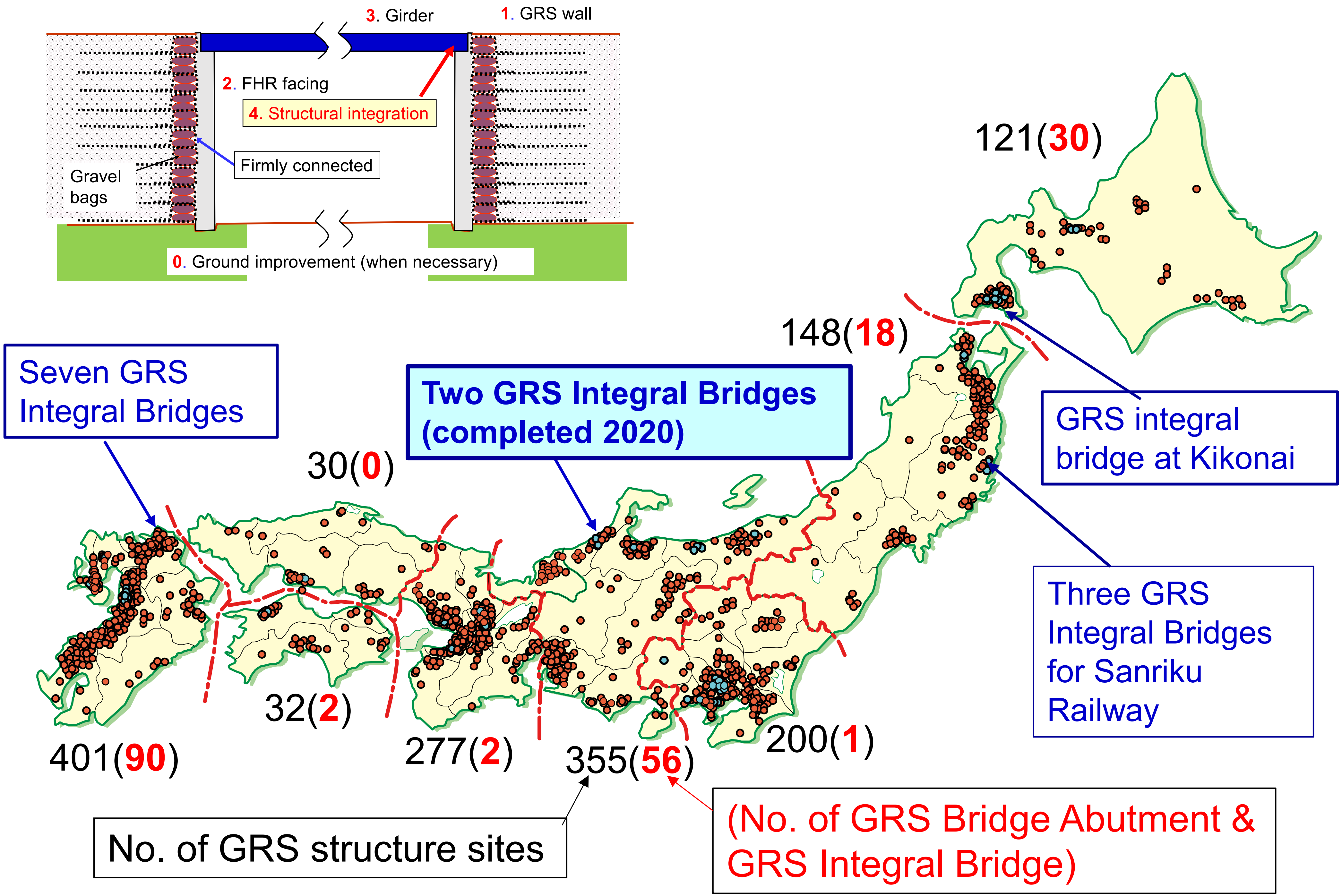
GRS Integral Bridge at Haipe, Sanriku Railway (total span length= 60 m)



- Slender girder & slender FHR facings, resulting from structural integration of the girder to the FHR facings connected to the reinforcement layersl
- No bump in the backfill right behind the facing

⇒ A large cost reduction in construction & maintenance

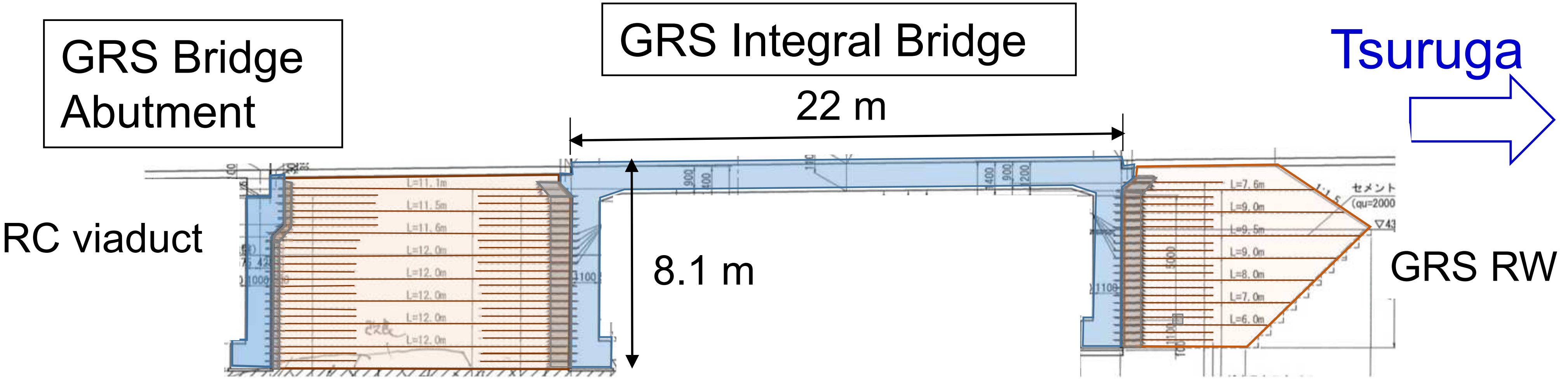
GRS Integral Bridges for railways

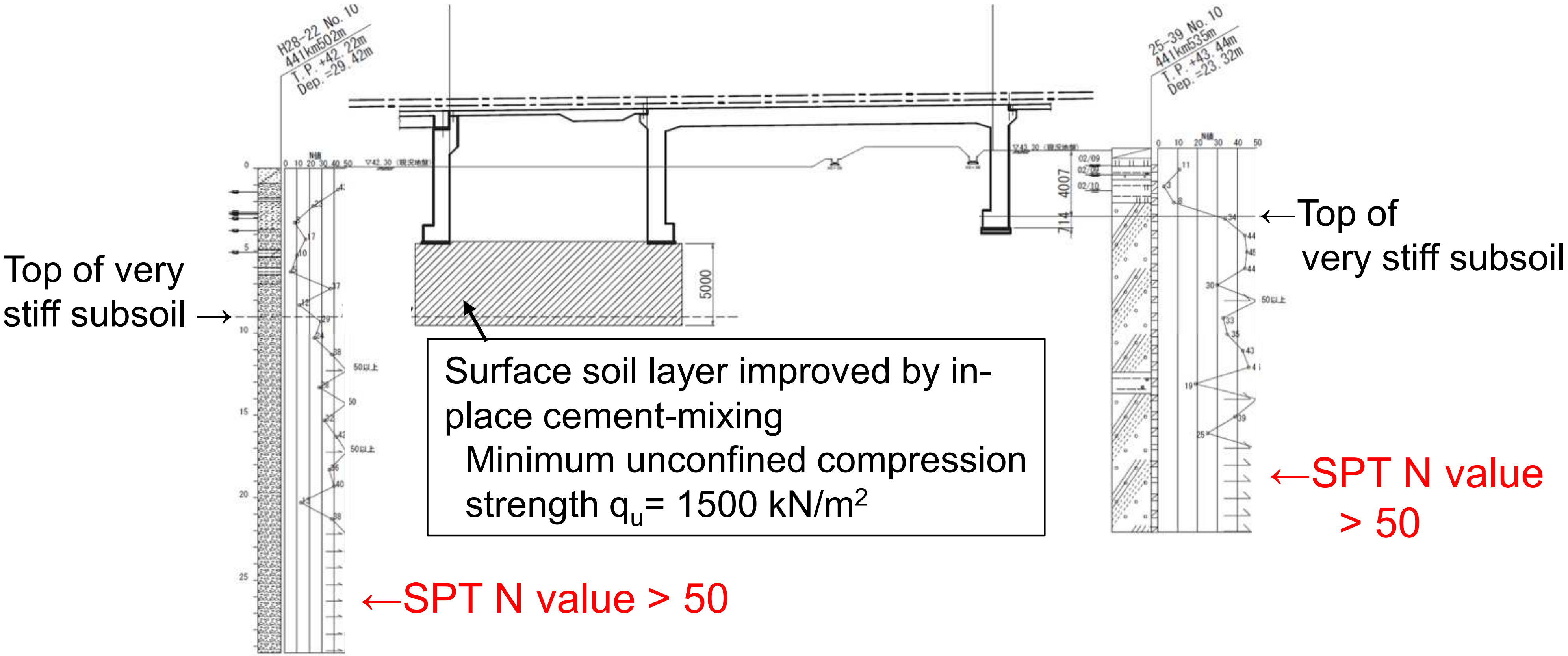


Consecutively constructed GRS Bridge Abutment & GRS Integral Bridge, Echizen Hirabayshi, Hokuriku Shinkansen, 2020

(by the courtesy of JRTT)

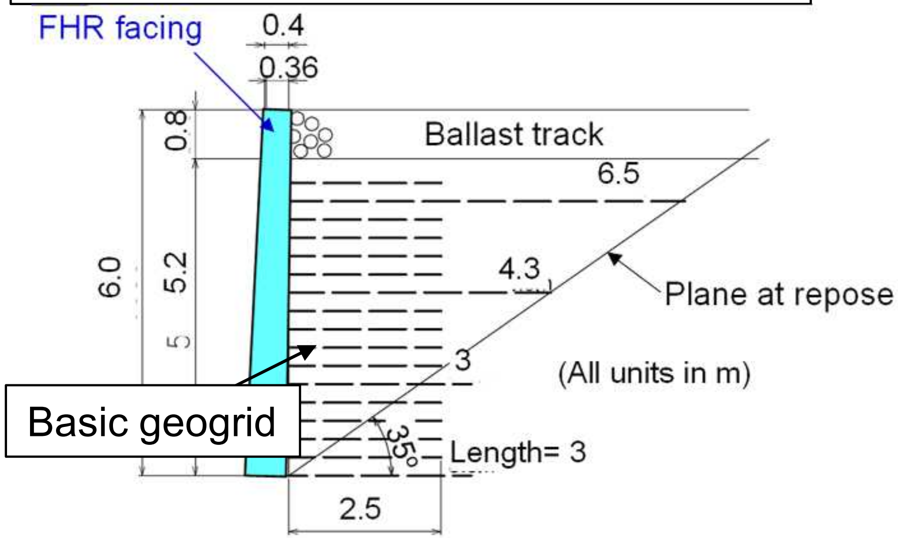
Hokuriku Shinkansen (by the courtesy of JRTT)





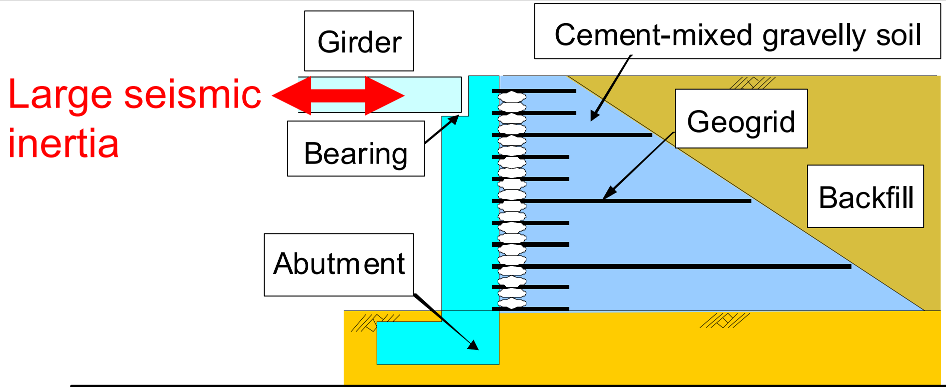
Different patterns of geogrid arrangement

GRS RW: longer geogrid at top



1) Short basic geogrid layers to minimize the slope excavation when constructed on an existing slope.
2) Several long geogrid layers at upper levels for high wall stability; and for high stability of surface soil layers subjected to intense traffic loads.
3) Limited effects of “a sudden change in the stiffness & settlement due to a sudden change in the geogrid density in the direction normal to wall face” on the smooth running of train/vehicle in the direction in parallel to wall face

GRS Bridge Abutment: longer geogrid at bottom

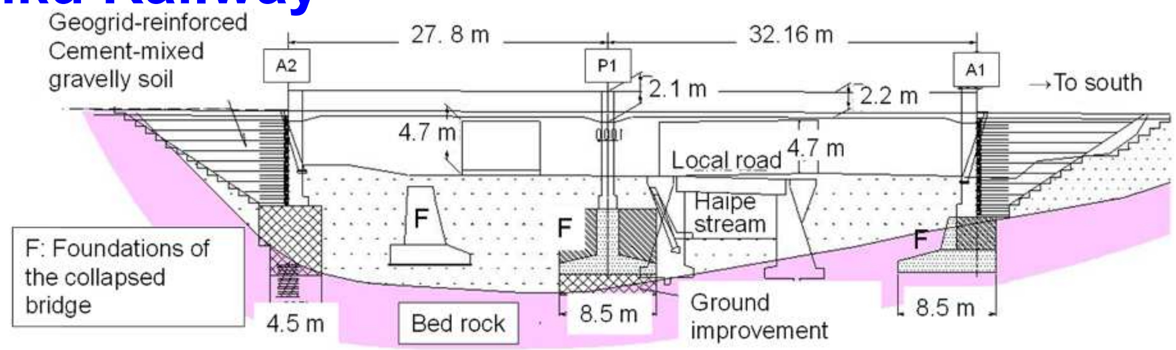


1) For a lower gravity center of the reinforced backfill zone for high stability against overturning moment about the facing base by large seismic inertia load of the girder.
2) To avoid cracking in the brittle cement-mixed backfill taking place if constructed overlying deformable unreinforced backfill.
3) To avoid a sudden change in the stiffness & settlement in the backfill in the direction normal to the wall face for smooth train/vehicle running (particularly when continuous RC slab track is used), it is necessary to smoothly increase the thickness of unreinforced backfill from zero in the direction normal to the wall face

Reinforced soil zone for GRS Bridge Abutment & Integral Bridge:
- the shape is adjusted based on each site conditions

GRS Integral Bridge, Haipe, Sanriku Railway

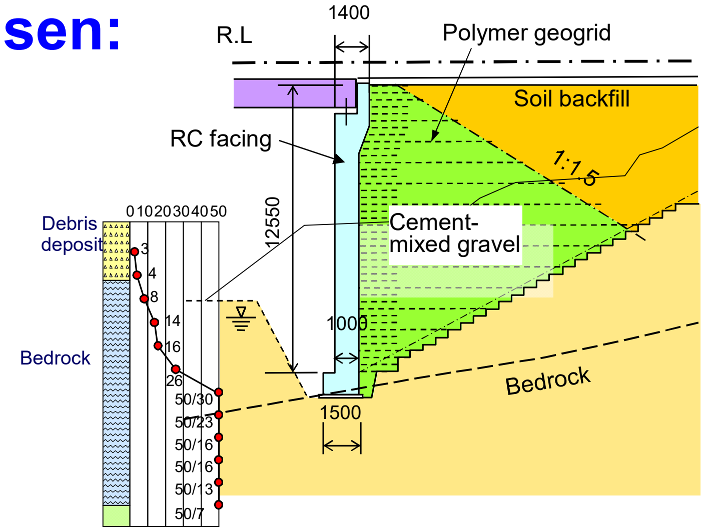
Constructed on steep slopes of rock or very stiff soil. Nearly the whole of the approach fill was cement-mixed geogrid-reinforced gravelly soil in the reversed trapezoidal shape.



GRS Bridge Abutment, Takada, Kyushu Shinkansen:

Constructed on a gentle rock slope.

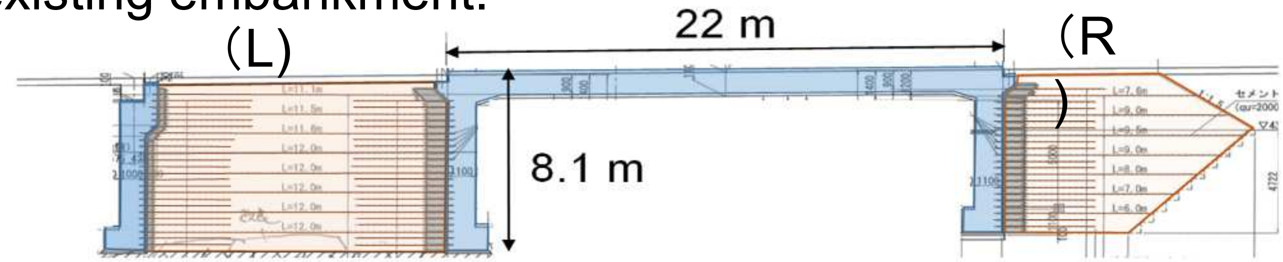
⇒ The bottom of the trapezoidal cement-mixed geogrid-reinforced backfill zone is truncated.



GRS Integral Bridge & GRS Bridge Abutment, Echizen Hirabayashi, Hokuriku Shinkansen:

(R) Cement-mixed geogrid-reinforced backfill zone was made wider while the bottom is truncated to restrict the size of excavation in an existing embankment.

(L) Two reinforced zones for GRS Integral Bridge and GRS Abutment are unified to a single reinforced zone.

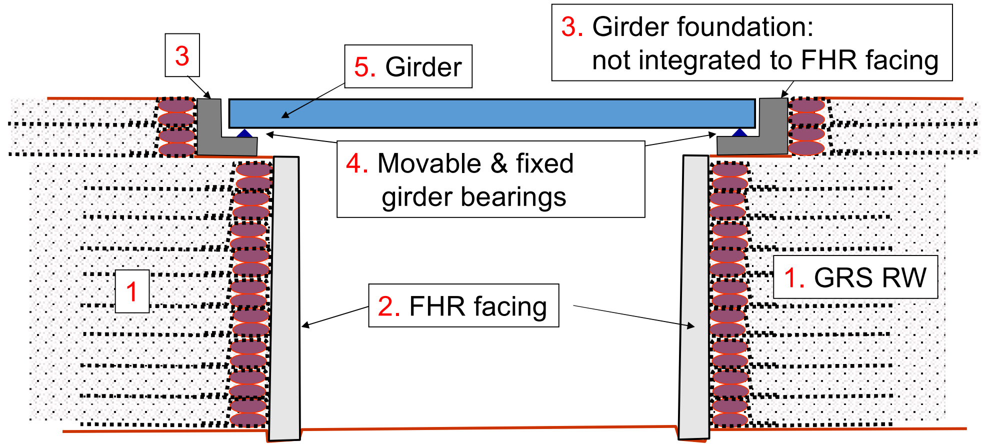


In any case, a high stability of the structure is ensured by stability analysis.

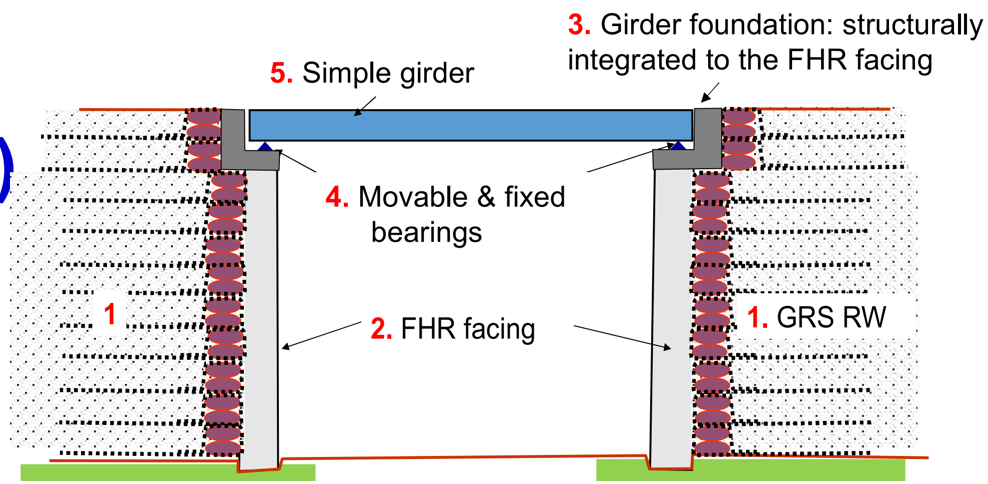
Summary – 1/2:

GRS Bridge Abutment (1nd generation) typically supports both ends of a simple girder with bearings (fixed or movable) arranged at <u>the girder foundations that are not structurally integrated to the FHR facing</u> of GRS RW.

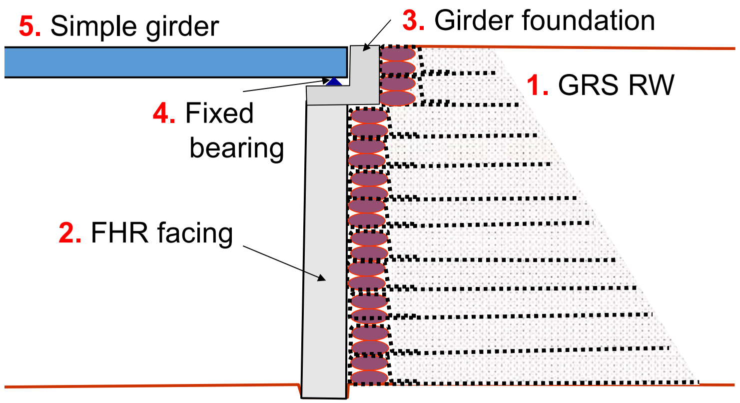
As a result, the girder becomes longer by a setback of the girder foundation. Besides, as the girder becomes long & heavy, the girder foundation may become unstable by seismic inertia loads of the girder, while the settlement of the girder foundation may become too large.



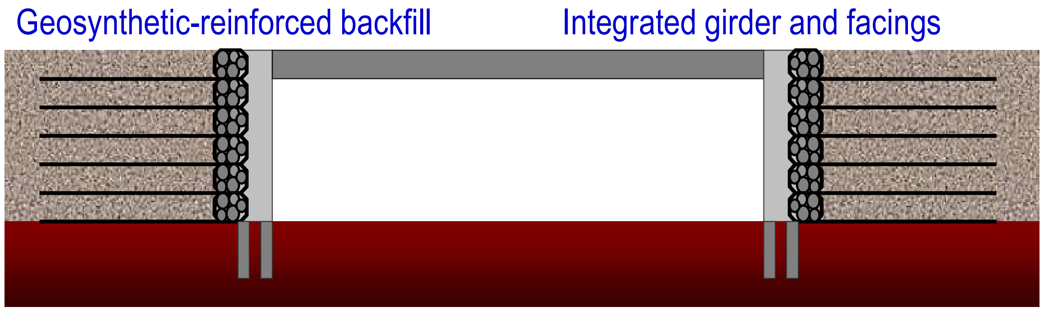
To alleviate these problems, **GRS Bridge Abutment (2nd generation)** was developed which <u>structurally integrates the girder foundations to the top of the FHR facing</u>.



Summary – 2/2:



GRS Bridge Abutment (2nd generation) is often used to support one end of a simple girder with a fixed bearing arranged at the girder foundation that is structurally integrated to the top of FHR facing.



GRS Integral Bridge structurally integrates both ends of a continuous girder to the top of FHR facings of a pair of GRS RWs, without using bearings.

Compared with the conventional simple girder bridges, both are much more cost-effective exhibiting no bump right behind the facing while much higher stability against severe seismic loads, strong floods, tsunamis, etc. during a long period of service.

They are now among the standard bridge structures for railways including High Speed Railways (Shinkansen).

Contents

1. Recent GRS structures for High-Speed Railways in Japan

2. Inextensible vs. extensible reinforcement and
 flexible vs. stiff facing- theoretical & technical background

3. Multiple functions of full-height rigid (FHR) facing

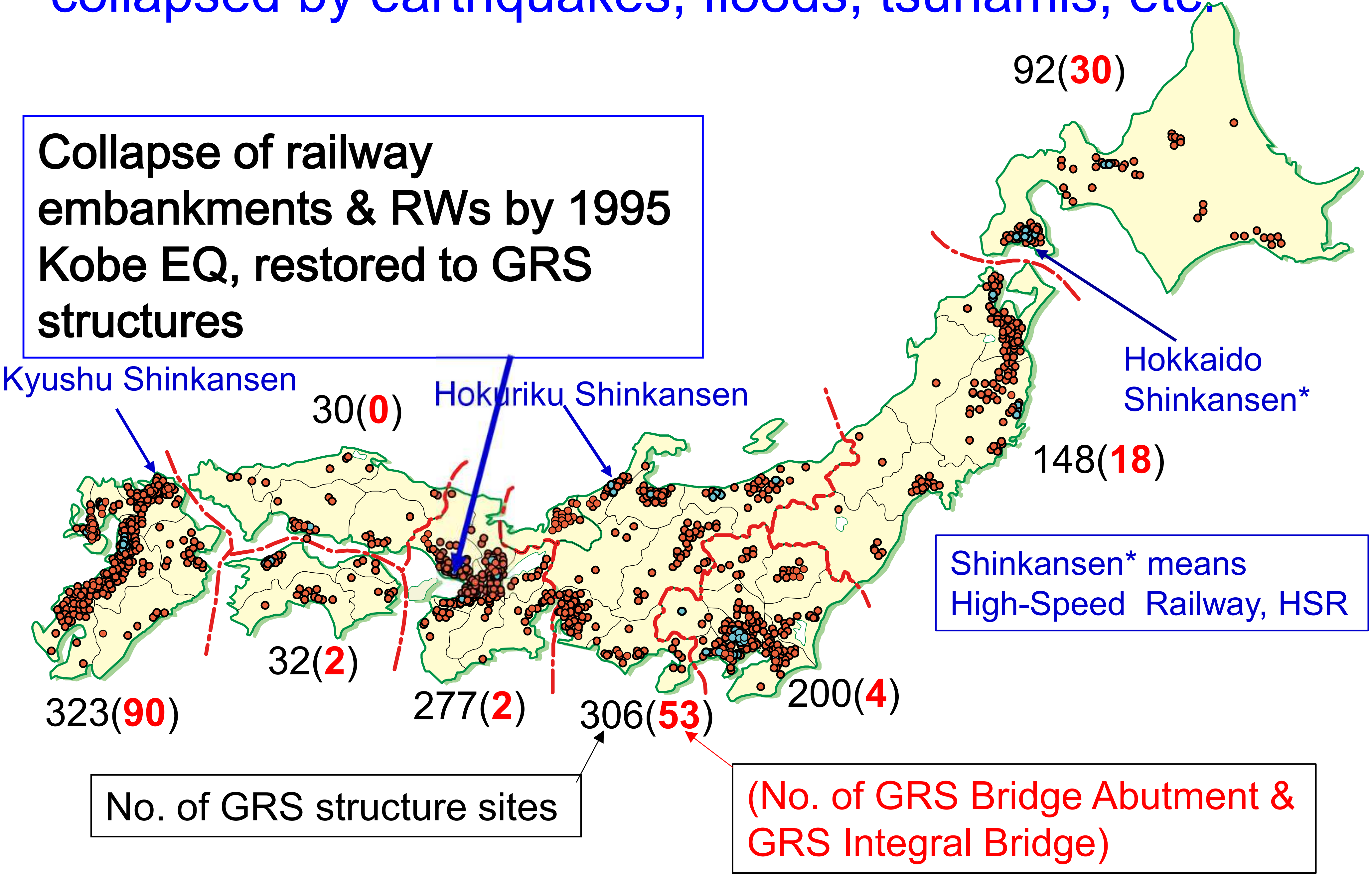
4. Advantages of the construction of FHR facing after the
 construction of reinforced backfill

5. GRS Bridge Abutment and GRS Integral Bridge

6. Restoration of soil structures that collapsed by earthquakes,
 floods and tsunamis to GRS structures

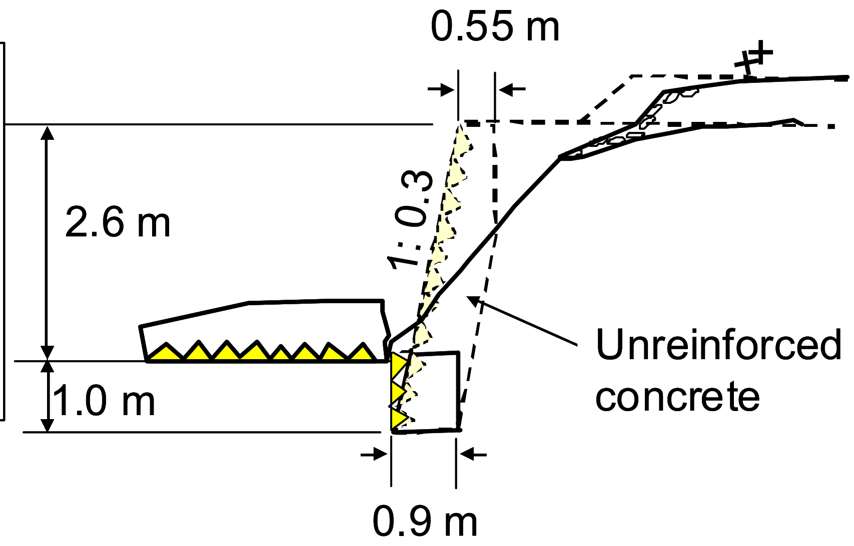
7. Concluding remarks

A number of GRS structures were constructed to restore conventional type soil structures that collapsed by earthquakes, floods, tsunamis, etc.



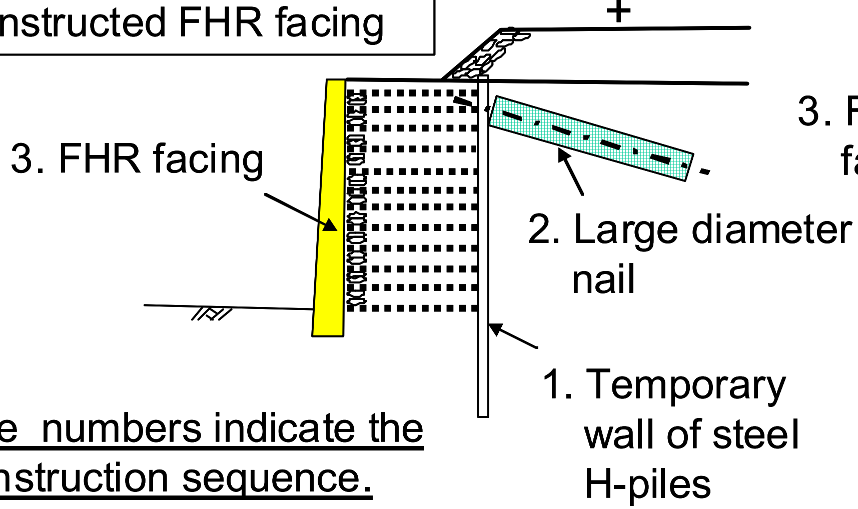
Collapse of gravity RWs by the 1995 Kobe EQ and restoration to GRS RWs & nailed RWs

The EQ took place 5:47 AM
→ no people was walking in front of the wall.



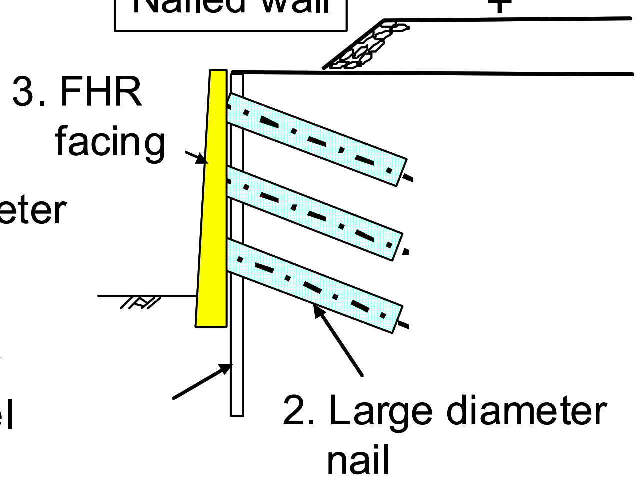
Restoration

GRS RW with a staged-constructed FHR facing

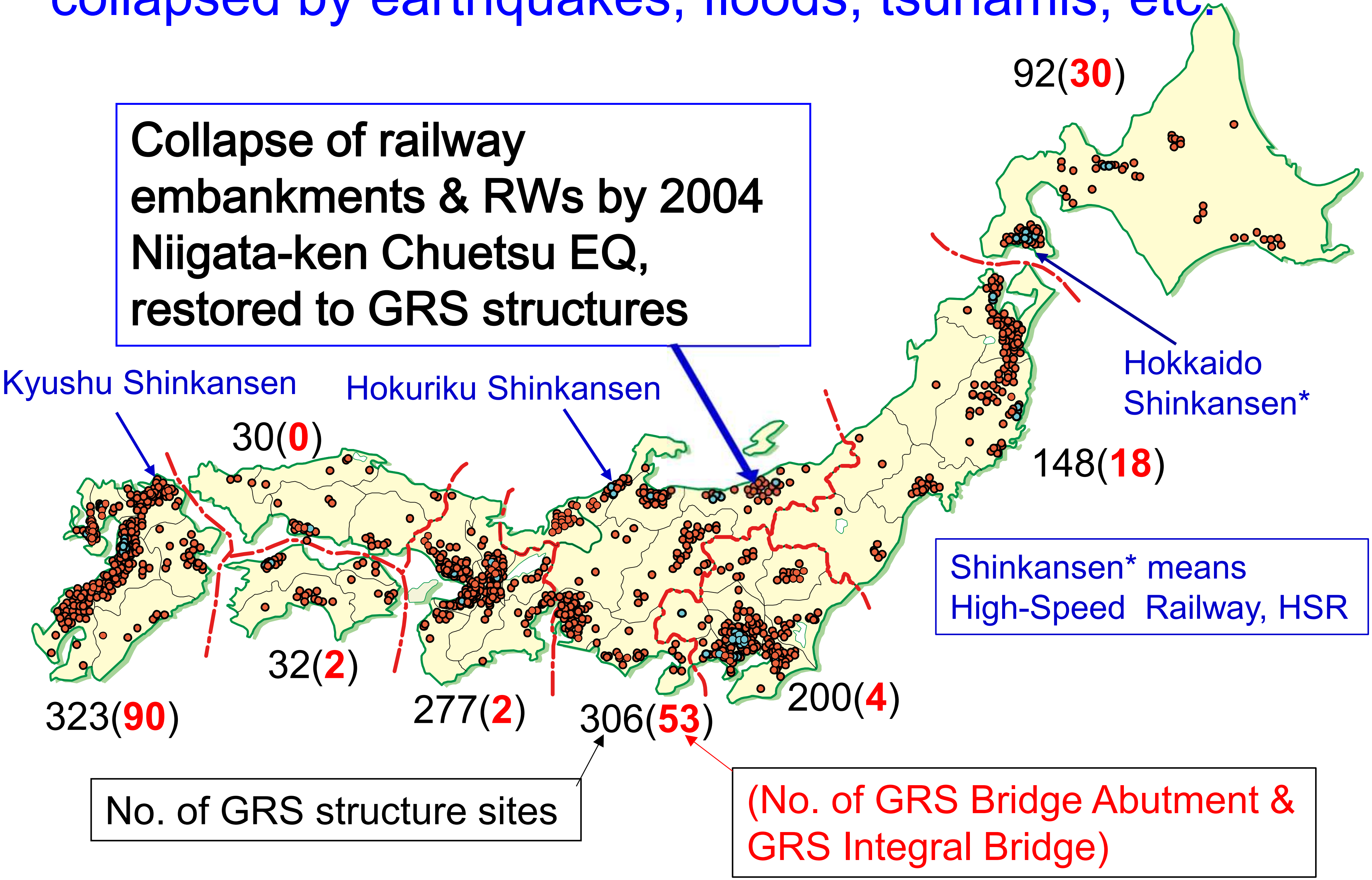


The numbers indicate the construction sequence.

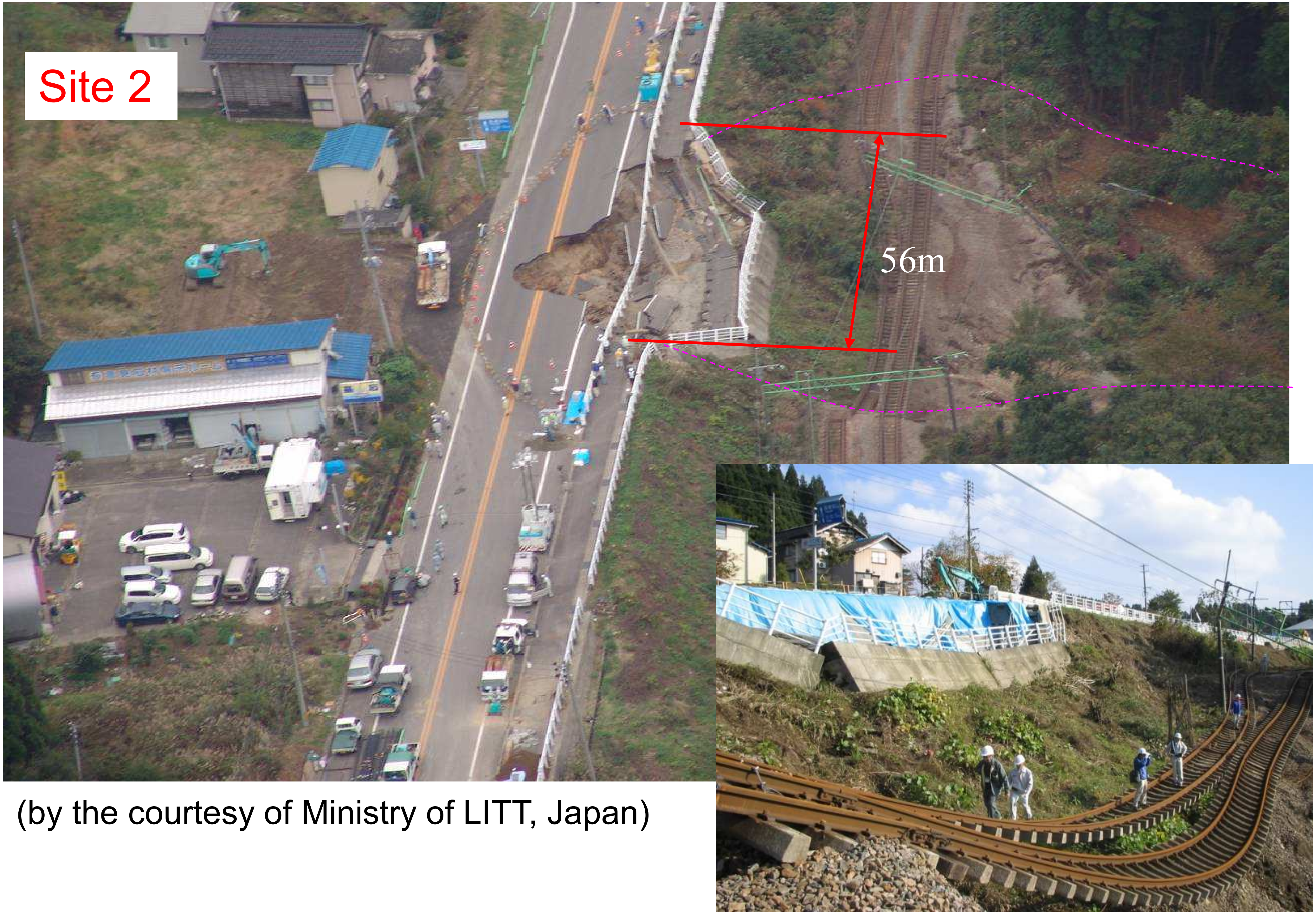
Nailed wall



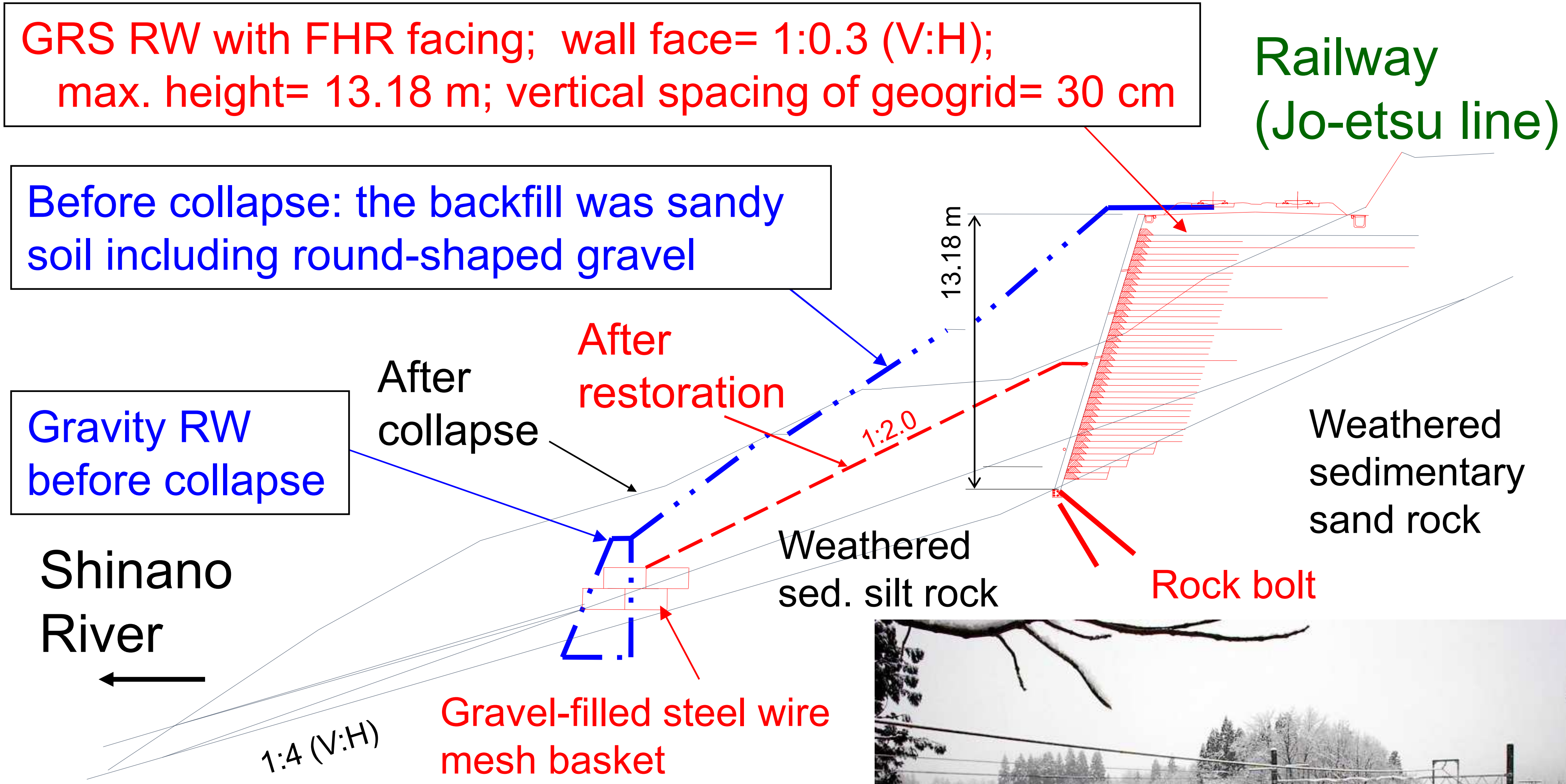
A number of GRS structures were constructed to restore conventional type soil structures that collapsed by earthquakes, floods, tsunamis, etc.



2004 Niigata-ken Chuetsu EQ, October 2004



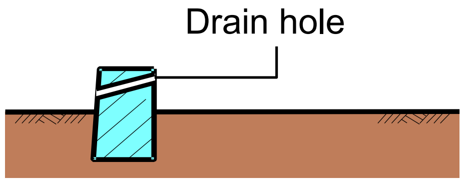
(by the courtesy of Ministry of LITT, Japan)



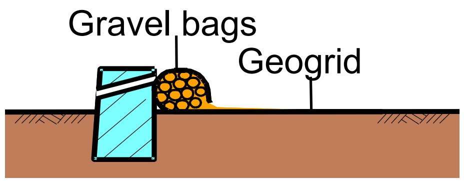
Site 2

First train

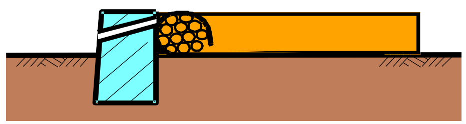
Staged construction of FHR facing



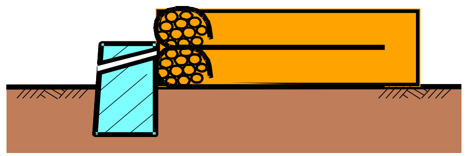
1) Levelling pad for facing



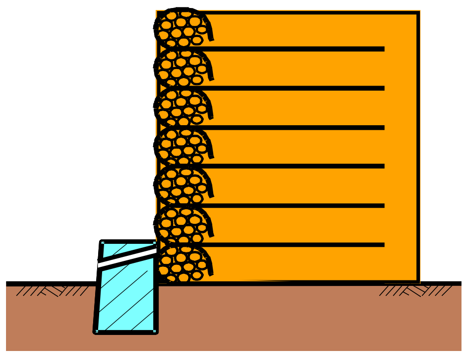
2) Placing geogrid reinforcement & gravel bags



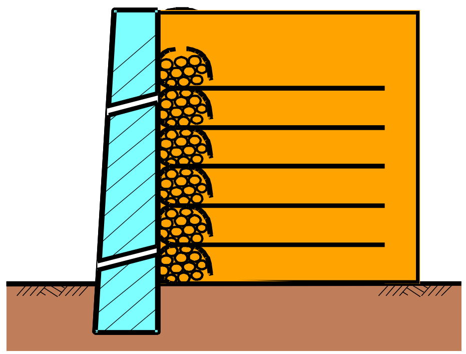
3) Backfilling & compaction



4) Second layer

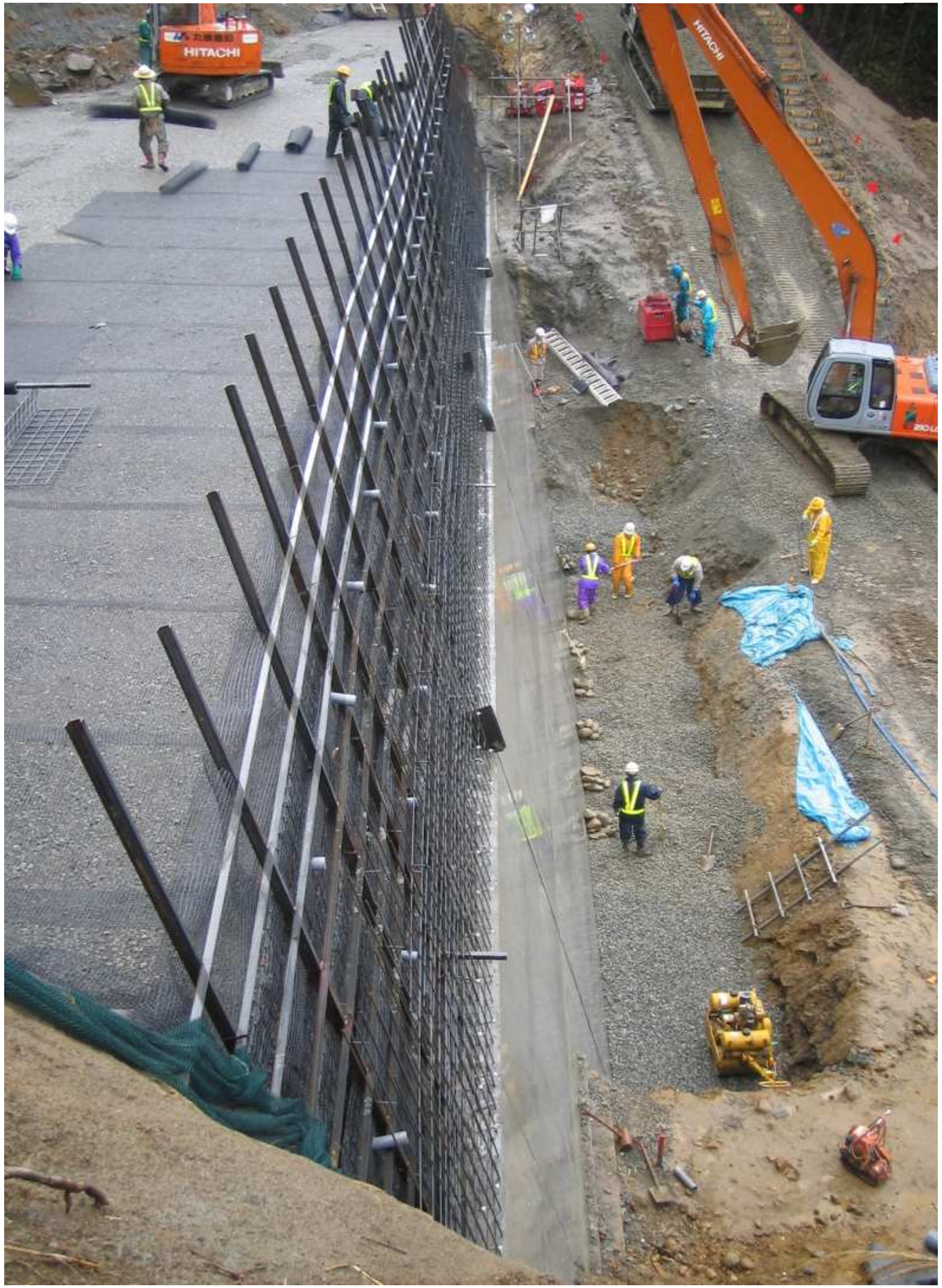


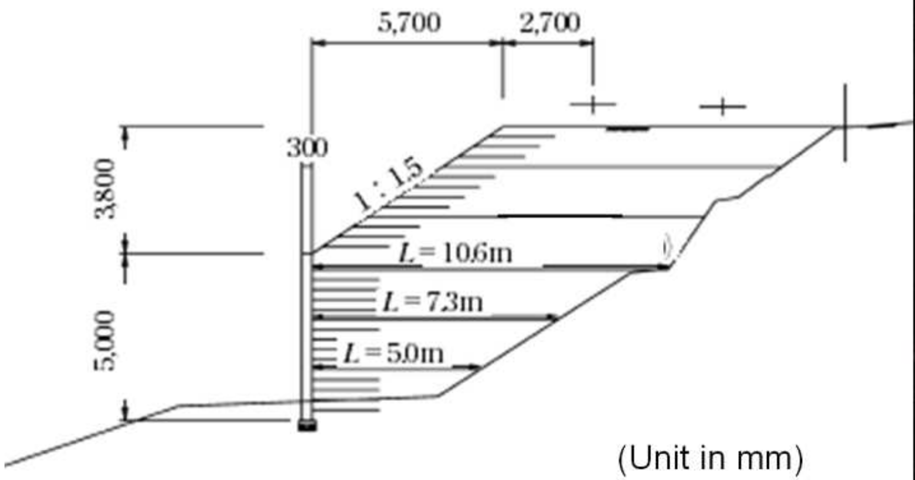
5) Completion of wrapped-around wall



6) Casting-in-place RC facing

Max. wall height = 13.18 m



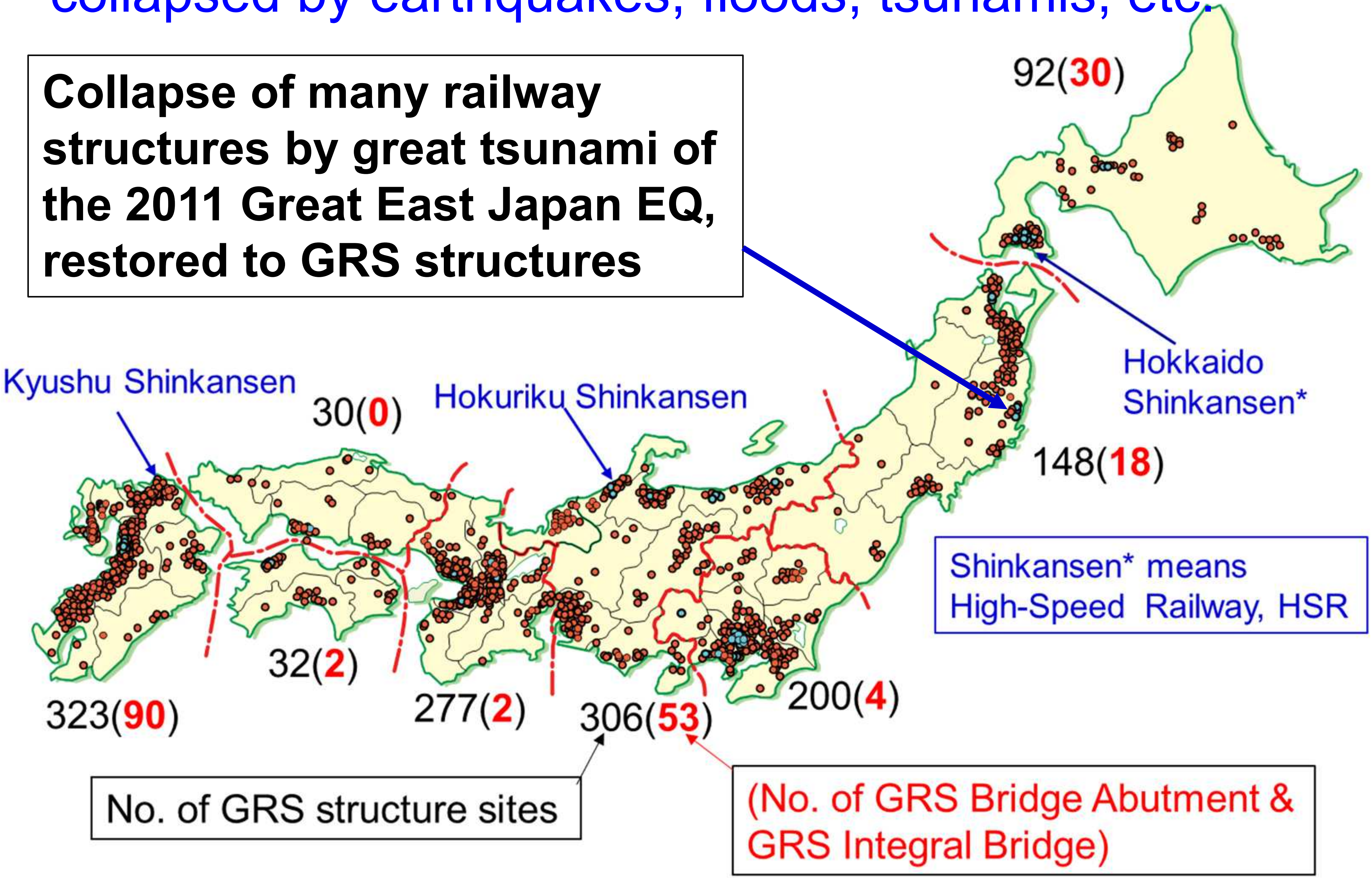


5,700
2,700
300
1 : 1.5
3,800
5,000
L = 10.6m
L = 7.3m
L = 5.0m
(Unit in mm)

2004/12/14

Site 3

A number of GRS structures were constructed to restore conventional type soil structures that collapsed by earthquakes, floods, tsunamis, etc.



Shima-no-koshi Station, Sanriku Railway

Before the 2011 Great East Japan Earthquake

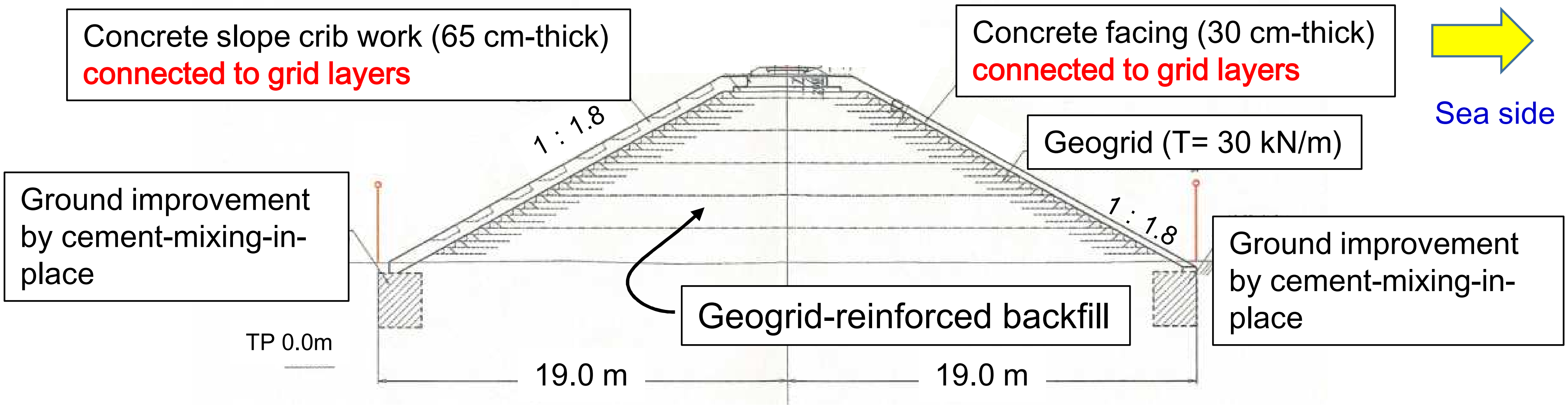
The tsunami was 8 – 9 m higher than the railway track at 14 m above the sea level

Tsunami

Collapse of RC viaduct by tsunami

Immediately after the 2011 E.Q.

Railway embankment, also as a tsunami-barrier

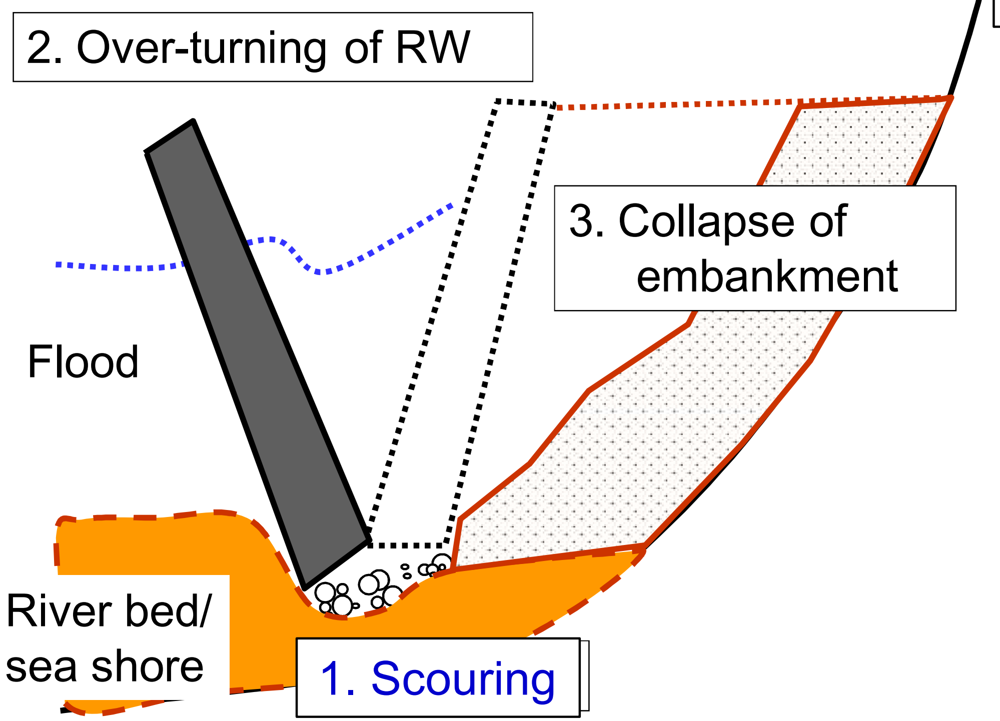


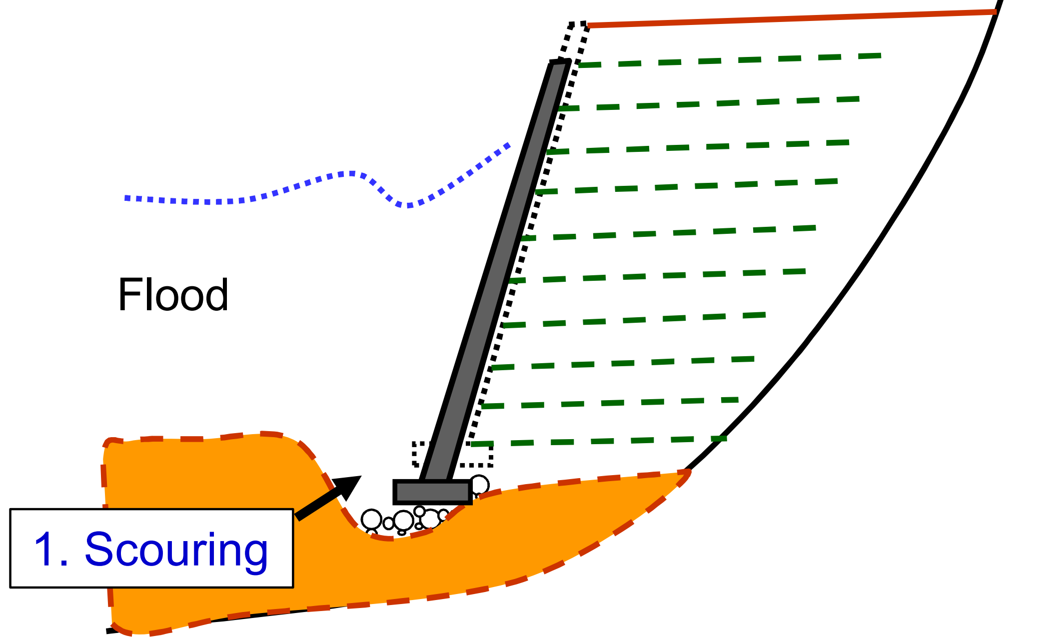
Conventional type cantilever RW

Often, over-turning failure by scouring below the wall, quickly followed by the global collapse of embankment, resulting in the close of road & railway

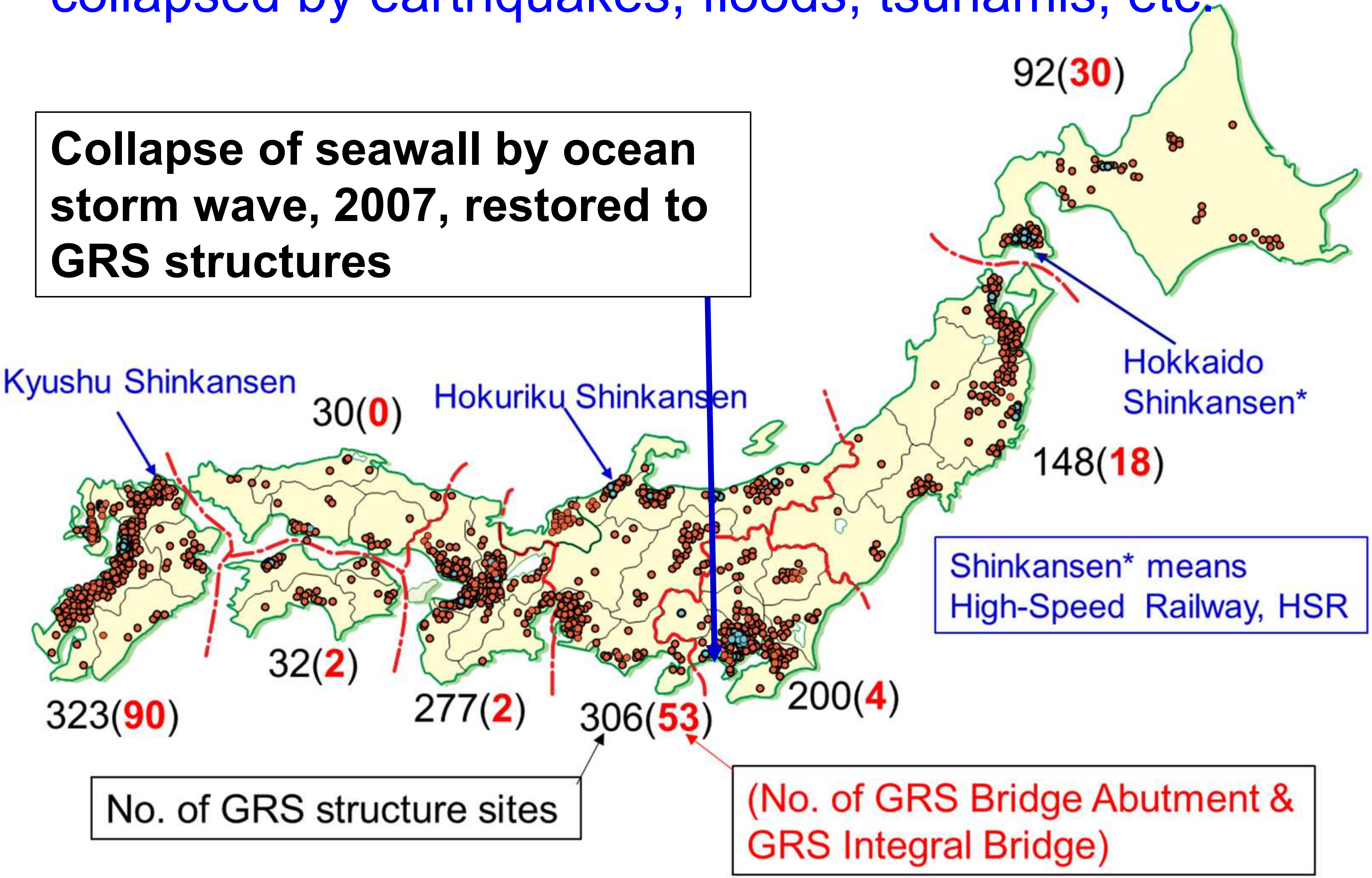
GRS-RW with FHR facing

Much better performance: i.e.,
1) over-turning failure of FHR facing by scouring is difficult to take place;
2) so, the embankment can survive allowing emergency use of road & railway.



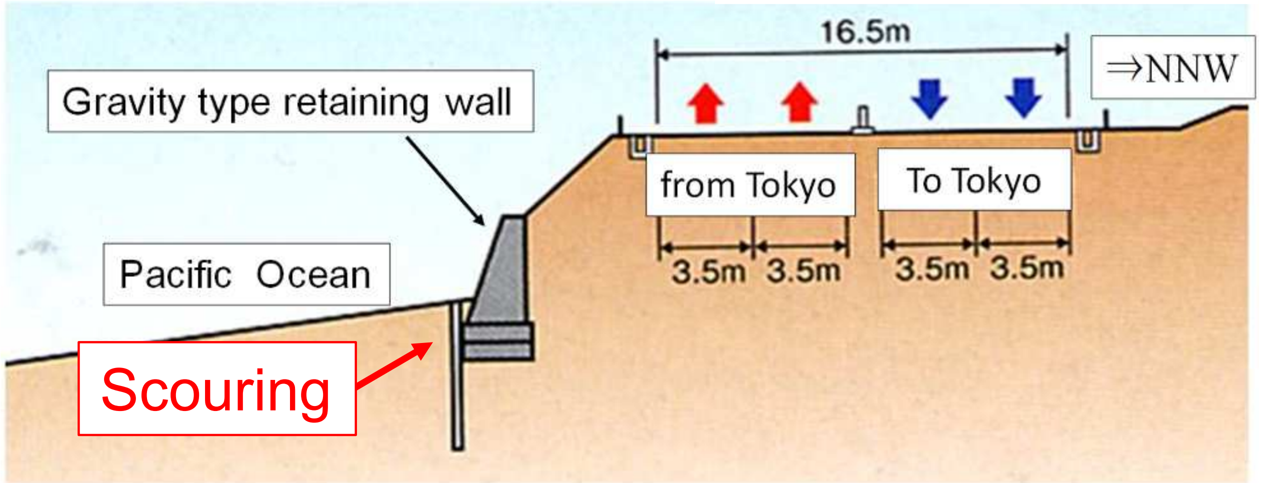


A number of GRS structures were constructed to restore conventional type soil structures that collapsed by earthquakes, floods, tsunamis, etc.

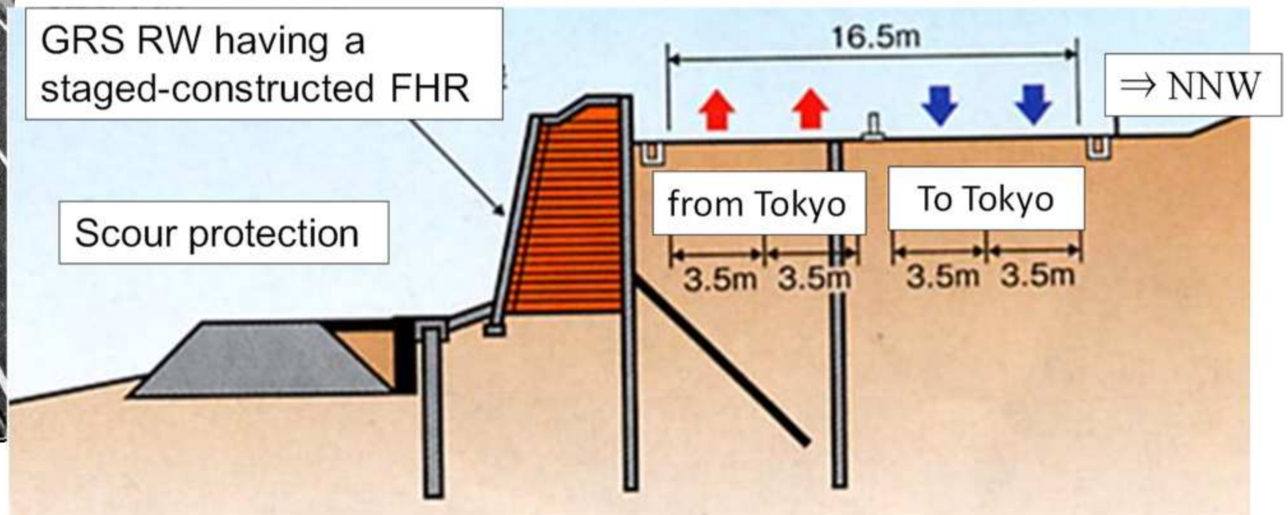


Collapse of gravity-type seawall for a length of 1.5 km by ocean waves during a storm (Typhoon No. 9), 8 Sept. 2007 National Road No. 1, southwest of Tokyo

Before collapse:

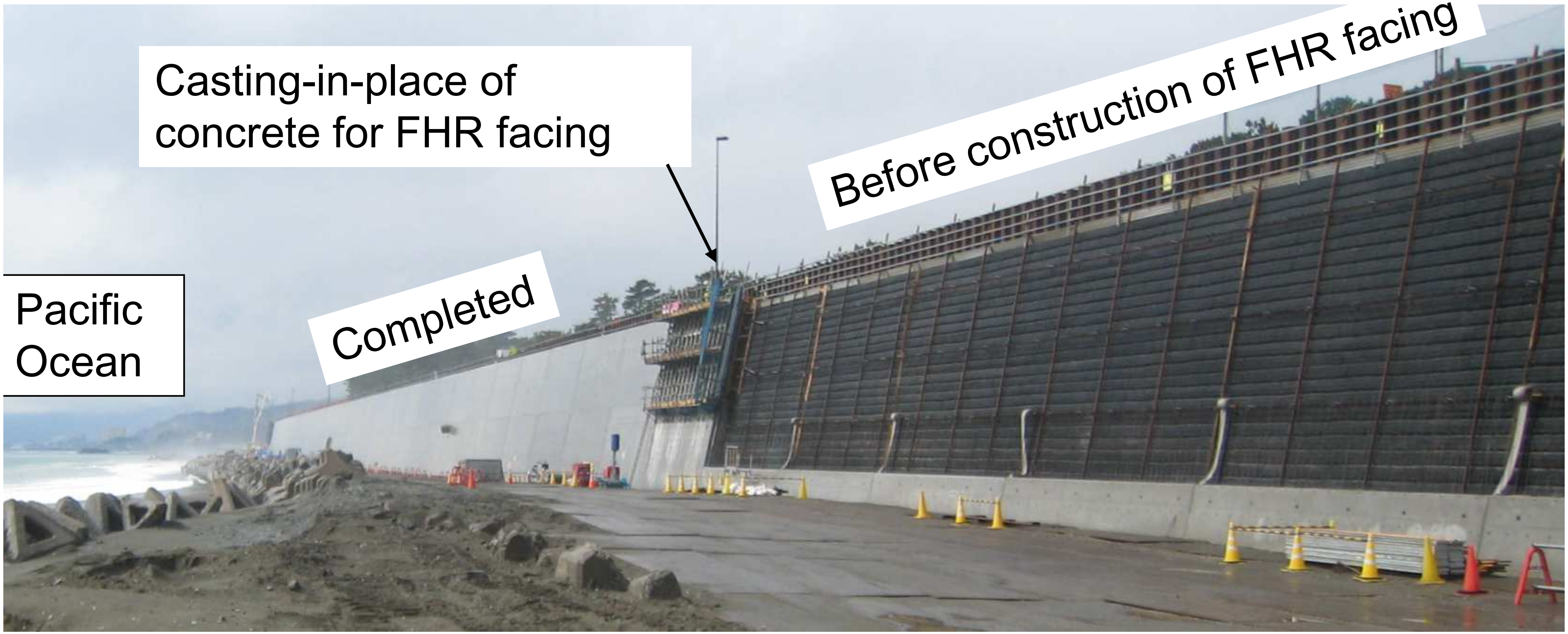


After restoration:



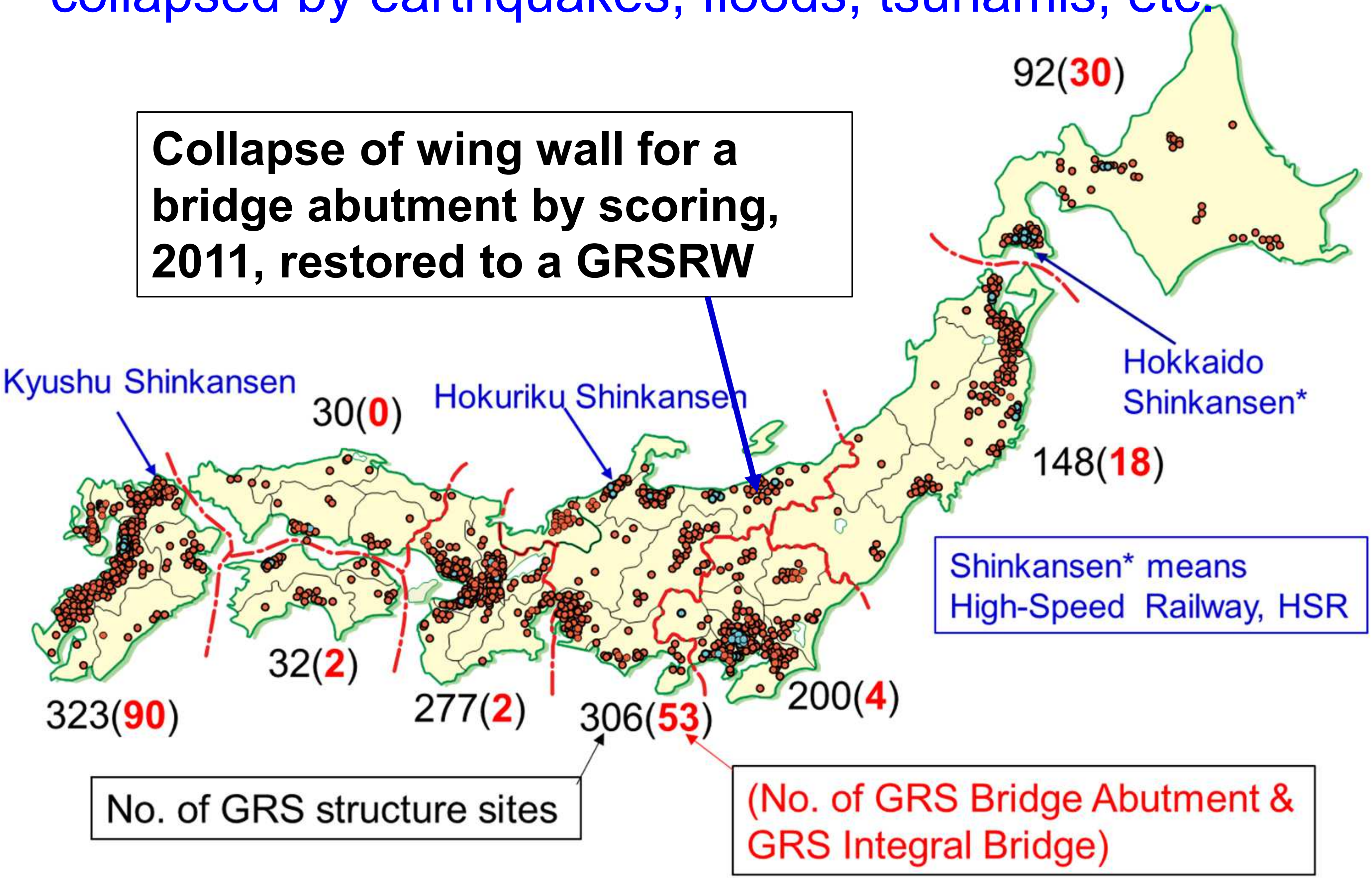
(by the courtesy of Ministry of LITT, Japan)

Restoration to GRS RW with FHR facing

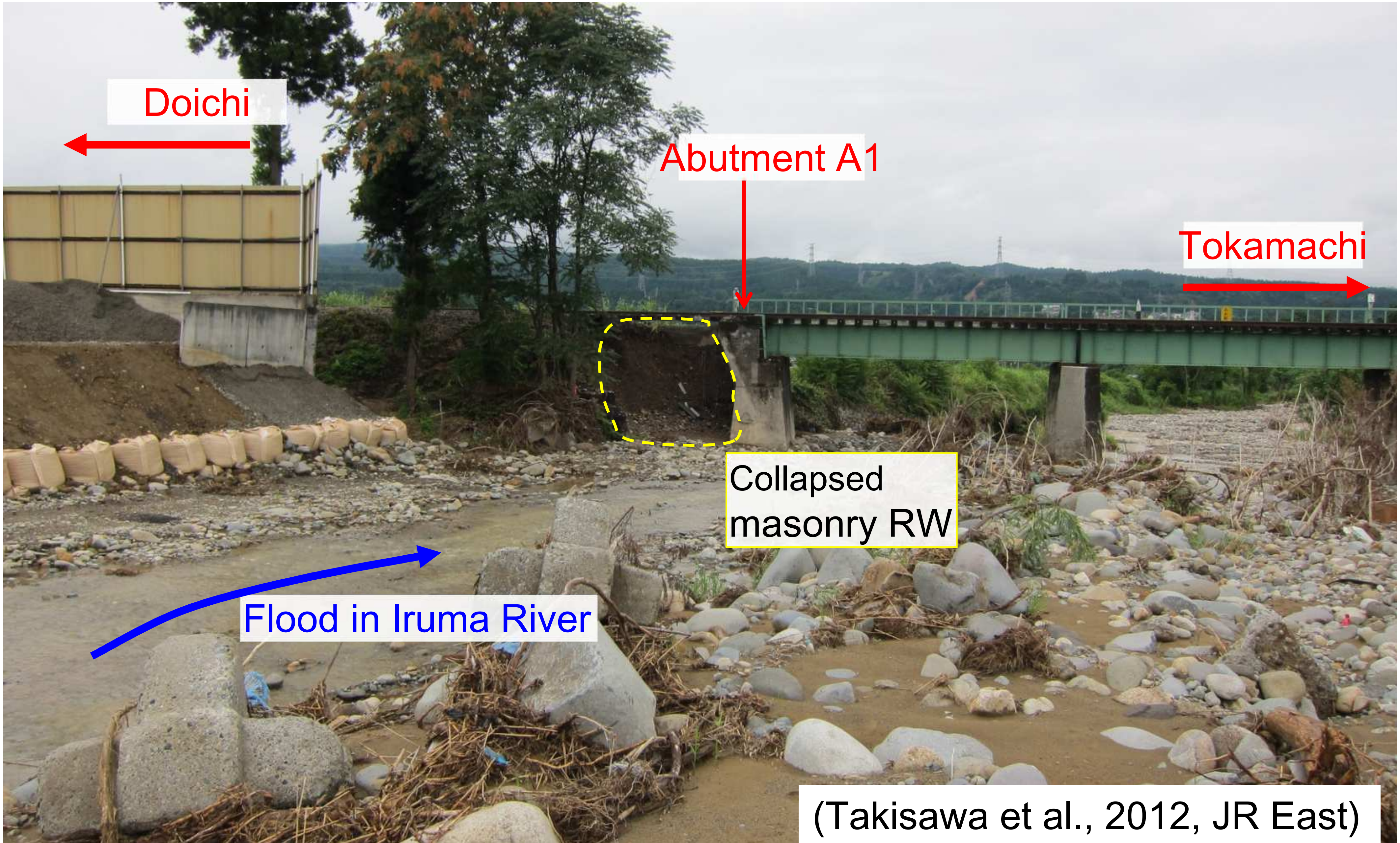


10 March 2010

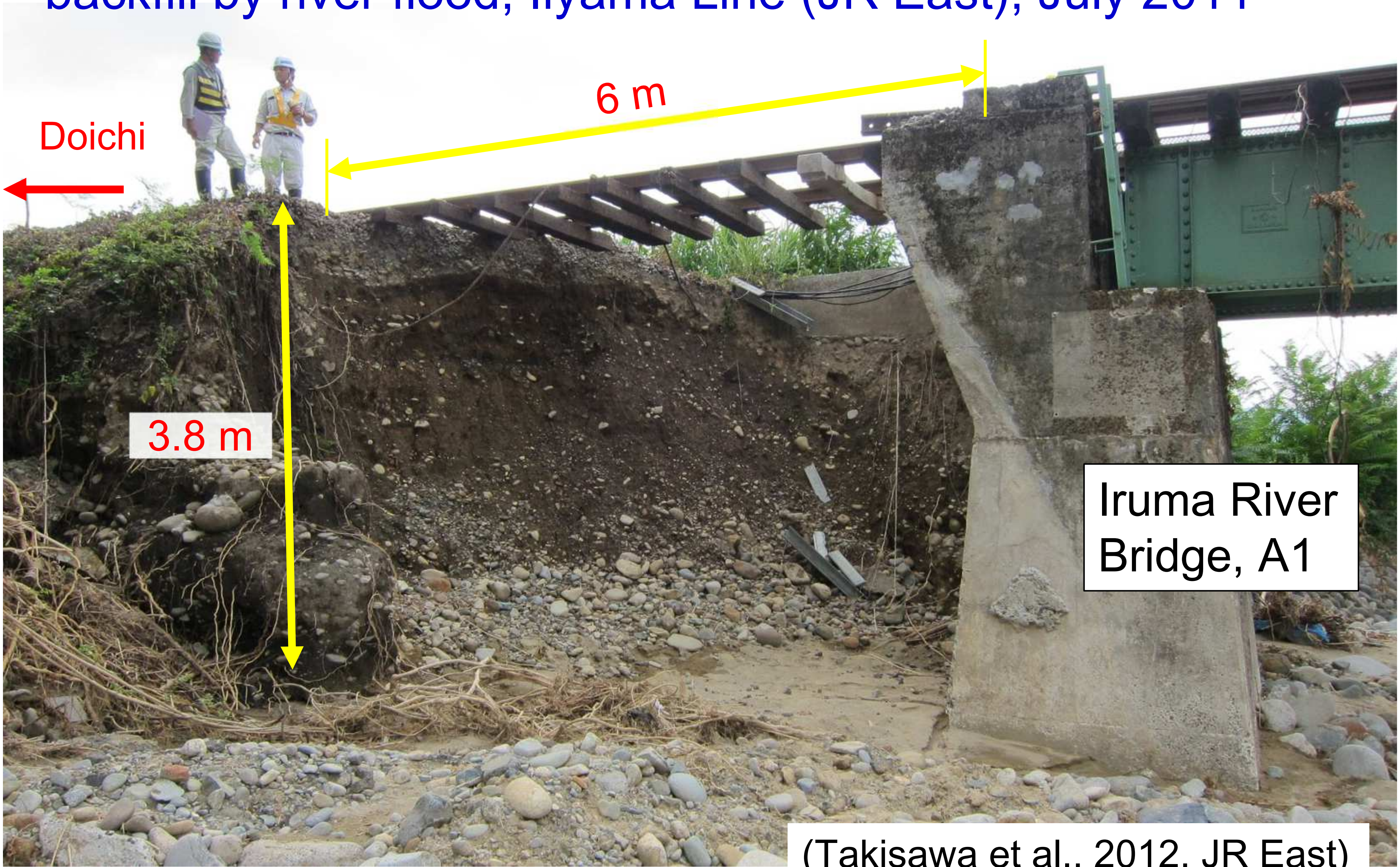
A number of GRS structures were constructed to restore conventional type soil structures that collapsed by earthquakes, floods, tsunamis, etc.



Collapse of a masonry wing RW for a RC bridge abutment by scouring in the subsoil and associated erosion of the backfill by river flood, Iiyama Line (JR East), July 2011



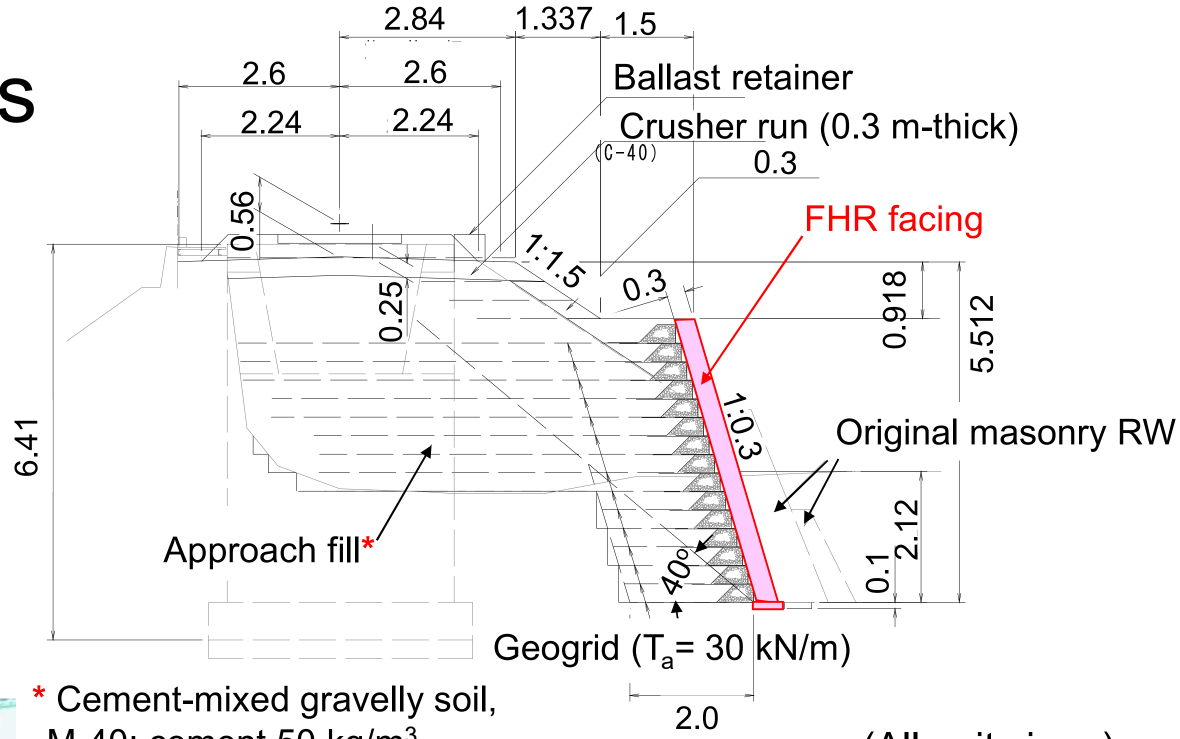
Collapse of a masonry wing RW for a RC bridge abutment by scouring in the subsoil and associated erosion of the backfill by river flood, Iiyama Line (JR East), July 2011



(Takisawa et al., 2012, JR East)

Restoration to GRS RWs

Only 10 days to re-open the service: much shorter than the period required to construct a conventional cantilever RC RW.



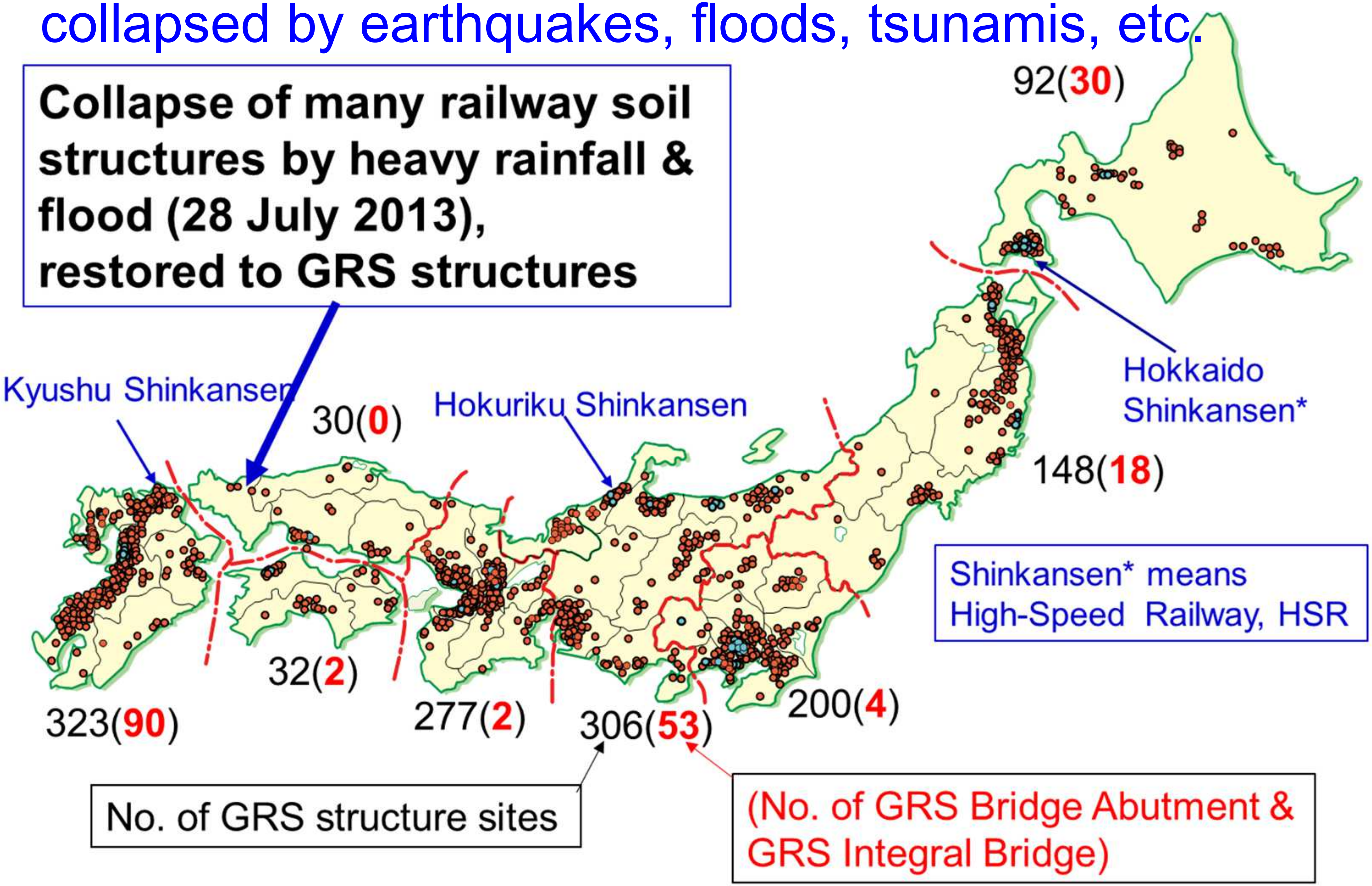
* Cement-mixed gravelly soil, M-40; cement 50 kg/m^3

(All units in m)

(Takisawa et al., 2012, JR East)

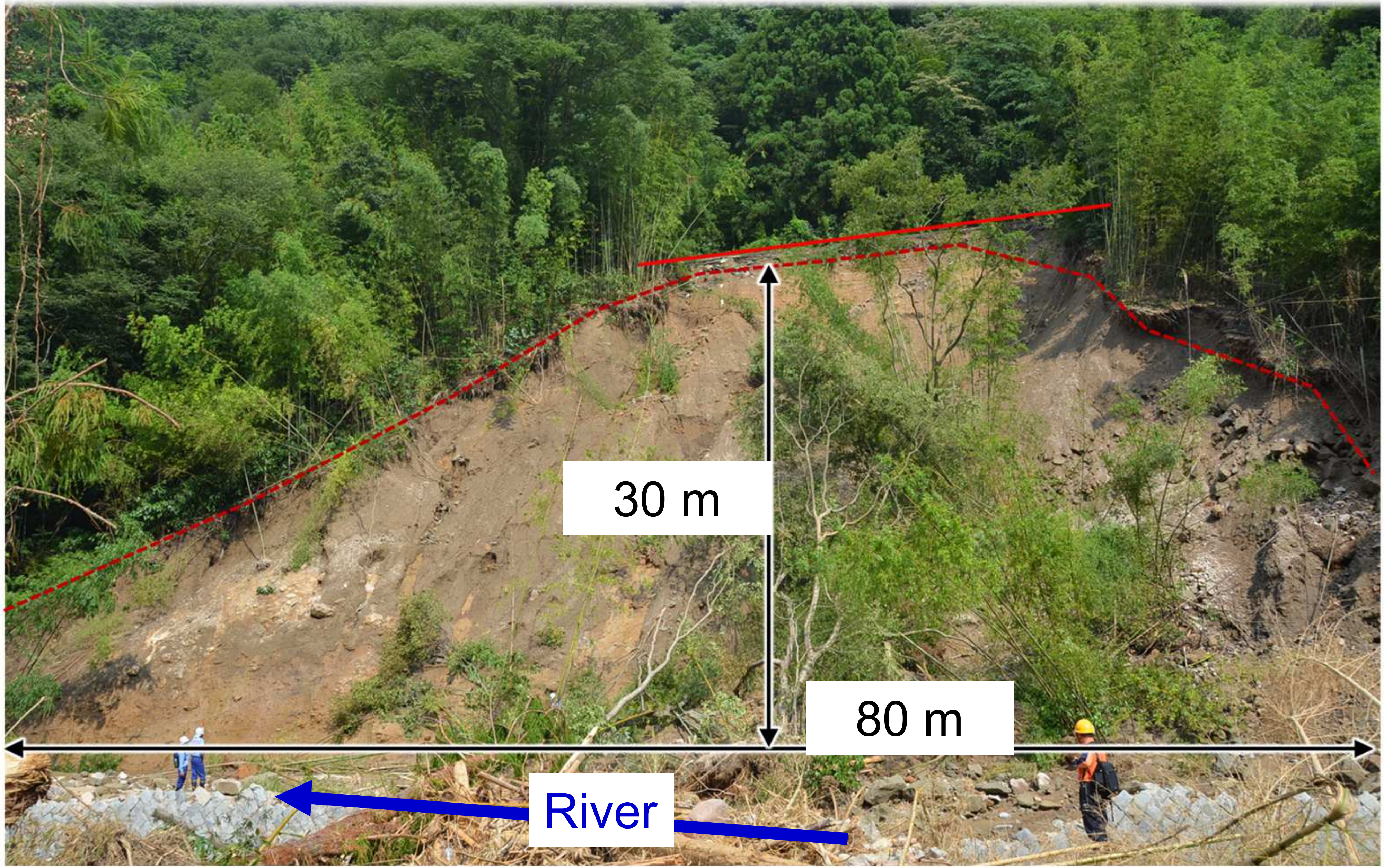
Construction of FHR facing after re-opening of service

A number of GRS structures were constructed to restore conventional type soil structures that collapsed by earthquakes, floods, tsunamis, etc.

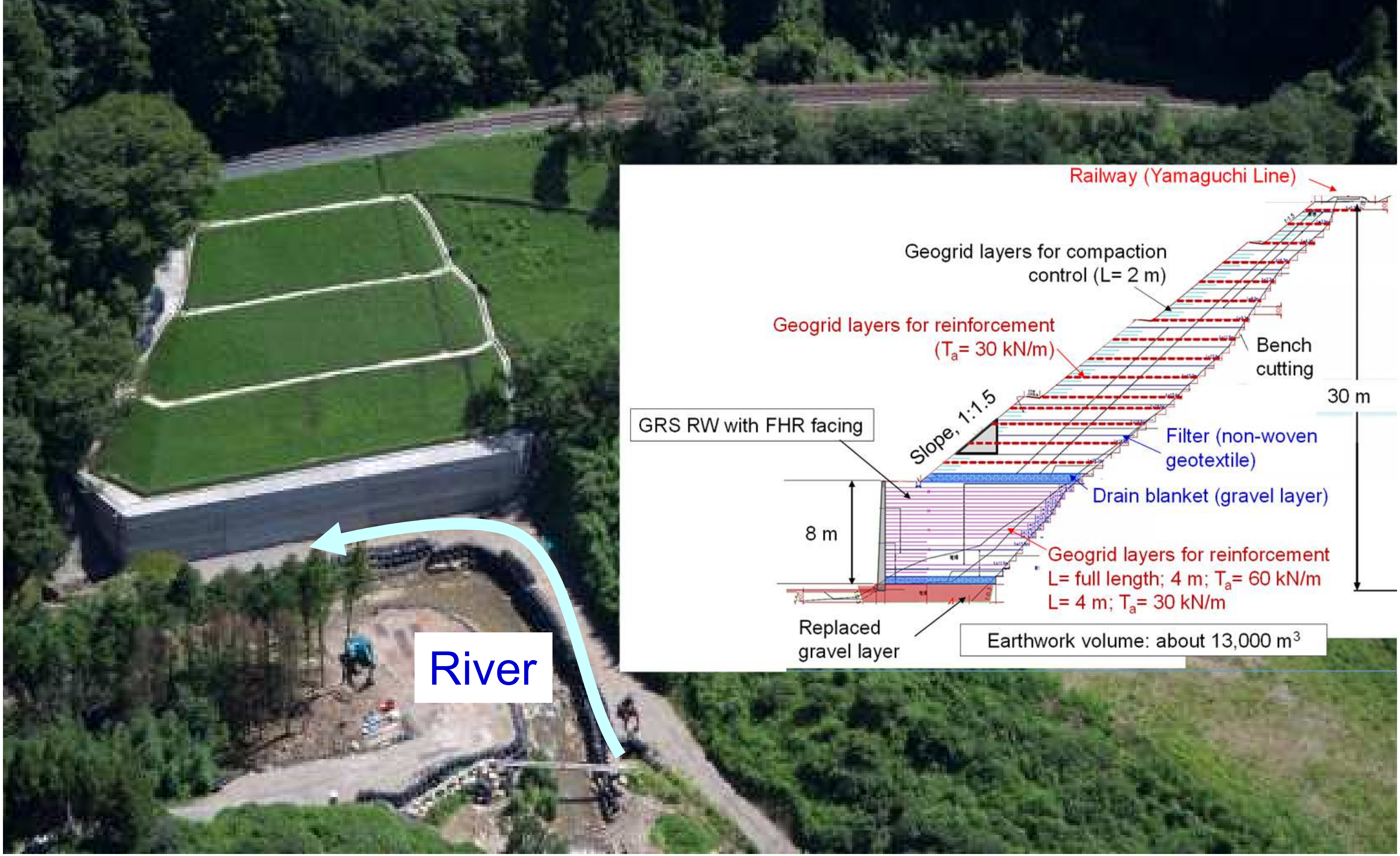


Collapse of railway embankment by scouring at the toe of embankment by river flood (28 July 2013)

JR West



GRS RW and GR slope (before the construction of FHR facing)




Completed GRS structure
FHR facing: very effective to prevent the failure of the wall by scouring
River

Summary:

A great number of embankments and conventional type RWs and bridges collapsed by recent severe earthquakes, heavy rainfalls, strong floods, high ocean storm waves, tsunamis, etc. in Japan.

Many of them were restored to GRS structures with FHR facing, because of:

1) fast restoration; and good constructivity even at remote places;
2) high stability against natural disasters, even when constructed on steep slopes; and
3) low cost for construction and long-term maintenance.

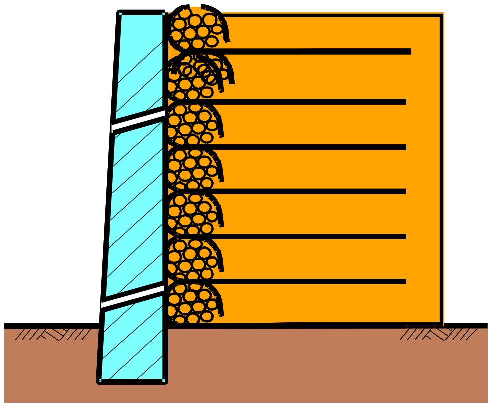
Contents

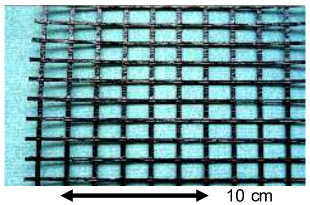
Concluding remarks – 1/5

A number of **GRS RWs with FHR facing, GRS Bridge Abutments, GRS Integra Bridges etc.** have been constructed as important permanent structures for a total wall length more than 200 km, many of them for high-speed railways (Shinkansen).

This accomplishment is due to their high cost-effectiveness by:

- **high performance** during long-term service and against severe earthquakes, heavy rainfalls, strong floods etc.; and
- **low cost** for construction and long-term maintenance.

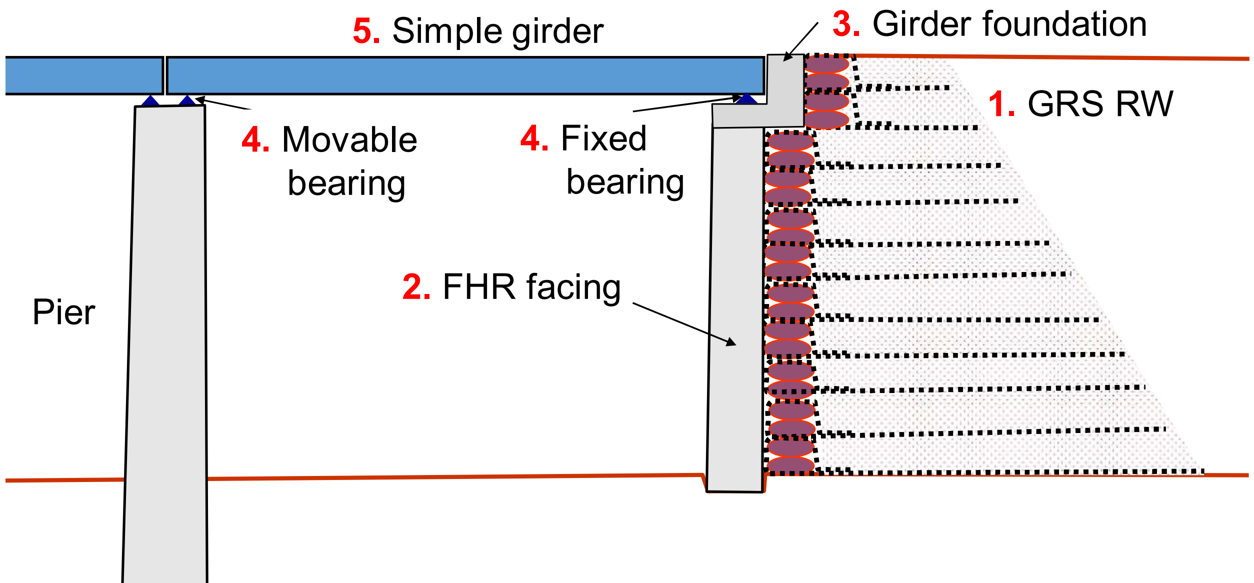




Typical polymer geogrid

Concluding remarks – 2/5

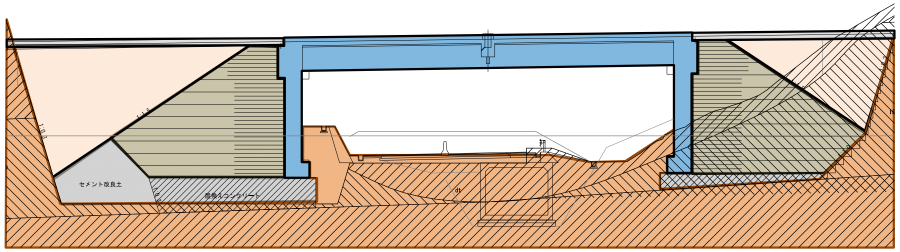
GRS Bridge Abutment is often used to support one end of a simple girder on a fixed bearing arranged at the girder foundation that is structurally integrated to the top of FHR facing of a GRS RW. This is much more cost-effective and much more stable than conventional type bridge abutments. In total 185 have been constructed. All are performing satisfactorily with essentially zero bump. This is now one of the standard bridge abutment structures for railways in Japan.



Concluding remarks – 3/5

GRS Integral Bridge consists of a continuous girder of which the both ends are structurally integrated to the crest of the FHR facings of a pair of GRS RWs, not using girder bearings. This is much more cost-effective and much more stable than conventional simple girder bridges. In total 14 have been constructed.

GRS Integral Bridge is now one of the standard bridge structures for railways in Japan.



Concluding remarks – 4/5

Many of the conventional type embankments, RWs and bridges that collapsed by recent severe earthquakes, heavy rainfalls, strong floods, high ocean storm waves, tsunamis etc. were restored to GRS structures having FHR facing.

Concluding remarks – 5/5

The following **three breakthroughs** were necessary to develop these GRS structures:

1) **The use of full-height rigid (FHR) facing** for changes:
   a) from low earth pressure to high earth pressure on the facing; and
   b) from the facing as a secondary non-structural component to the facing as a primary structural component.

2) **Structural integration of:**
   a) **the FHR facing to the reinforced backfill**; and
   b) **the girder to the FHR facing with GRS Integral Bridge**: for a change from a statically determinate but unstable structure to a statically in-determinate but stable one.

3) **Staged construction** for a construction sequence change: from the facing before the backfill to the facing after the backfill.

Thank you very much for your kind attentions.

The PDF files of the related technical papers of GRS structures by Tatsuoka et al. can be downloaded from the following:

https://www.dropbox.com/sh/nr01g7cangu3dkv/AACTs1F2AEI0gOjhn1IgcFMIa?dl=0

RRR Construction Technology Lecture
24 May 2023

www.rrr-sys.gr.jp/en/

Railway Technical Research Institute
https://www.rtri.or.jp/eng/

Design, construction and material regulation of RRR-GRS structures

Susumu Nakajima
Railway Technical Research Institute

Introduction

2001:Bachelor(Agriculture) (Tokyo University of Agriculture and Technology)

2001-2004: Honmagumi corporation

2004-2008:Master(2005) and Doctor(2008) University of Tokyo

2008-2011:Public Works Research Institute(PWRI)

2011-: Railway Technical Research Institute(RTRI)

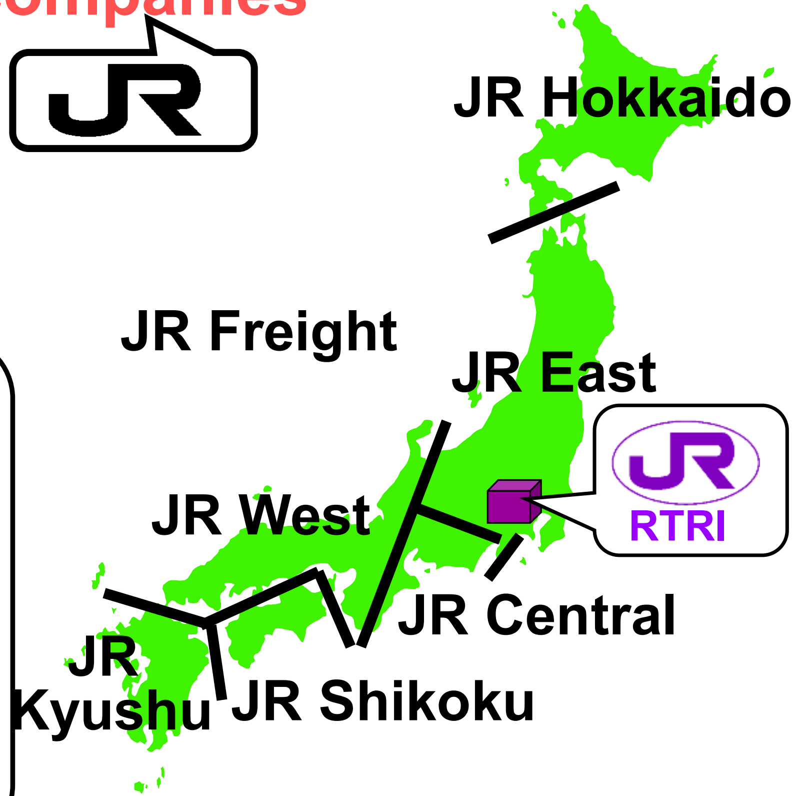
Railway companies in Japan and RTRI

Japan national railways

1987

Division and privatization

- ■ Railway Technical Research Institute
- ■ Railway Information Systems Co., Ltd.
- ■ 7 railway companies



- Publishing design standard for railway structure
  (Technical guide line, practical manual, etc)
- Supporting railway company
  (providing technical solutions, assisting disaster retrofitting and relevant technical judgement)

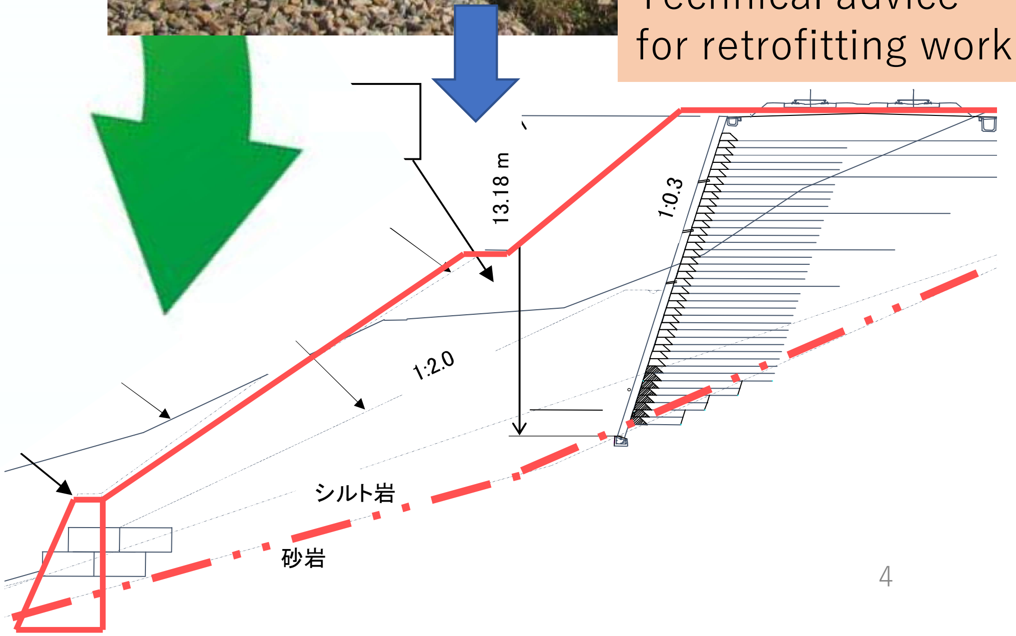
Work of RTRI

RRR-GRS retaining wall

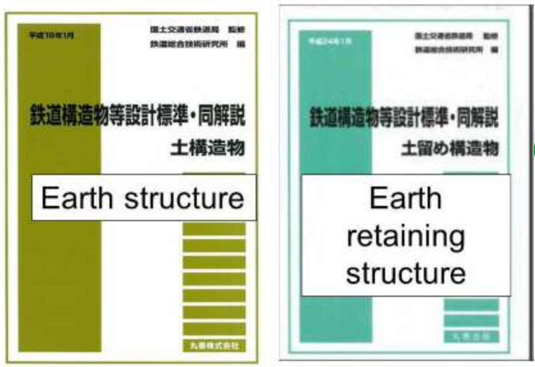
Research

Consulting

Technical advice for retrofitting work



Publishing

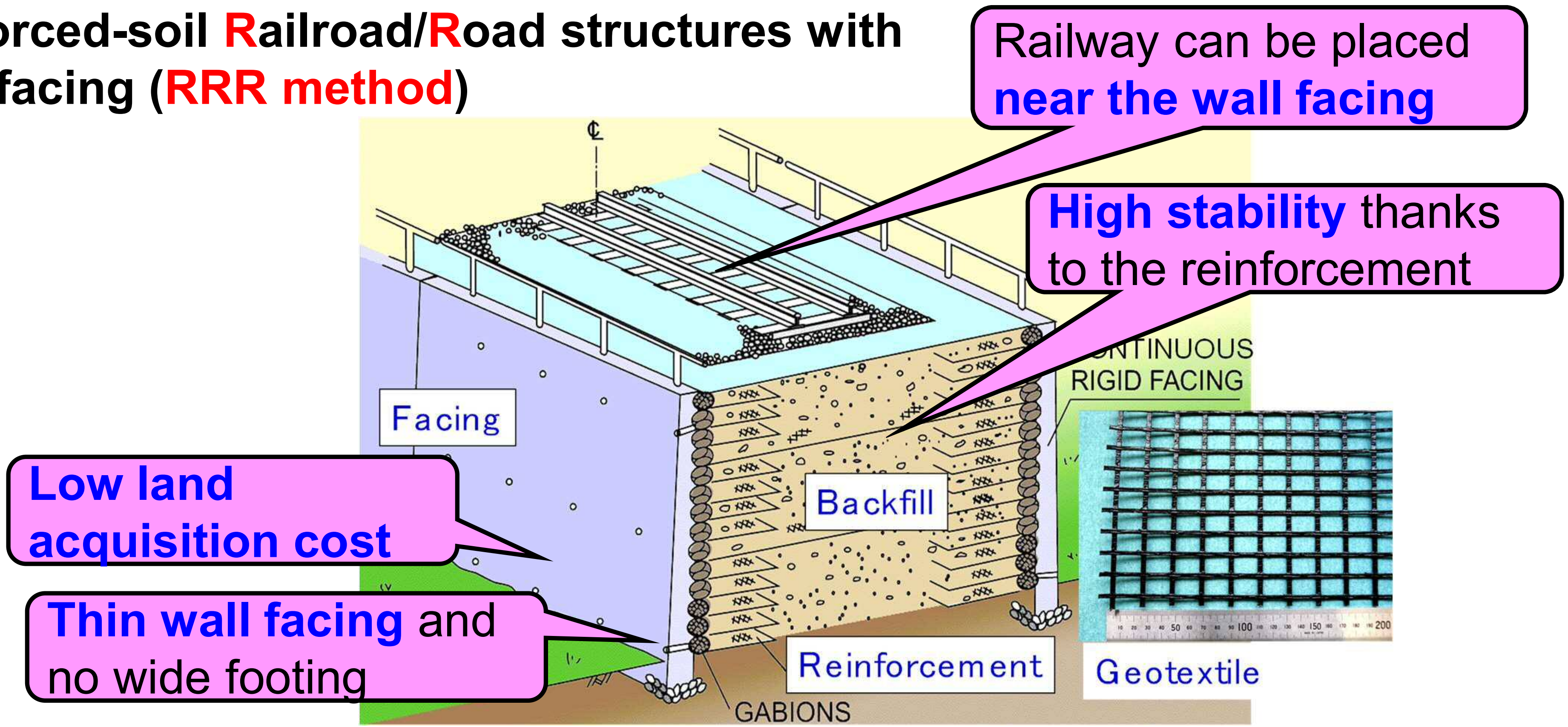


OUTLINE

1. Design standard of Japanese railway
2. Material regulation and construction of GRS retaining wall
3. Recent application for disaster retrofitting
4. Summary
5. Appendix to introduce applied project outside of Japan.

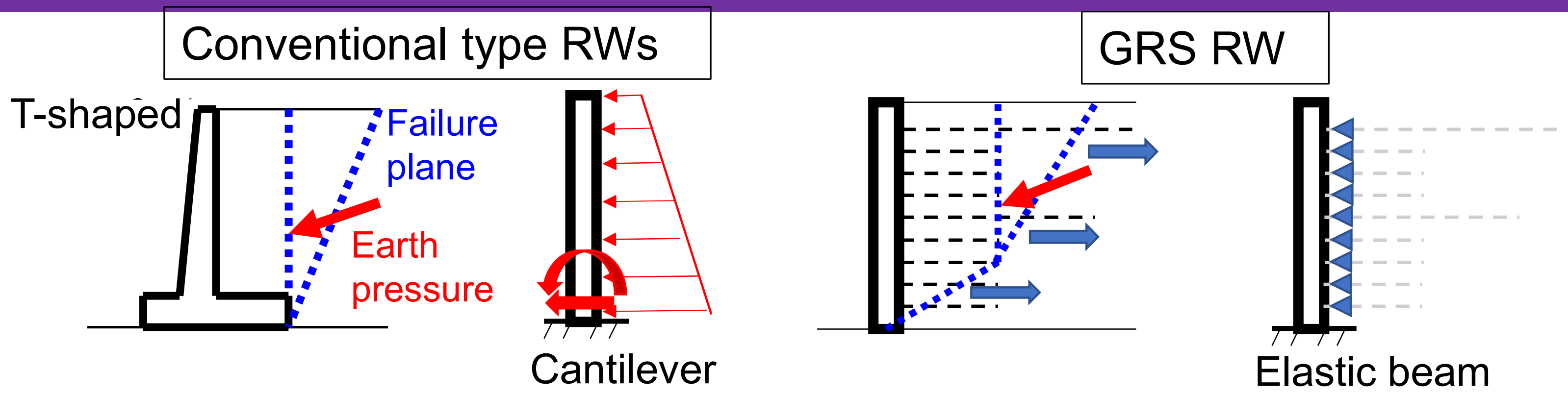
RRR-Geosynthetic-Reinforced Soil retaining wall

Reinforced-soil Railroad/Road structures with Rigid facing (RRR method)



- **Composite structure** consisting of the **continuous rigid wall facing**, **backfill** and **reinforcement**.
- Wall facing is free from the settlement due to embankment construction thanks to the **staged construction**.

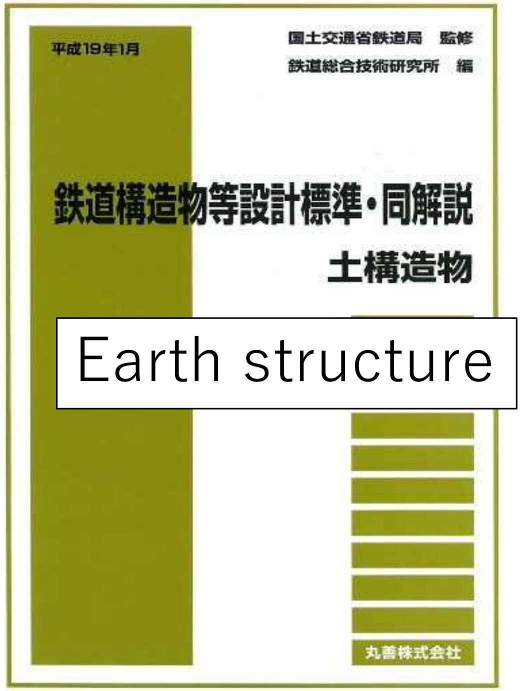
RRR-GRS wall and conventional wall

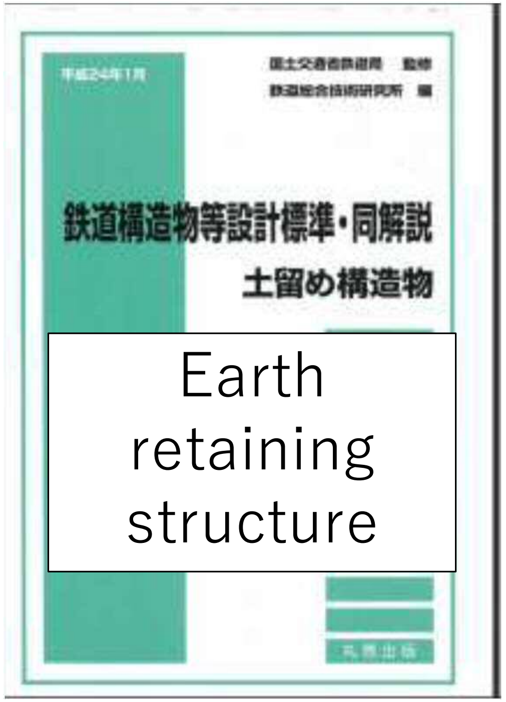


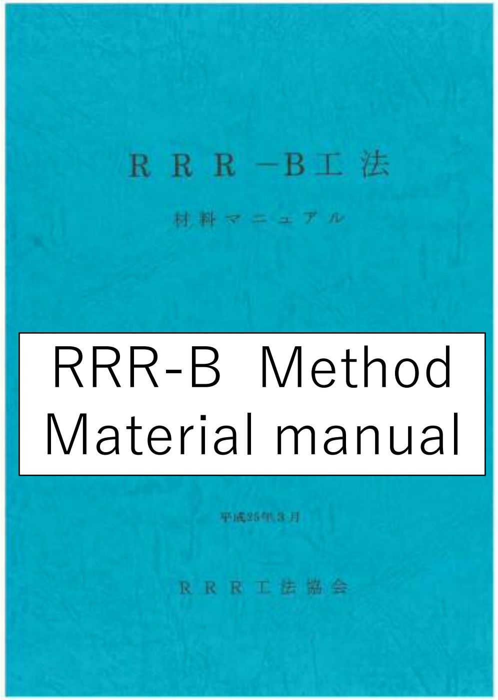
- To increase their stability
  - GRS wall: Arrangement can be changed
  - Conventional: Increase self weight and footing width
- Failure of wall facing
  - GRS wall: Arrangement can be changed
  - Conventional: Increasing wall thickness

- **Composite structure** consisting of the **continuous rigid wall facing**, backfill and reinforcement.
- Wall facing is free from the settlement due to embankment construction thanks to the **staged construction method**.

Design and construction of RRR-GRS RWs

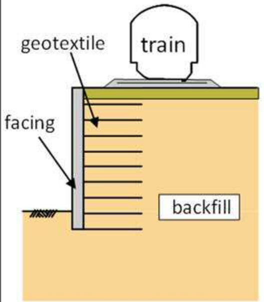
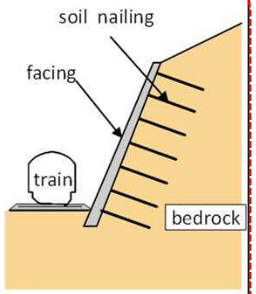
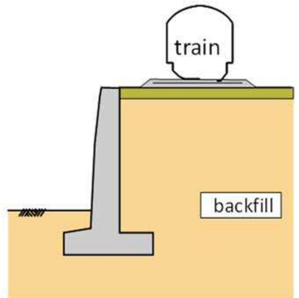
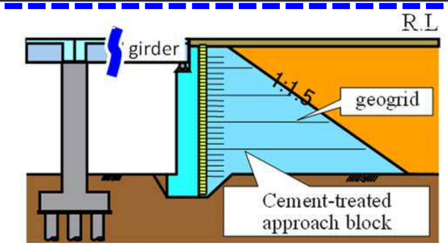
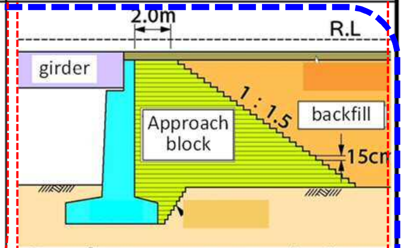






Design standard for railway structure
- -Earth structure
- -Earth retaining structure
- -Seismic design

Design standards for retaining structure

	Type of structure		
	GRS, NRS type		Conventional-type
Retaining wall	 GRS RW	 NRS RW	 **Earth pressure-resisting retaining wall**
Bridge abutment	 GRS Bridge abutment		 **Earth pressure-resisting bridge abutment**

- These all structure types are now covered in the same design standard (2012) (performance-based design)
- The performances can be verified with an equivalent index

Required performance of retaining wall

1. **Safety is performance to ensure that the earth retaining structure does not threaten the life of users or people nearby** based on all presumed actions. Safety includes the structural and the functional safety of an earth retaining structure.

2. **Serviceability is performance to ensure comfortable use of the earth retaining structure by users, that people nearby can live comfortably**, and the various functions required of the earth retaining structure based on presumed actions.

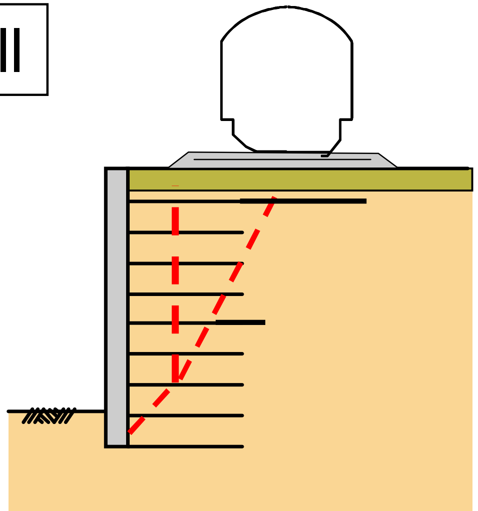
3. **Restorability is performance for maintaining the functions of the earth retaining structure in a usable state or holding in a restorable state** within a short duration based on presumed action

Required performance and performance rank

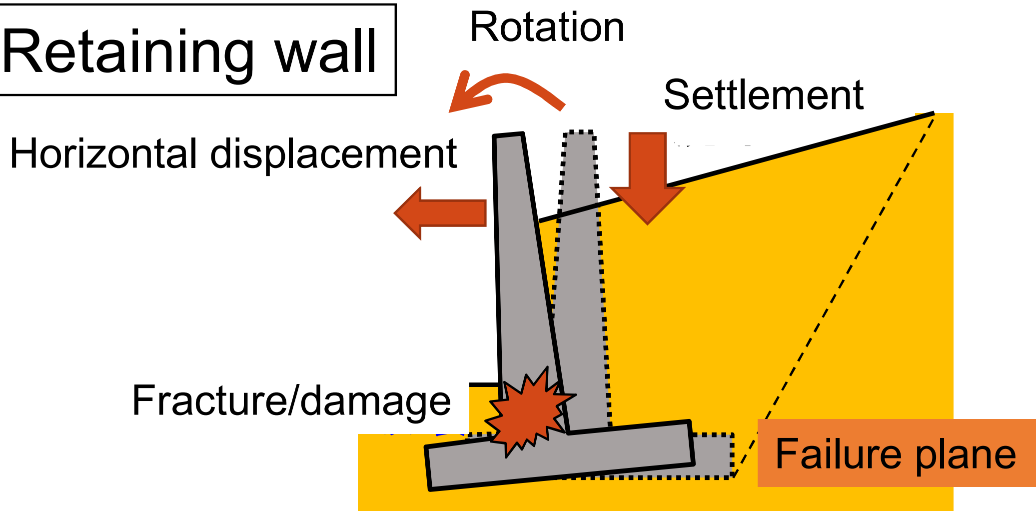
Performance rank	Example of application	Action in normal use	Moderate Action(highly expected for design life)	Extreme Action(maximum possible for design life)
1		No (Negligible) deformation	Limited deformation managing normal deformation	Small deformation allowing rapid restoration
2		Limited deformation managing normal maintenance	No deformation or very small deformation allowing restart of service supply after minor retrofitting work (if necessary)	No failure
3	Structures in rural area, Temporal structures	Some extents of deformation is applicable	No failure	Such action is not considered in design.

Required performance and performance item

GRS wall



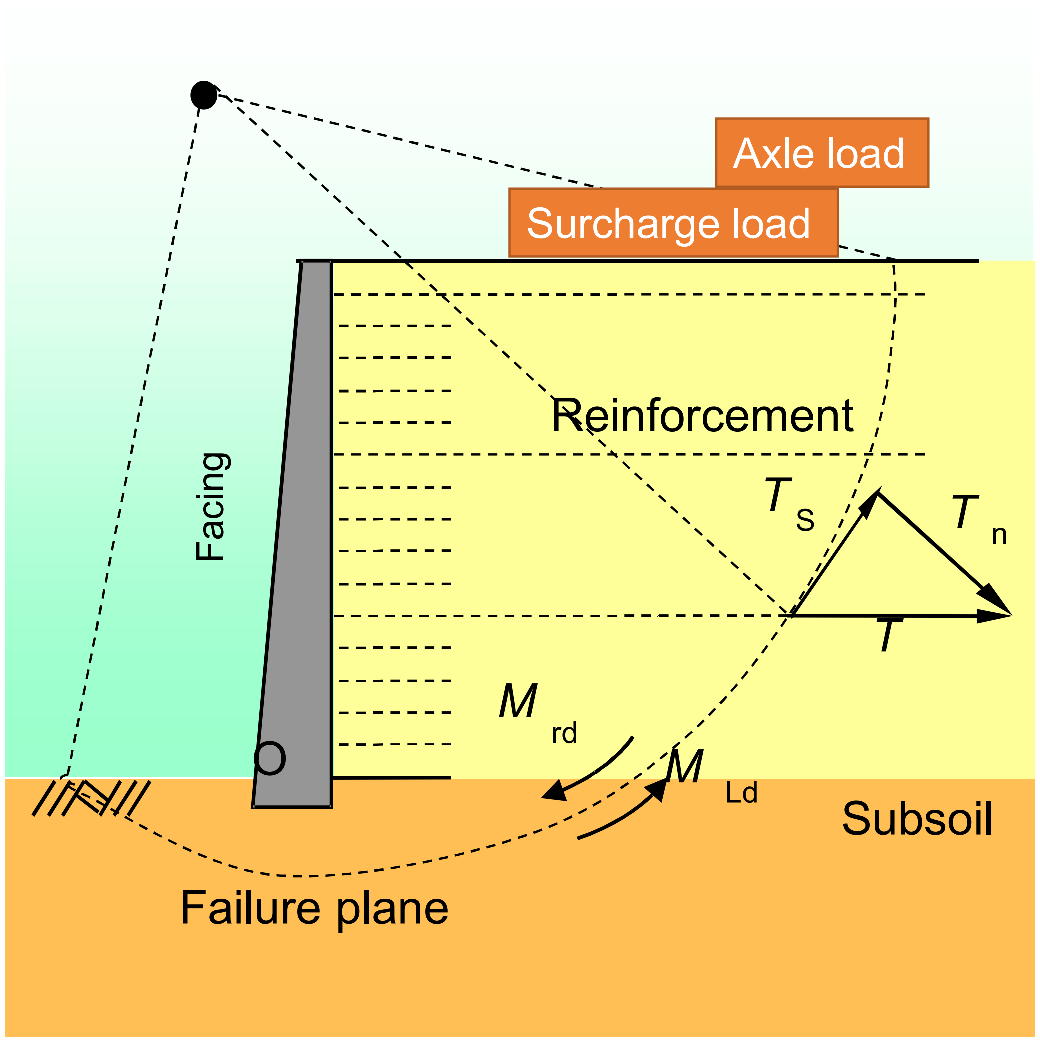
Retaining wall



- Fracture/damage of wall
- Stability of reinforced backfill
- Fracture/damage of reinforcement
- Deformation of backfill（L2 earthquake）
  -due to sliding, rotation, and shear deformation of reinforced backfill

- Fracture/damage of wall
- Stability of foundation
- Deformation of backfill（L2 earthquake ）
  -due to sliding and rotation of wall

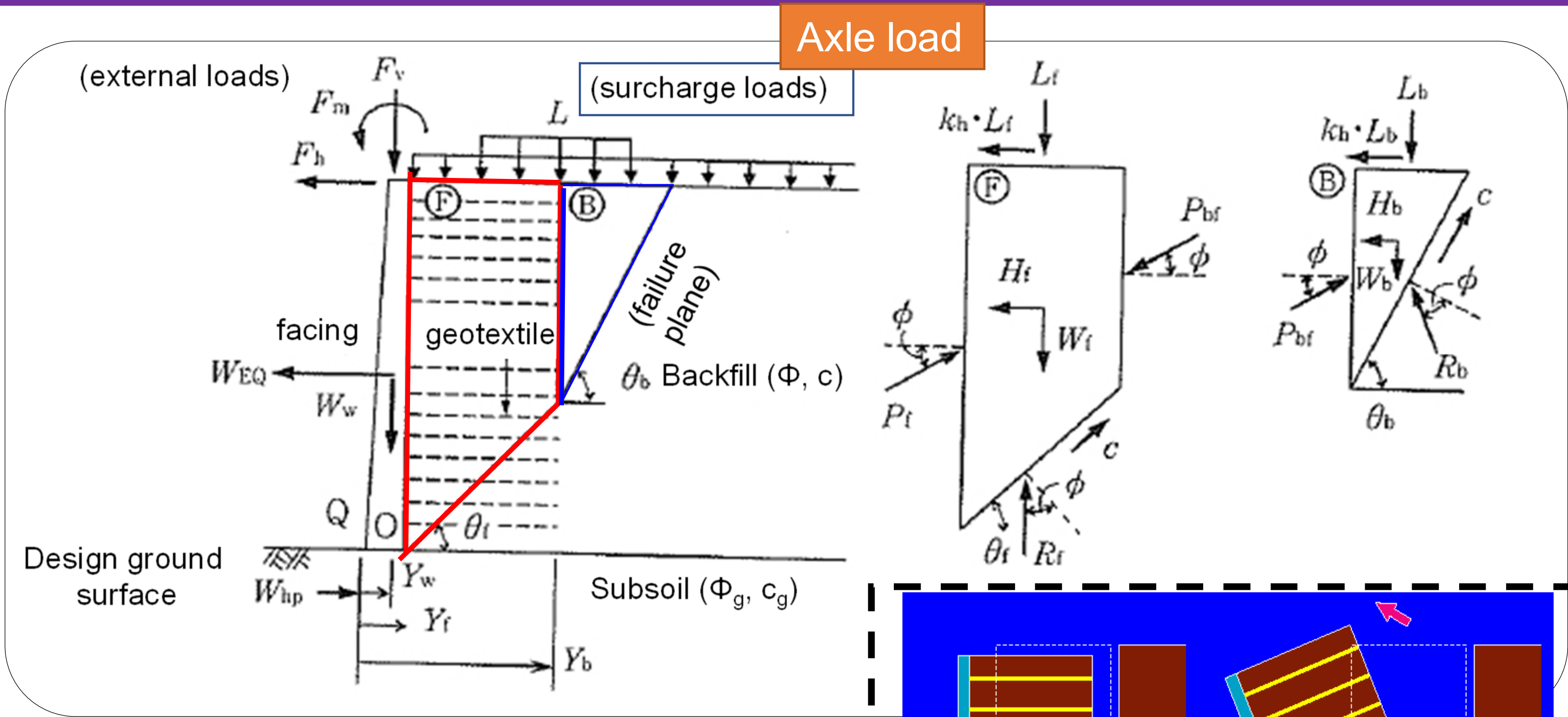
External stability analysis of GRS-RW



Fellenius method

The stability of the structure as a whole contained subsoil is verified.

Internal stability analysis of GRS-RW

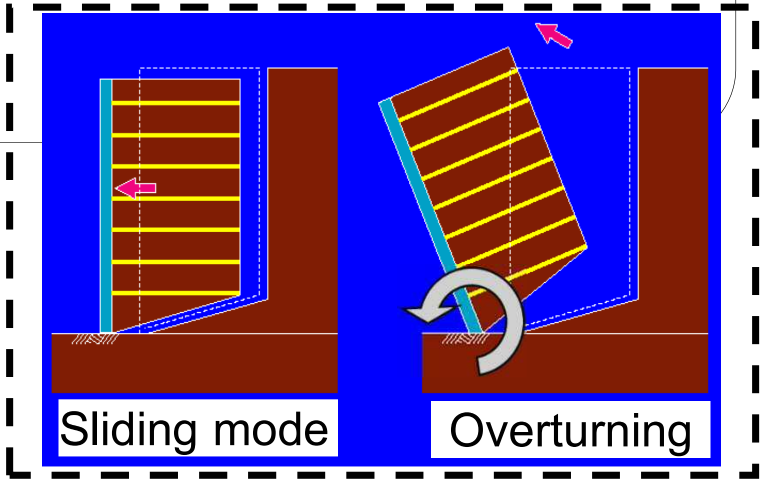


<u>Two-wedge method</u>

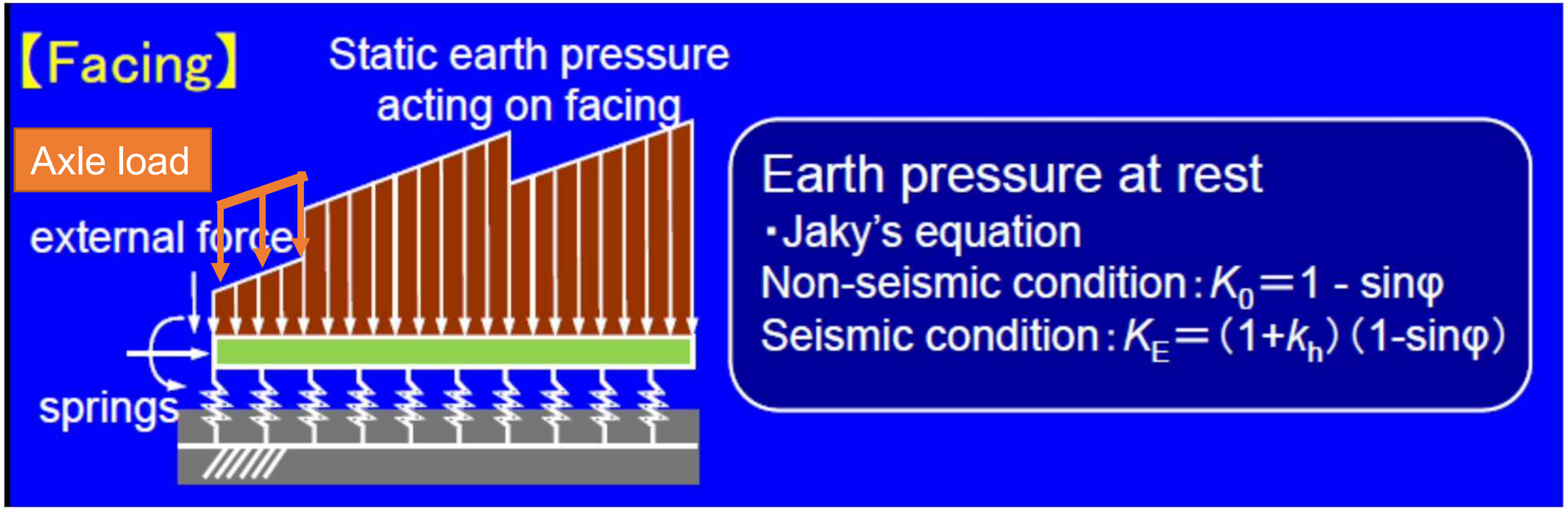
Searching 2 failure plane

1) reinforced zone
2) unreinforced zone

against "sliding" and "overturning"



Evaluation of response of wall facing

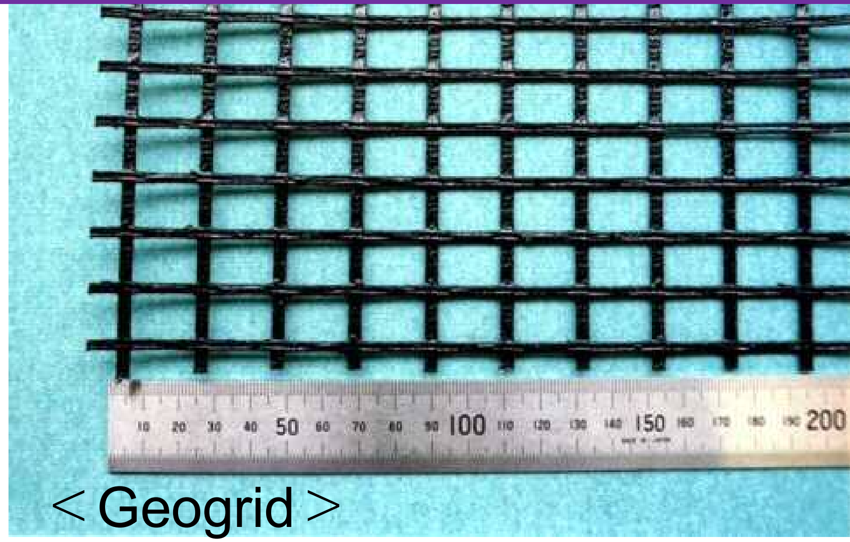


Wall facing is assumed to be an elastic beam supported by multi springs, which is assured by the strong connection between wall facing and reinforcement in backfill.

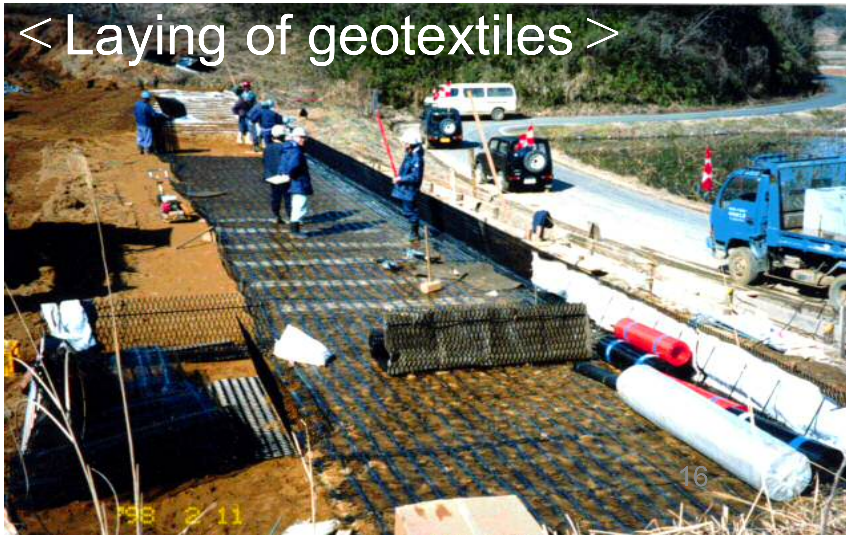
Wall facing thickness(200mm-300mm at the top) can be reduced as compared with conventional retaining wall.

Reinforcements used in reinforced-backfill retaining walls

The reinforcements used in reinforced-backfill retaining walls shall be those whose quality has been ascertained and their characteristic values and design values shall be appropriately determined taking into account various factors, such as the variability of test values and the experimental conditions.

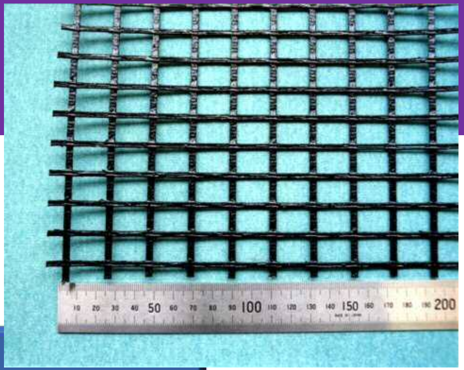


＜Geogrid＞



＜Laying of geotextiles＞

Setting of design tensile strength



Item	General actions	Variable action during construction	Actions including Level 2 seismic load	Remarks
Standard tensile strength	T_k(kN/m)			determined taking into account variability
Material correction factor	$\rho_m = 0.8$	$\rho_m = 0.8$	$\rho_m = 1.0$	–
Characteristic tensile strength	$T_a = \rho_m \cdot T_k$(kN/m)			–
Material factors	$f_{eg} = 0.4–0.7$	$f_{eg} = 0.6–0.95$	$f_{eg} = 0.7–1.0$	Depending on types of action, with α_i obtained experimentally
Design tensile strength	$T_d = f_{eg} \cdot T_a$(kN/m)			–

Reduction factors

Action combination	Reduction factors (○ : Considered)				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	−	−
Permanent action + variable action (train)	○	○	−	−	○
Permanent action + seismic action (L1 seismic ground motion) + secondary variable action	○	○	−	○	−
Permanent action + seismic action (L2 seismic ground motion) + secondary variable action	○	○	−	○	−
During construction	−	○	−	−	−

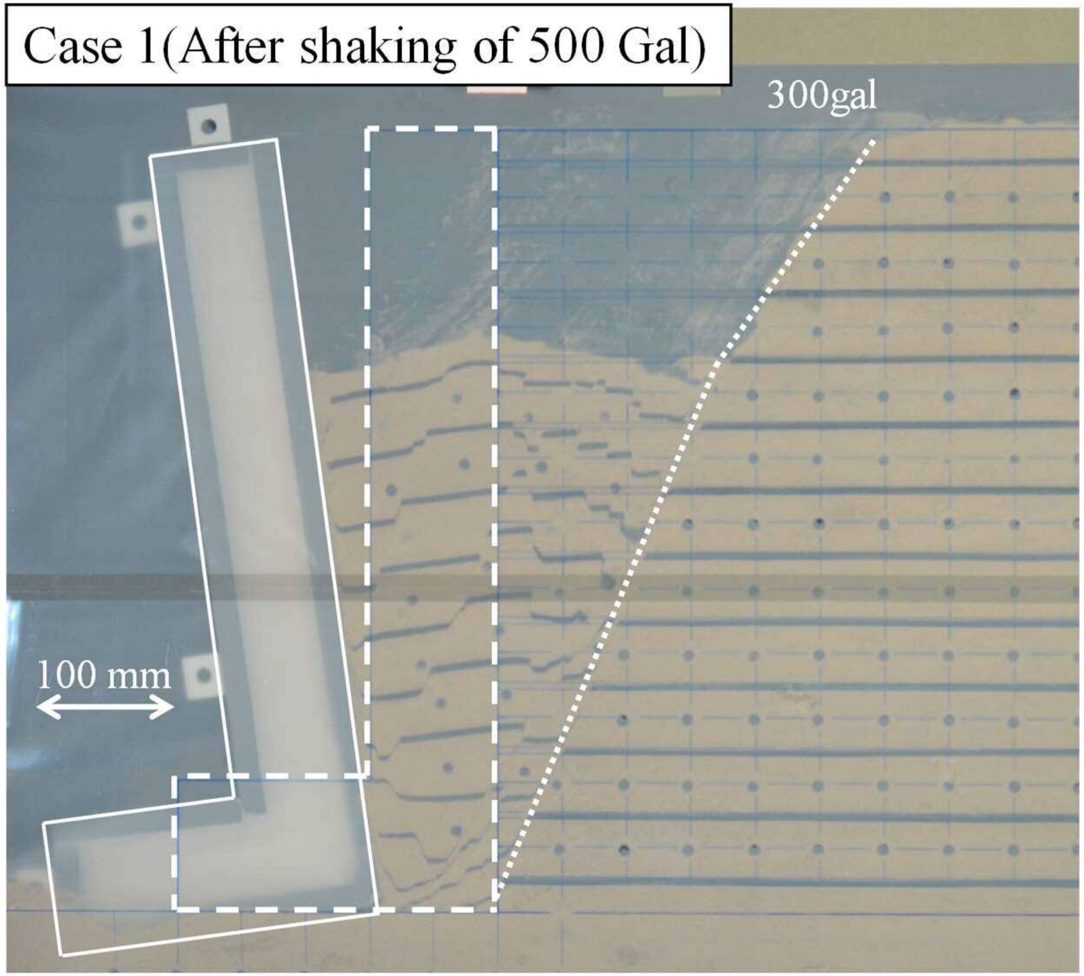
α_1 : Reduction factor considering alkaline resistance
α_2 : Reduction factor related to damage during construction
α_3 : Reduction factor related to creep α_4 : Reduction factor for momentary load
α_5 : Reduction factor related to train load

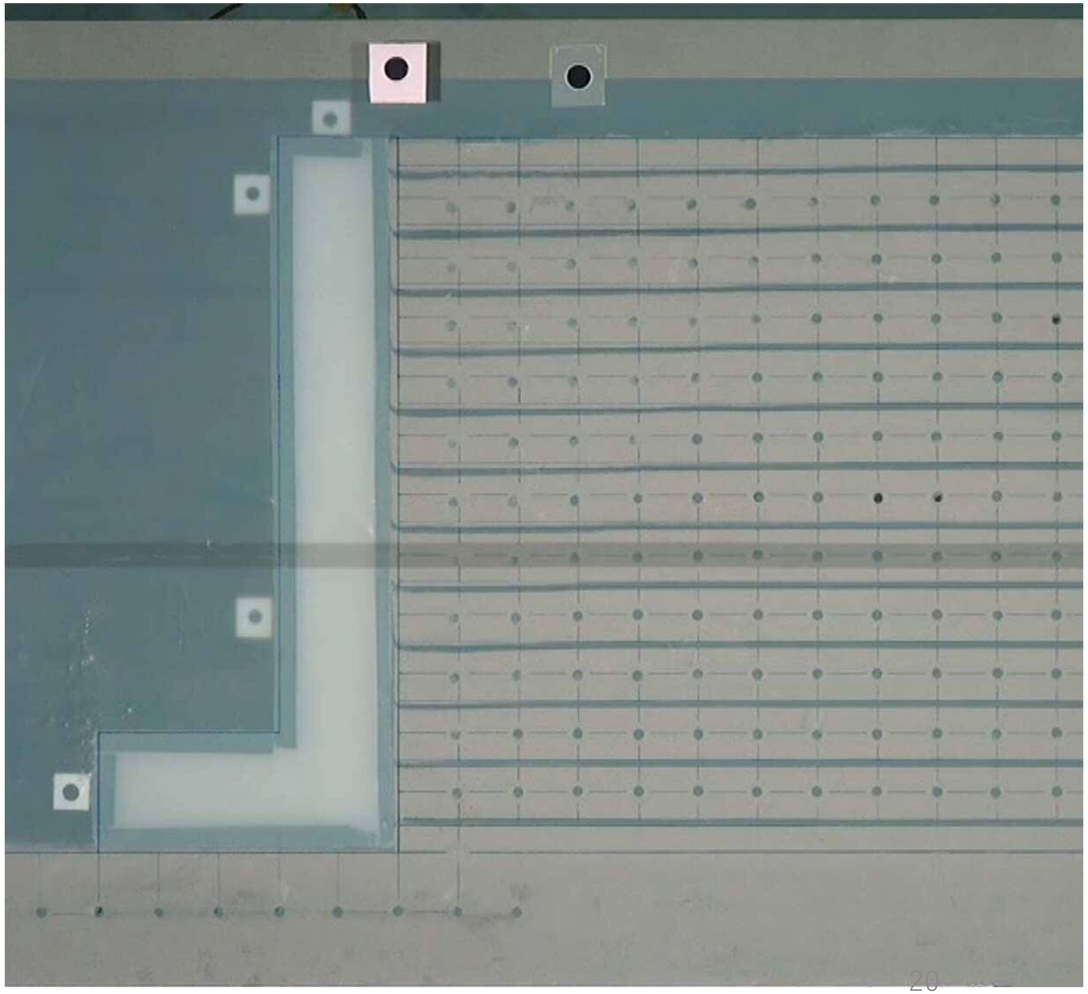
Summary 1

1. Railway structures adopt a performance-based design system. Structural evaluation is possible with the same index as concrete structures and tunnels.
2. Structure modeling and verification items in design are set according to the characteristics of the structure.
3. RRR-GRS structures have a performance rank that indicates the required level of required performance.
4. Analytical methods for overall stability, stability of reinforced earth bodies, and damage to reinforcement materials and walls have been developed.

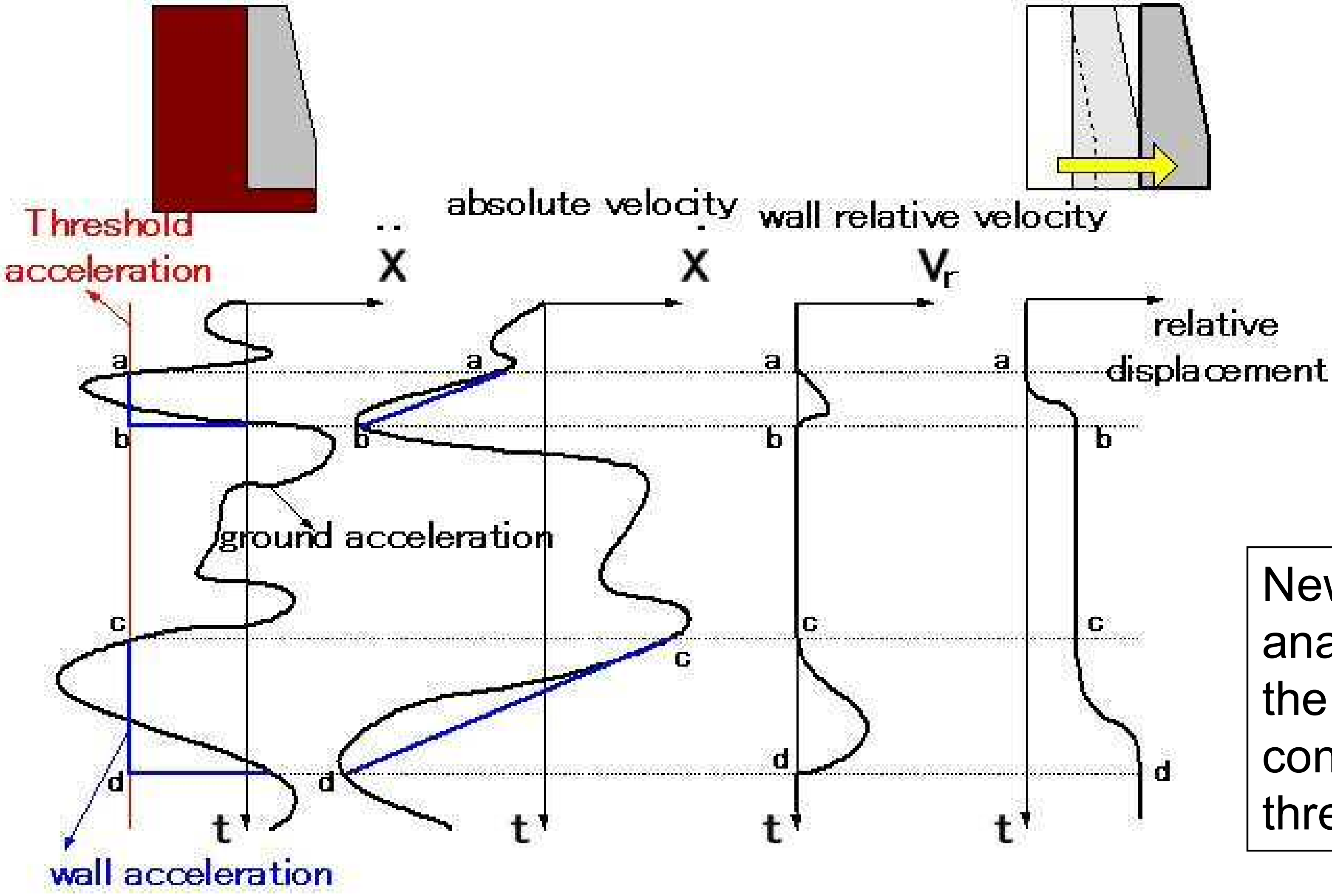
The case study to examine the analytical model is introduced

Verification of design methodology



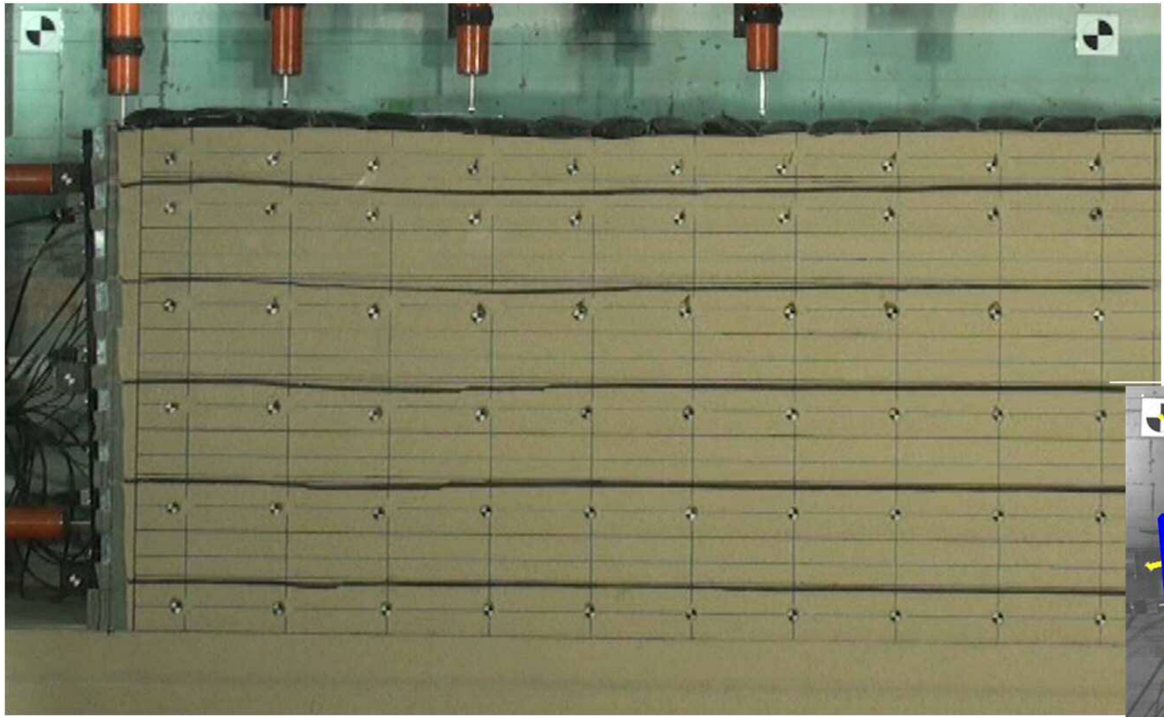


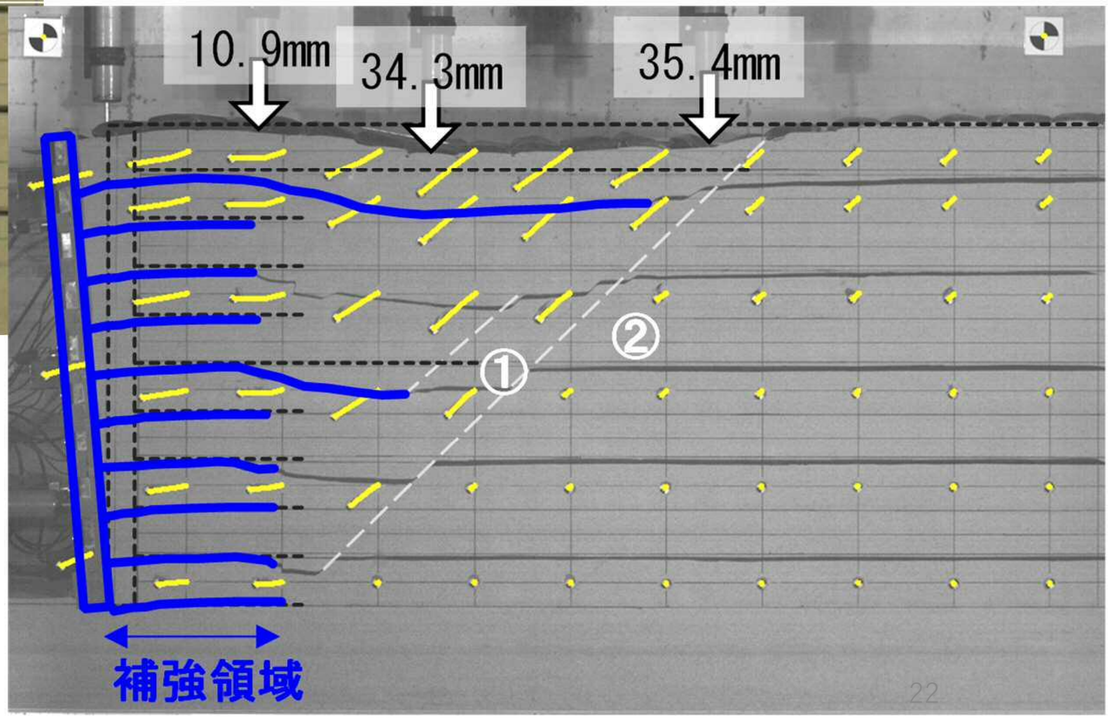
Verification of design methodology



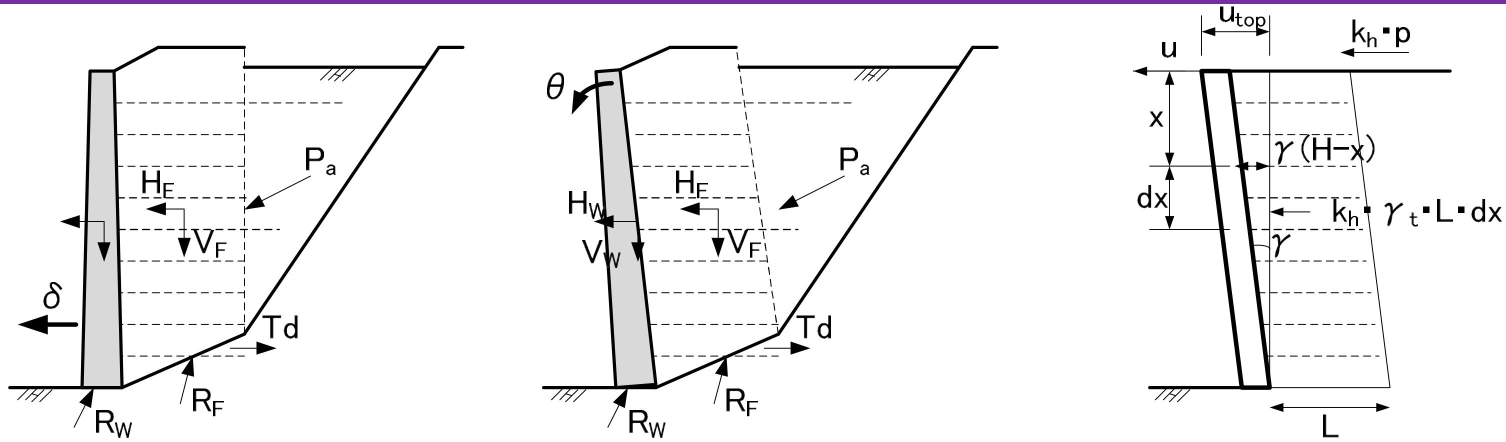
Newmark displacement analysis is adopted, while the stability analysis is conducted to evaluate threshold acceleration.

Verification of design methodology



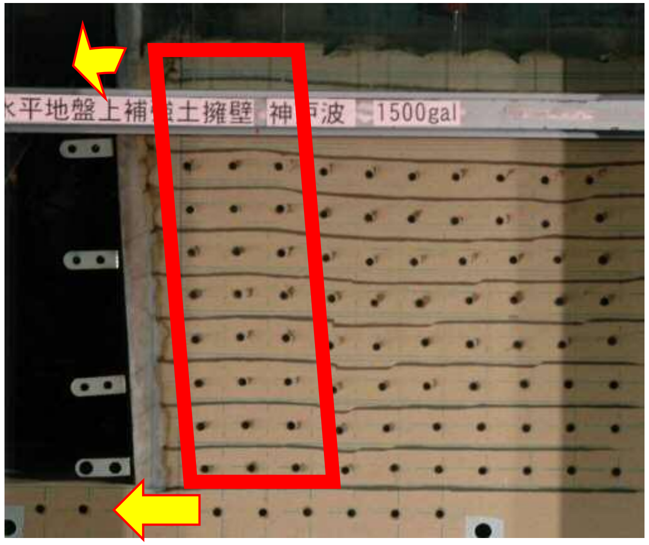


Stability analysis and deformation analysis



Sliding deformation
Overturning deformation
Shear deformation

Horii et. al (1995)

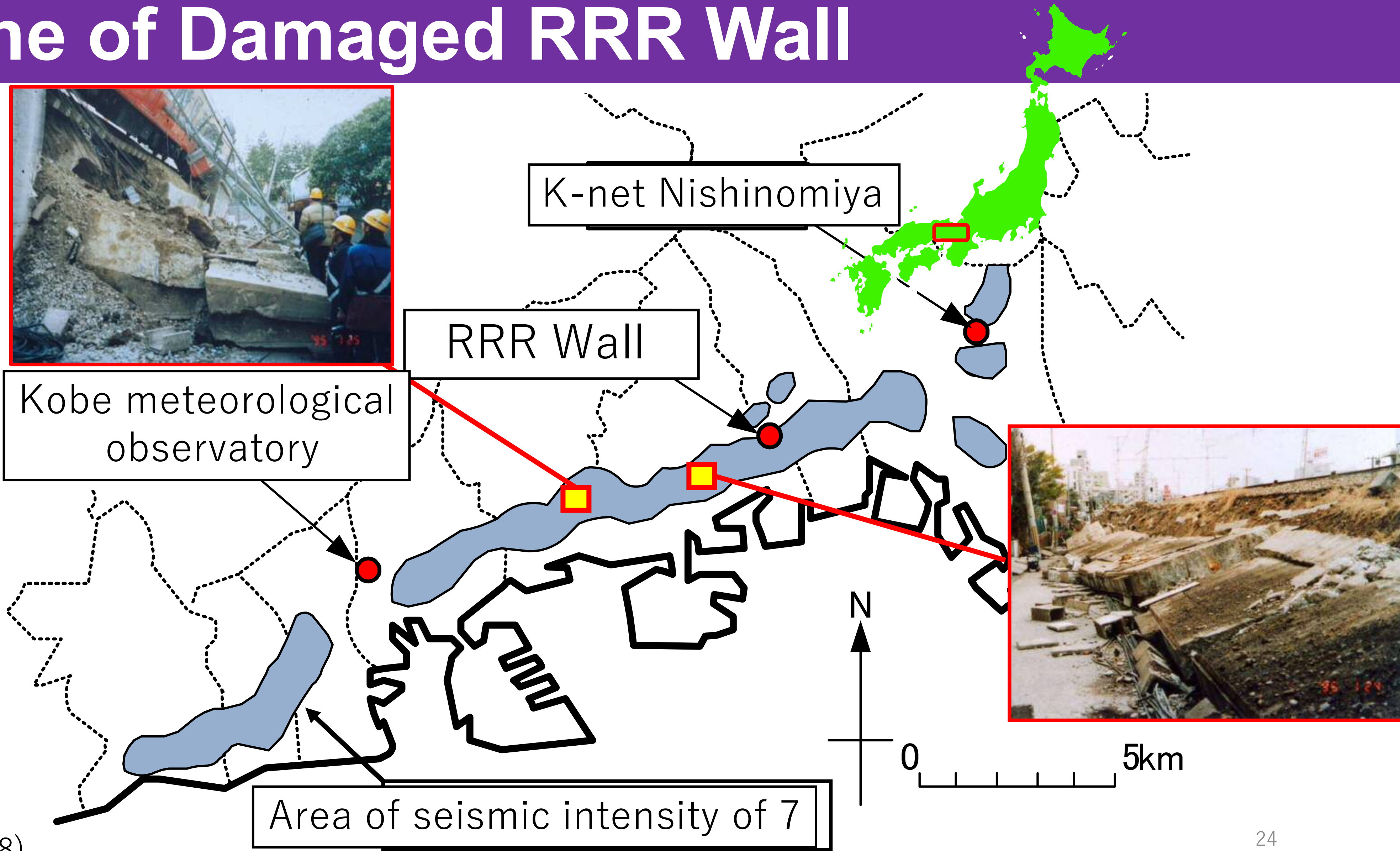


Residual displacement is evaluated using Newmark deformation analysis by assuming three mode of deformation.

For sliding and overturning ,
threshold value is evaluated by stability analysis

$$\delta = \iint \frac{H_{Rd} - H_{Ld}}{M} dt^2 \qquad \theta = \iint \frac{M_{Rd} - M_{Ld}}{J} dt^2$$

Outline of Damaged RRR Wall

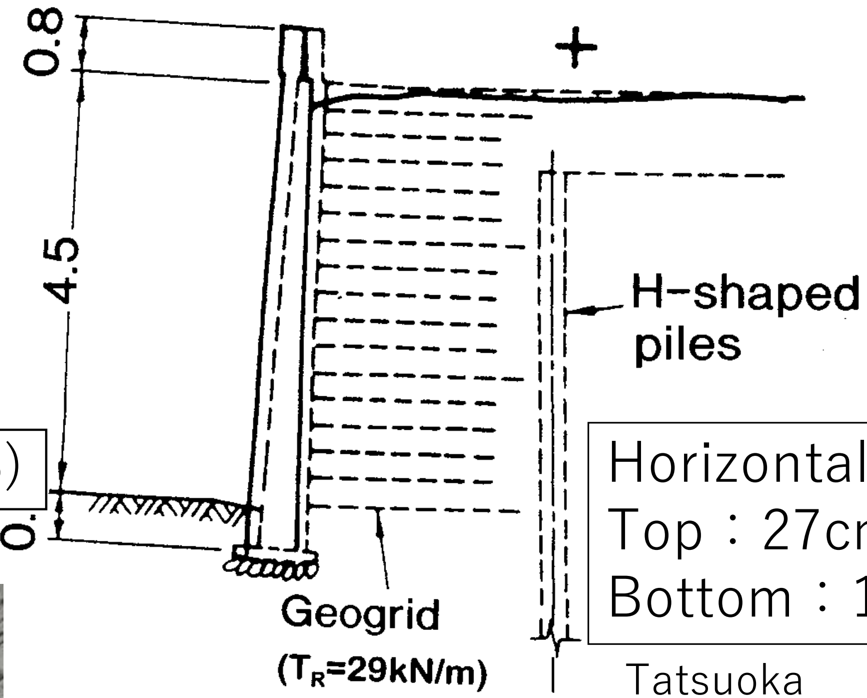


Tatsuoka et.al.(1998)

Damage and retrofitting work

After earth quake (1995)

Current situation (2016)

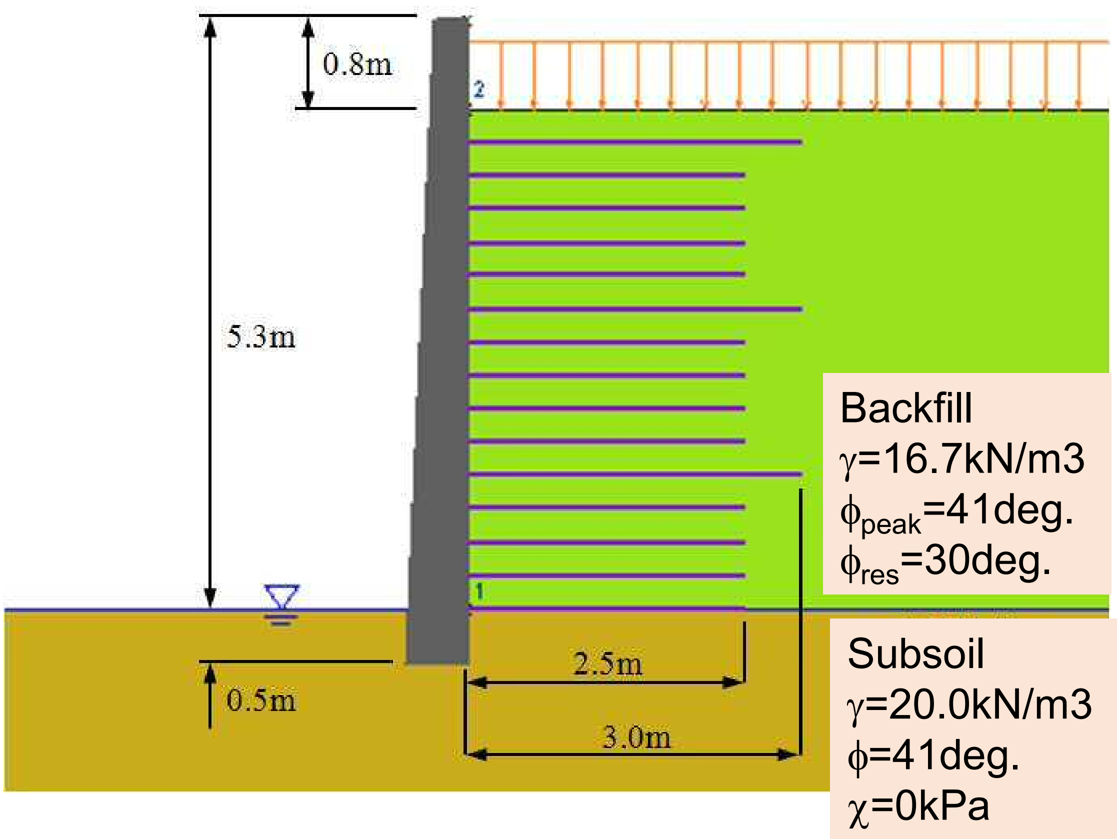


Horizontal disp.
Top：27cm
Bottom：10cm

Tatsuoka et.al.(1998)

Backfill settlement was repaired in retrofitting work and the wall has been continuously used since 1995.

Analytical model

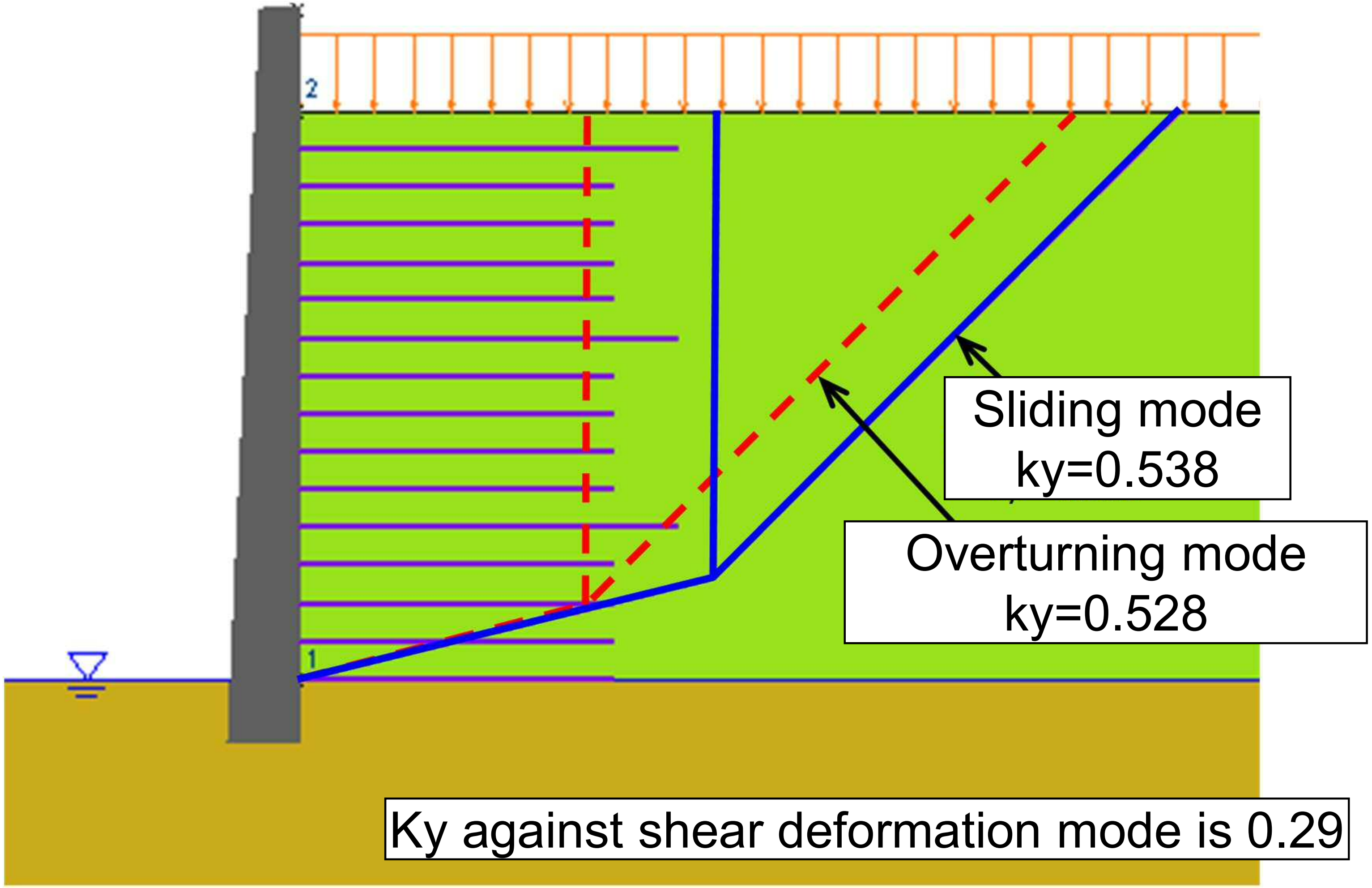


Result of ground survey

		Backfill	Subsoil
Unit weight (kN/m^3)	γ	16.7	20.0
Angle of internal friction (deg.)	ϕ_{peak}	41	41
	ϕ_{res}	30	—
Cohesion(kPa)	c	0.0	0.0
Initial Shear modulus (kPa)	G_0	30,000	—

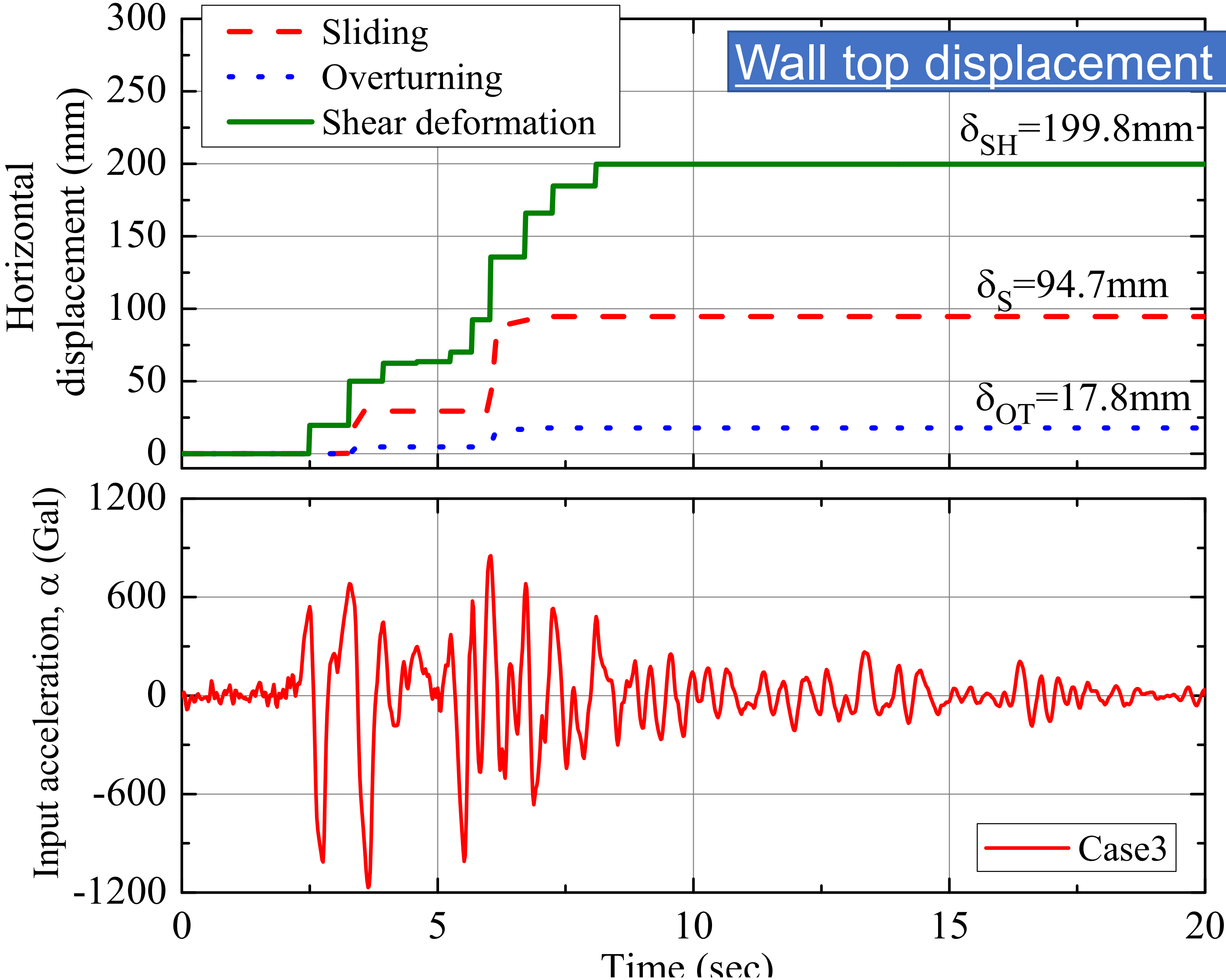
Design standard

Evaluation of yield seismic coefficient（sliding•overturning）

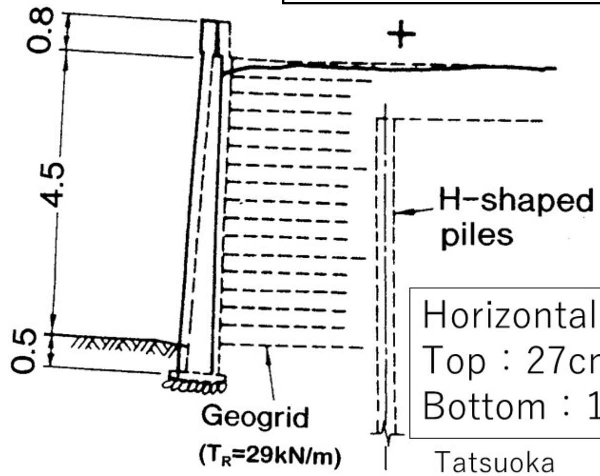


(ky: yield seismic coefficient)

Example of deformation analysis



Actual displacement
Bottom：100mm
Walltop：270mm



Horizontal disp.
Top：27cm
Bottom：10cm

Tatsuoka et.al.(1998)

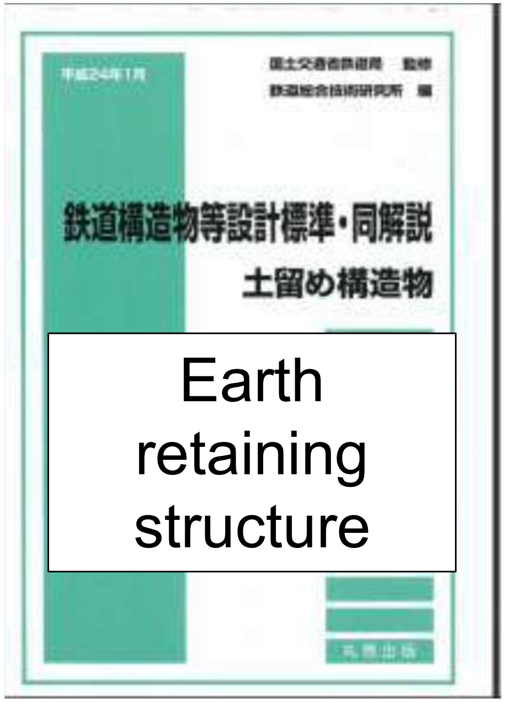
Summary 1-2

1. Railway structures adopt a performance-based design system. Structural evaluation is possible with the same index as concrete structures and tunnels.
2. Structure modeling and verification items in design are set according to the characteristics of the structure.
3. RRR-GRS structures have a performance rank that indicates the required level of required performance.
4. Analytical methods for overall stability, stability of reinforced earth bodies, and damage to reinforcement materials and walls have been developed.
5. **The analytical model is verified by the slightly damaged RRR-GRS retaining wall, and the amount of residual displacement and deformation mode agreed with the measured one.**

OUTLINE

1. Design standard of Japanese railway
2. Material regulation and construction of GRS retaining wall
3. Recent application for disaster retrofitting
4. Summary
5. Appendix to introduce applied project outside of Japan.

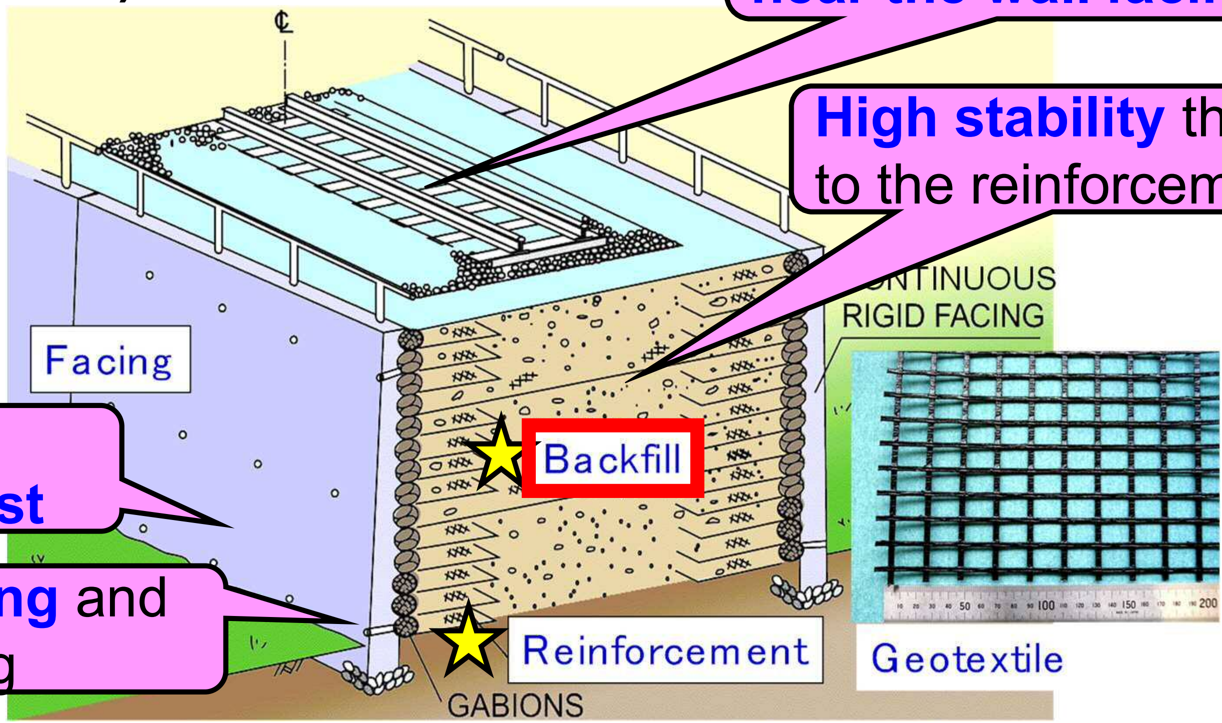
Design and construction of GRS RWs



Design standard for railway structure
- Earth structure
- Earth retaining structure
- Seismic design

Geosynthetic-reinforced soil retaining wall

Reinforced-soil Railroad/Road structures with Rigid facing (RRR method)

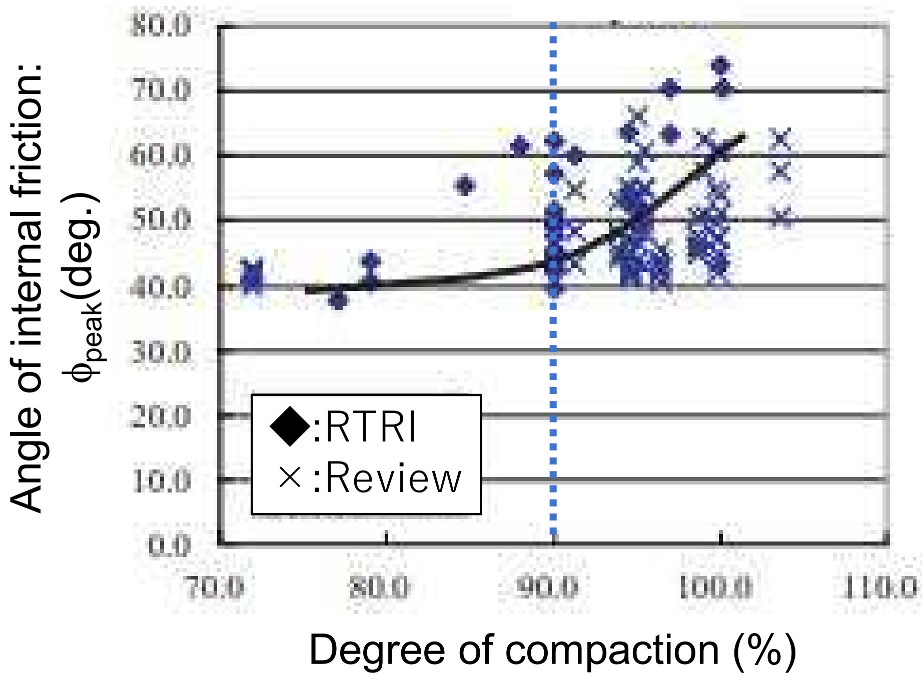


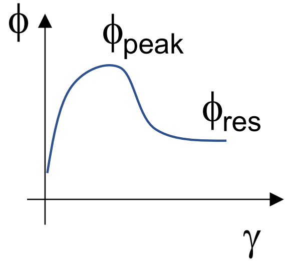
- **Composite structure** consisting of the **continuous rigid wall facing**, **backfill** and **reinforcement**.
- Wall facing is free from the settlement due to embankment construction thanks to the **staged construction**.

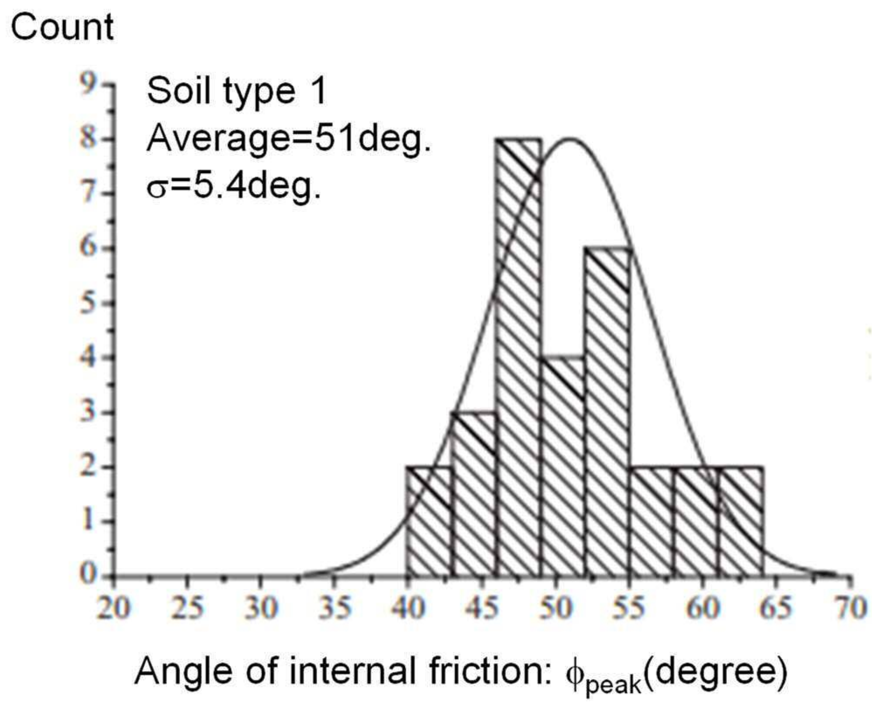
Physical and strength characteristics in design

Soil type	Soil classification based on AASHTO		γ_t (kN/m³)	Seismic action (Level 2 earthquake)		Other than seismic action(including Level 1 earthquake)
				ϕ_{peak}(degree)	ϕ_{res}(degree)	ϕ (degree)
Type1	G, G-S, GS G-F, G-FS, GS-F	**Performance rank I**	20	55	40	40
Type2	S, S-G, SG※2 S-F, S-FG, SG-F※3	**Peformance rank II～III**	19	50	35	35
Type3	GF, GF-S, GFS SF, SF-G, SFG※5		18	45	30	30
Type4	ML, CL, MH, CH OL, OH, OV, Pt, Mk VL, VH1, VH2		16	40	30	30

Triaxial compression test







- Classify embankment materials and set the strength that can be expected when a specified degree of compaction is achieved based on the results of systematic soil tests, taking into account variations.

- Residual strength is used during normal condition, and both peak and residual strength are used in seismic design.

Material regulation and compaction management

Material regulation

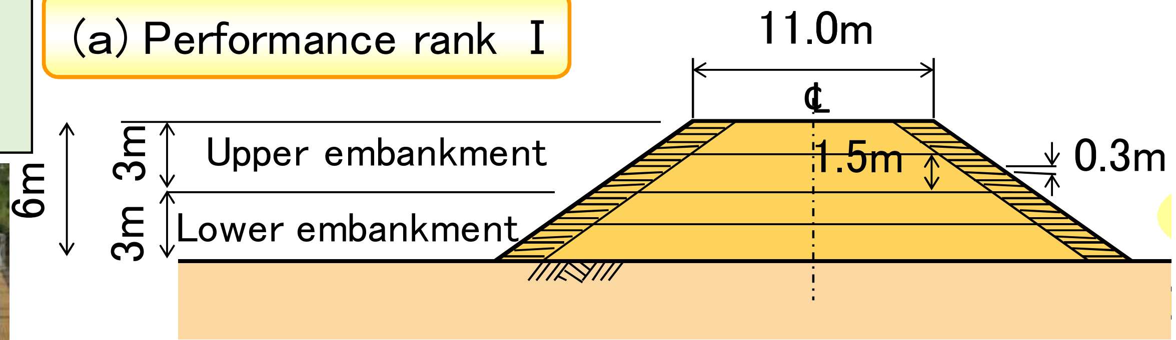
PF rank	Upper part of embankment	Lower part of embankment
I	〔A〕 Stabilized〔B〕 Recycled material	〔A〕 Stabilized〔B〕 Recycled material
II	〔A〕〔B〕 Stabilized〔C〕〔D1〕〔V〕 Recycled material	〔A〕〔B〕 Stabilized〔C〕〔D1〕〔D2〕〔V〕 Recycled material
III	〔A〕〔B〕 Stabilized〕〔D1〕〔V〕 Recycled material	〔A〕〔B〕〔C〕 Stabilized〔D1〕〔D2〕〔V〕 Recycled material

Performance rank	Upper embankment		Lower embankment
	Degree of compaction	Value of K_{30}	Degree of compaction
I	Average ≧95% （Minimum≧92%）	Average ≧110MN/m^3 （Minimum≧70MN/m^3）	Gravel ：Average ≧90% （Minimum≧87%） Sand：Average ≧95% （Minimum≧92%）
II	Average ≧90% （Minimum ≧87%）	Average：$70 \leqq K_{30} < 110$MN/m^3 （Minimum≧50～70MN/m^3） or Average ≧110MN/m^3 （Minimum≧70MN/m^3）	Average ≧90% （Minimum≧87%）
III	Average ≧90%	Average ≧70MN/m^3	Greater than 90%(Fc<20%) air content：v_a ・Fc≧50%　$v_a \leqq 10$% ・Fc 20 to 50%　$v_a \leqq 15$%

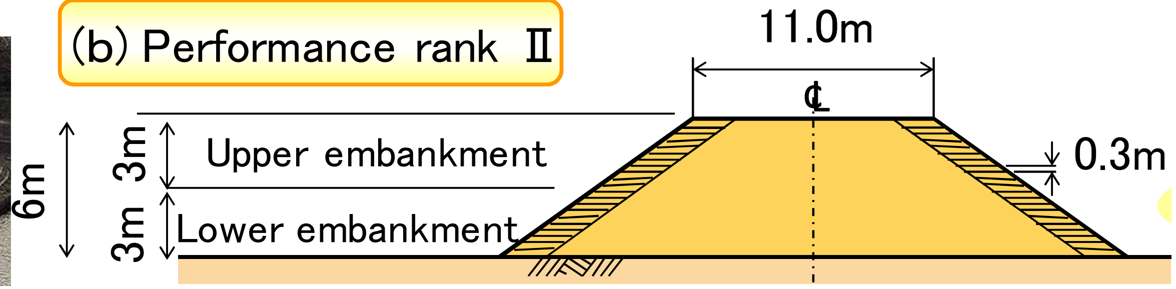
Compaction management

Current design standard（2007）

(a) Performance rank Ⅰ



(b) Performance rank Ⅱ



Material classification for embankment construction

Group code	Soil class code	Remarks
A group	(G) (G-S) (GS)	
	(G-F) (G-FS) (GS-F)	Excluding the ones that fine content is manly organic soil
	(S) (S-G) (SG)	Satifies Uc≧10 and 1<Uc'<$Uc^{0.5}$
	(S-F) (S-FG) (SG-F)	Excluding the ones that fine content is manly organic soil or volcanic ash soil
	Crashed hard rock	
B group	(G-F) (G-FS) (GS-F)	In case fine content is mainly organic soil
	(GF) (GF-S) (GFS)	Excluding the ones that fine content is manly organic soil or volcanic ash soil
	(S) (S-G) (SG)	Other than that with grading Uc≧10 and 1<Uc'<$Uc^{0.5}$
	(S-F) (S-FG) (SG-F)	In case fine content is manly organic soil or volcanic ash soil
	(SF) (SF-G) (SFG)	Excluding the ones that fine content is manly organic soil or volcanic ash soil
	Crushed hard rock, crushed weak rock	Excluding that which is part of D1 group
C group	(GF) (GF-S) (GFS)	In case fine content is manly organic soil or volcanic ash soil
	(SF) (SF-G) (SFG)	In case fine content is manly volcanic ash soil
	(ML) (CL)	
D1 group	(MH) (CH)	
	Crushed weak rock	
D2 group	(SF)(SF-G)(SFG)	In case fine content is manly organic soil
	(OL) (OH)(OV) (Pt) (Mk)	
V group	(VH) (VH1) (VH2)	
Others	Artificial materials (Wa) (I)	

Note) The maximum grading of crushed rock and rocky material is approximately 300 mm
(Wa) and (I) refer to artificial materials that are waste or improved soil
and Uc: unifomity coefficient, Uc':coefficient of curvature

PF rank and applicable embankment material

PF rank	Upper part of embankment	Lower part of embankment
I	〔A〕 Stabilized〔B〕 Recycled material	〔A〕 Stabilized〔B〕 Recycled material
II	〔A〕〔B〕 Stabilized〔C〕〔D1〕〔V〕 Recycled material	〔A〕〔B〕 Stabilized〔C〕〔D1〕〔D2〕〔V〕 Recycled material
III	〔A〕〔B〕 Stabilized〕〔D1〕〔V〕 Recycled material	〔A〕〔B〕〔C〕 Stabilized〔D1〕〔D2〕〔V〕 Recycled material

Compaction control

Performance rank	Upper embankment		Lower embankment
	Degree of compaction	Value of K_{30}	Degree of compaction
I	Average ≧95% (Minimum≧92%)	Average ≧110MN/m^3 (Minimum≧70MN/m^3)	Gravel : Average ≧90% (Minimum≧87%) Sand : Average ≧95% (Minimum≧92%)
II	Average ≧90% (Minimum ≧87%)	Average : 70≦K_{30}<110MN/m^3 (Minimum≧50～70MN/m^3) or Average ≧110MN/m^3 (Minimum≧70MN/m^3)	Average ≧90% (Minimum≧87%)
III	Average ≧90%	Average ≧70MN/m^3	Greater than 90%(Fc<20%) - - - - - - - - air content : v_a ・Fc≧50% v_a≦10% ・Fc 20 to 50% v_a≦15%

Sand replacement/RI

Plate loading test / FWD

Sand replacement/RI

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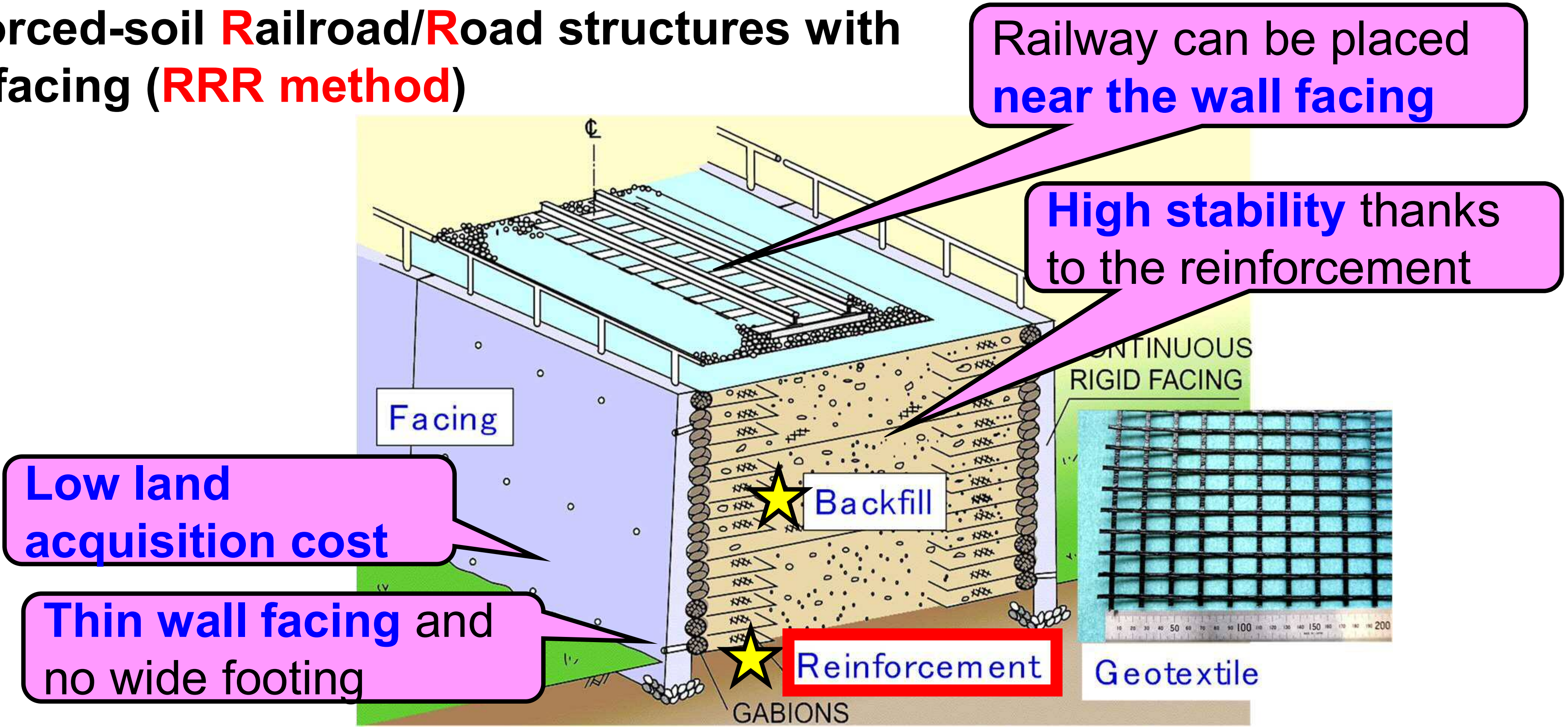
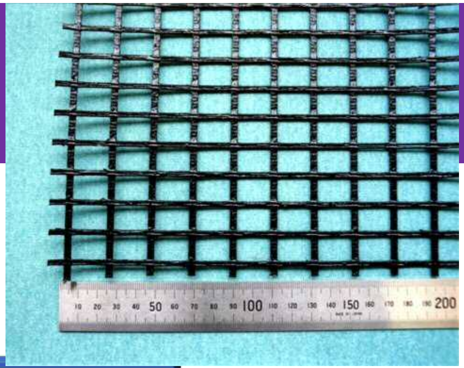
Geosynthetic-reinforced soil retaining wall

Reinforced-soil Railroad/Road structures with Rigid facing (RRR method)



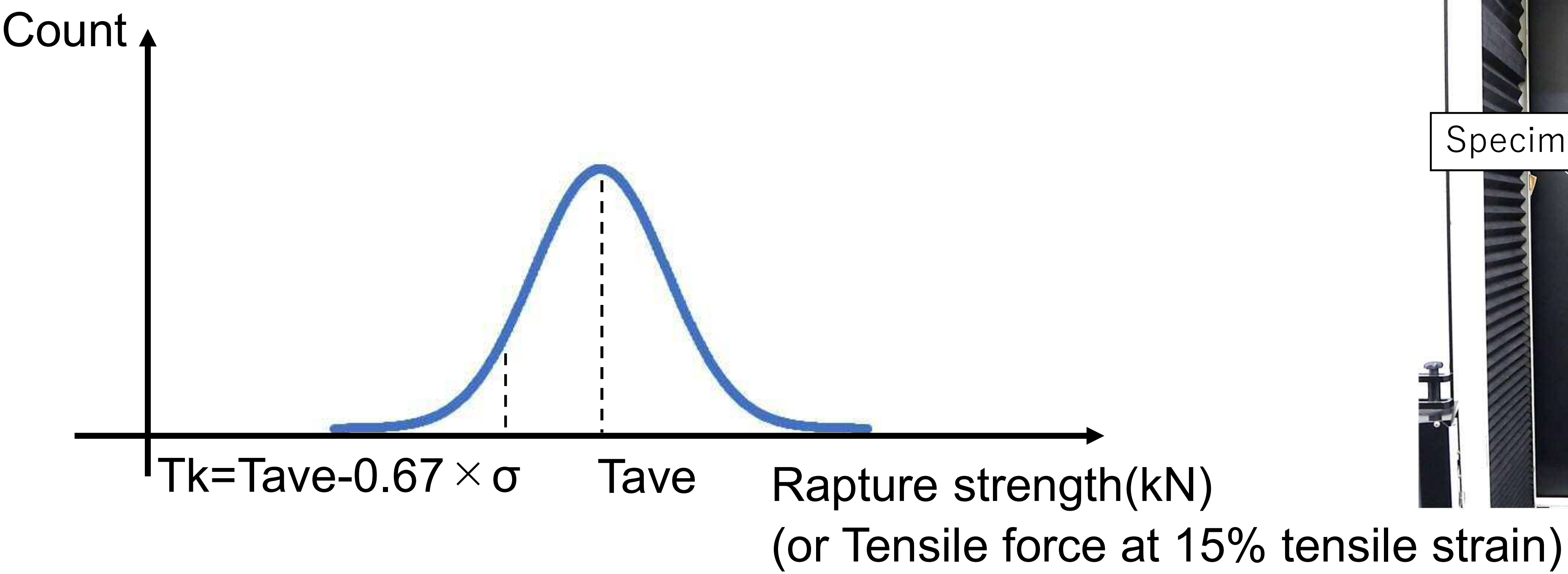
- **Composite structure** consisting of the **continuous rigid wall facing**, **backfill** and **reinforcement**.
- Wall facing is free from the settlement due to embankment construction thanks to the **staged construction**.

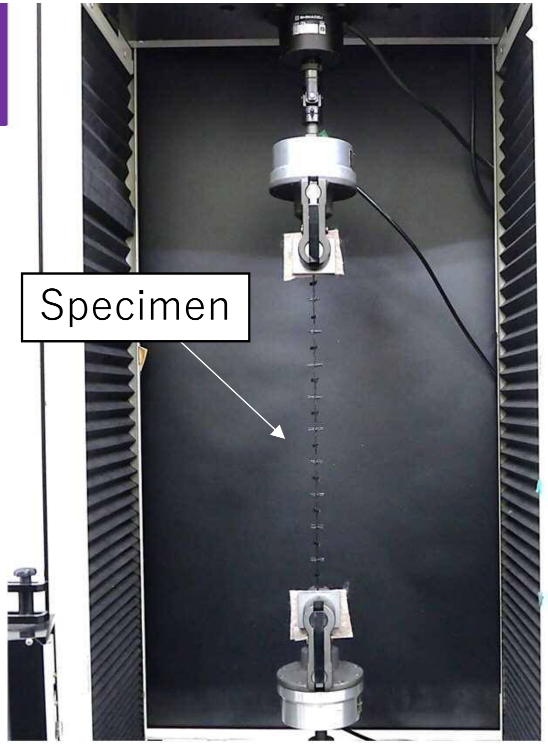
Reinforcements used in GRS RWs



Item	General actions	Variable action during construction	Actions including Level 2 seismic load	Remarks
Standard tensile strength	T_k(kN/m)			determined taking into account variability
Material correction factor	$\rho_m = 0.8$	$\rho_m = 0.8$	$\rho_m = 1.0$	–
Characteristic tensile strength	$T_a = \rho_m \cdot T_k$(kN/m)			–
Material factors	$f_{eg} = 0.4–0.7$	$f_{eg} = 0.6–0.95$	$f_{eg} = 0.7–1.0$	Depending on types of action, with α_i obtained experimentally
Design tensile strength	$T_d = f_{eg} \cdot T_a$(kN/m)			–

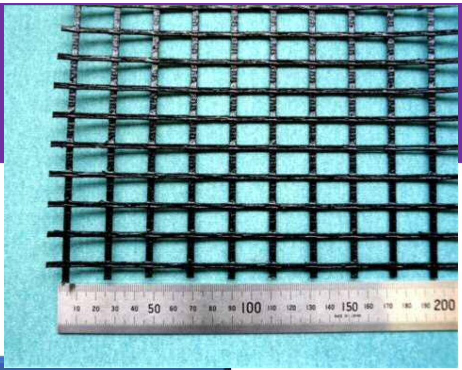
Standard Tensile strength





- Number of specimens (=number of tests)：n＝20
- Loading rate：5%／min
- Specimen length：40cm（clamp distance）
- Clamp type：parallel type air clamp
- Specimen width：1 grid element (geogrid), 5cm (geotextile sheet)
- Room temperature：25 ℃

Reinforcements used in GRS RWs



Item	General actions	Variable action during construction	Actions including Level 2 seismic load	Remarks
Standard tensile strength	T_k(kN/m)			determined taking into account variability
Material correction factor	$\rho_m = 0.8$	$\rho_m = 0.8$	$\rho_m = 1.0$	–
Characteristic tensile strength	$T_a = \rho_m \cdot T_k$(kN/m)			–
Material factors	$f_{eg} = 0.4–0.7$	$f_{eg} = 0.6–0.95$	$f_{eg} = 0.7–1.0$	Depending on types of action, with α_i obtained experimentally
Design tensile strength	$T_d = f_{eg} \cdot T_a$(kN/m)			–

Reinforcements used in GRS RWs

Item	General actions	Variable action during construction	Actions including Level 2 seismic load	Remarks
Standard tensile strength	T_k(kN/m)			determined taking into account variability
Material correction factor	$\rho_m = 0.8$	$\rho_m = 0.8$	$\rho_m = 1.0$	–
Characteristic tensile strength	$T_a = \rho_m \cdot T_k$(kN/m)			–
Material factors	$f_{eg} = 0.4–0.7$	$f_{eg} = 0.6–0.95$	$f_{eg} = 0.7–1.0$	Depending on types of action, with α_i obtained experimentally
Design tensile strength	$T_d = f_{eg} \cdot T_a$(kN/m)			–

Evaluation of reduction factor

Action combination	Reduction factors（○：Considered）				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	–	–
Permanent action＋variable action (train)	○	○	–	–	○
Permanent action＋seismic action（L1 seismic ground motion）＋secondary variable action	○	○	–	○	–
Permanent action＋seismic action（L2 seismic ground motion）＋secondary variable action	○	○	–	○	–
During construction	–	○	–	–	–

α_1 ：Reduction factor considering alkaline resistance

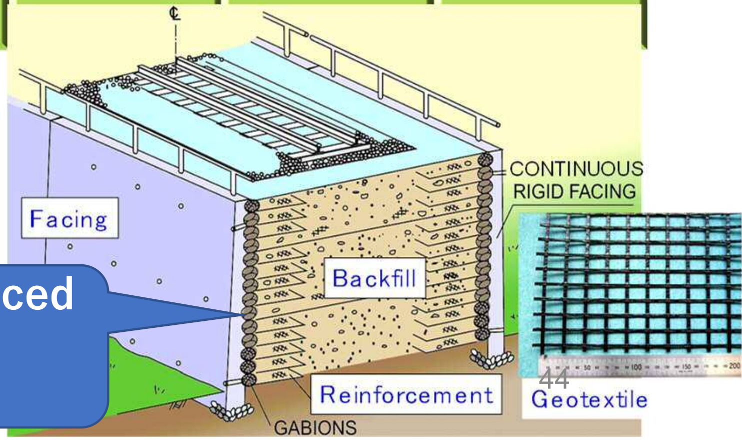
α_2 ：Reduction factor related to damage during construction

α_3 ：Reduction factor related to creep

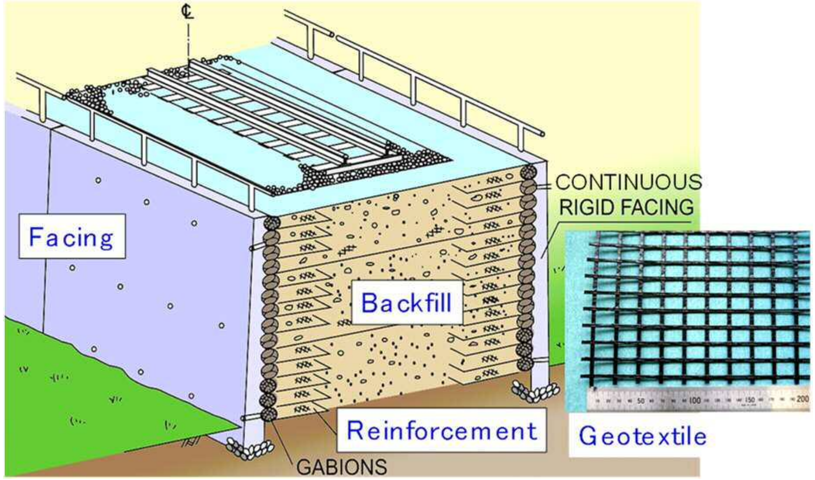
α_4 ：Reduction factor for momentary load

α_5 ：Reduction factor related to train load

Reinforcement are placed in high alkaline circumstance



Test to evaluate reduction factor a1(Effect of alkaline reaction)



Submersion conditions

-Alkaline solution：aqueous solution of calcium hydroxide

-Controlled temperature：50℃

-Submersion time：90days

- ✓ The PH of newly cast-in-place concrete is about 12, and it reduces with time. The PH of 12 is kept about 2 years.
- ✓ Based on the deterioration process, the rapture strength of the material immersed in the solution of PH12 for 700 days at temperature of 20 degree in Celsius was evaluated.

Reduction factor a1
=Tk after submersion/Tk without deterioration

An increase in temperature of 10℃ is deemed equivalent to a 2-fold increase in alkalinization rate（e.g., a submersion at a controlled temperature of 50℃ corresponds to a 23 ＝8 –fold increase in alkalinization i.e. to a 90-day submersion

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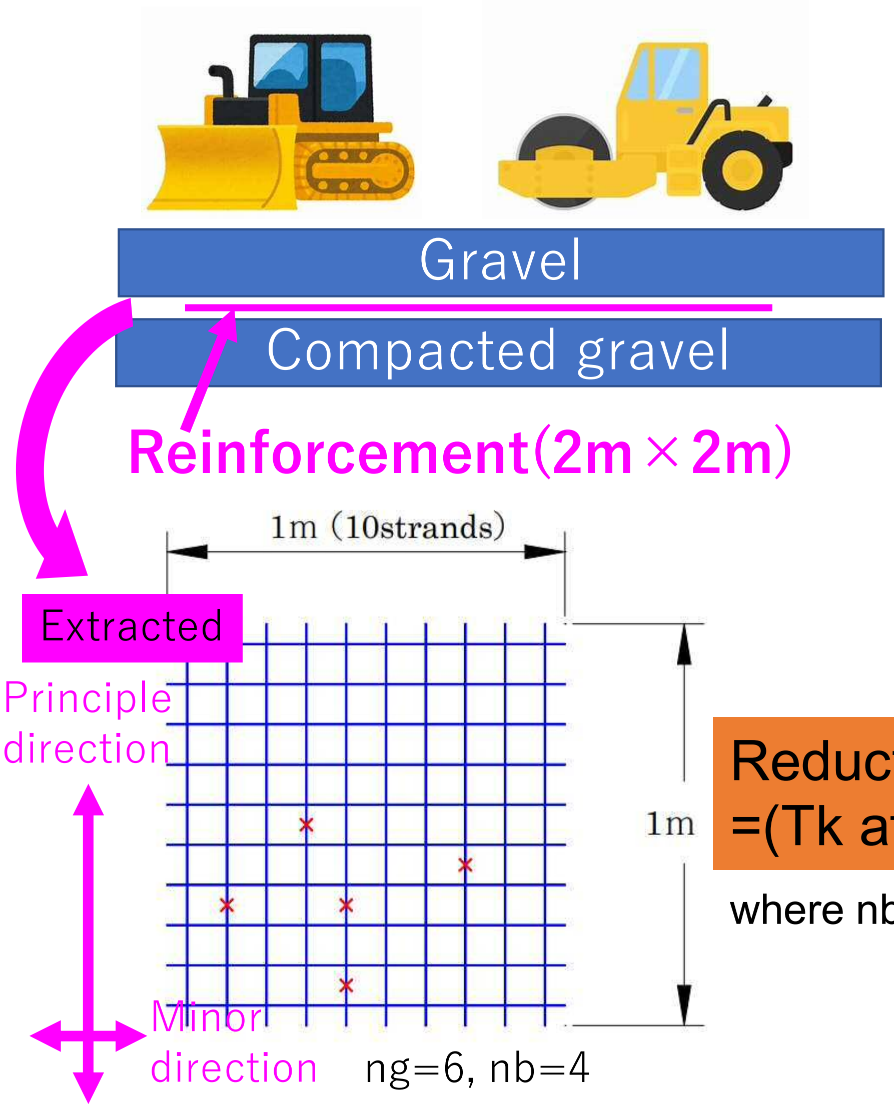
Evaluation of reduction factor

Action combination	Reduction factors （○：Considered）				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	－	－
Permanent action＋variable action (train)	○	○	－	－	○
Permanent action＋seismic action （L1 seismic ground motion） ＋secondary variable action	○	○	－	○	－
Permanent action＋seismic action （L2 seismic ground motion） ＋secondary variable action	○	○	－	○	－
During construction	－	○	－	－	－

α_1 ：Reduction factor considering alkaline resistance
α_2 ：Reduction factor related to damage during construction
α_3 ：Reduction factor related to creep
α_4 ：Reduction factor for momentary load
α_5 ：Reduction factor related to train load

Reinforcement is damaged by compaction

Test to evaluate reduction factor a2 (Effect of compaction)



- ✓ The reinforcement is subjected to the load in construction processes.
- ✓ In evaluating reduction factor a2, actual construction process achieving sufficient compaction degree is simulated.

Reduction factor a2
=(Tk after compaction/Tk without compaction)×ng/(ng+nb)

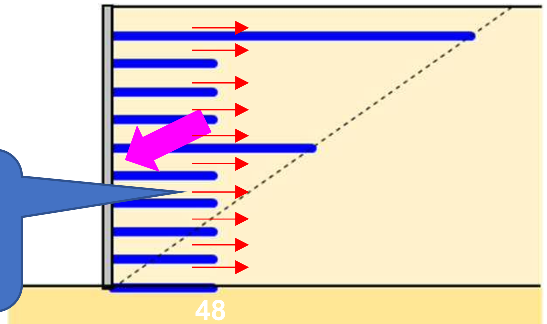
where nb is the number of damaged strands, ng is the number of intact strands

Evaluation of reduction factor

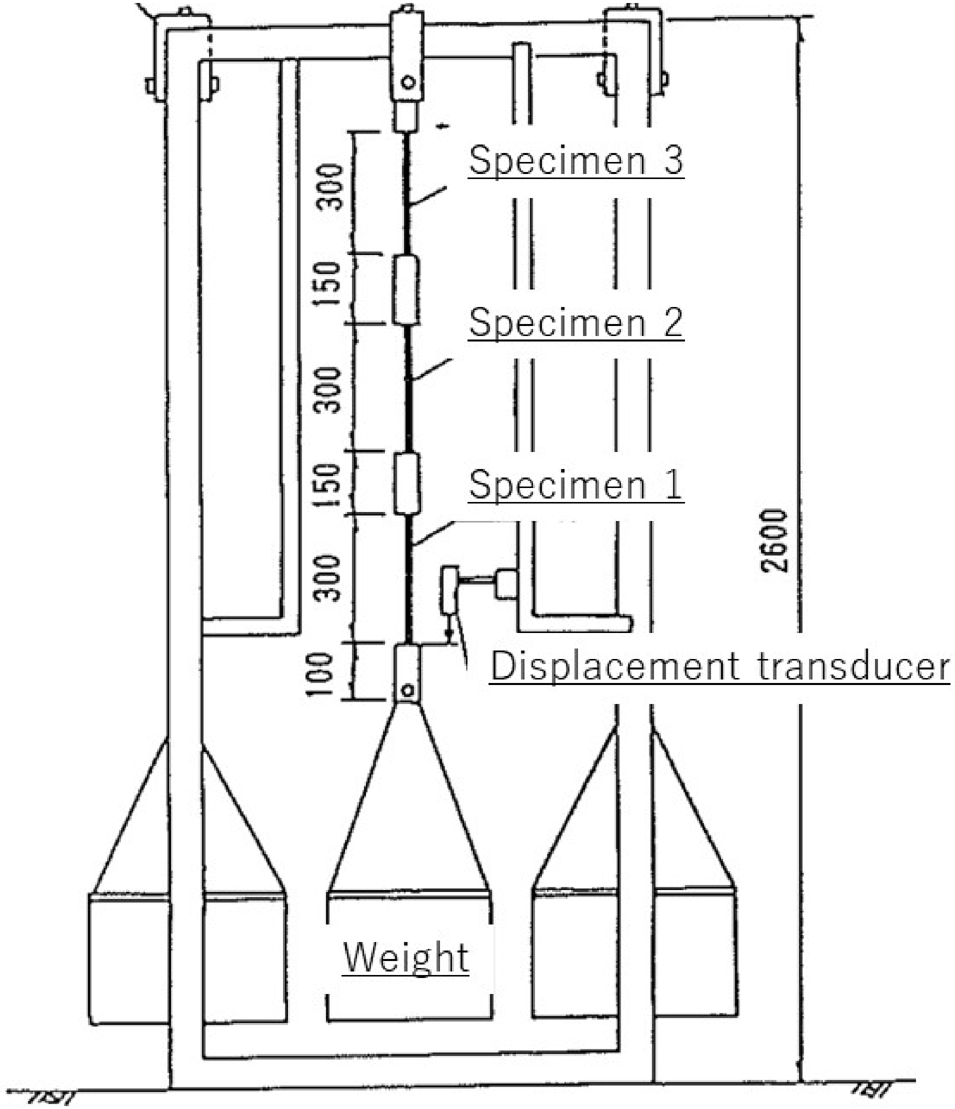
Action combination	Reduction factors （○：Considered）				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	－	－
Permanent action＋variable action (train)	○	○	－	－	○
Permanent action＋seismic action （L1 seismic ground motion） ＋secondary variable action	○	○	－	○	－
Permanent action＋seismic action （L2 seismic ground motion） ＋secondary variable action	○	○	－	○	－
During construction	－	○	－	－	－

α_1 ：Reduction factor considering alkaline resistance
α_2 ：Reduction factor related to damage during construction
α_3 ：Reduction factor related to creep
α_4 ：Reduction factor for momentary load
α_5 ：Reduction factor related to train load

Reinforcement are subjected to sustained loading (creep loading)



Test to evaluate reduction factor a3(Effect of creep)

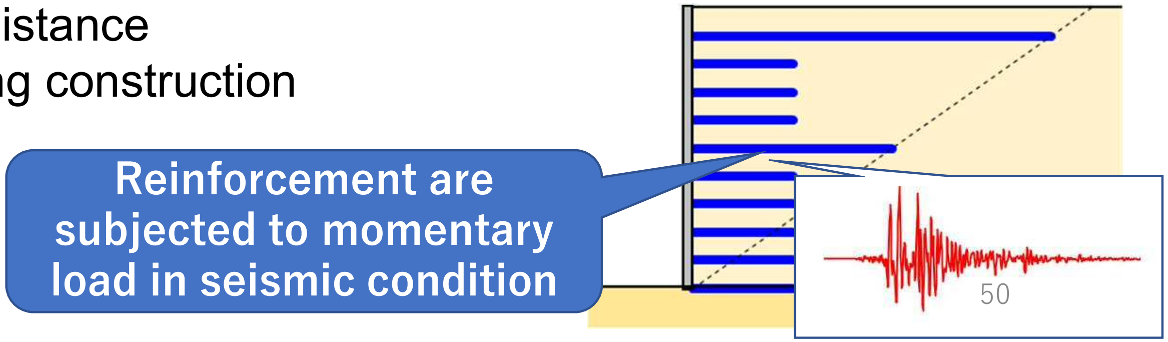


- By creep loading test, creep loading level TL is investigated.
- In the creep loading test, dead weight are applied to the three specimens.
- TL is determined as the tensile force in which strain increment in the specified duration satisfies the limitation.
- Creep reduction factor a3 is determined as the ratio of TL to Tk.

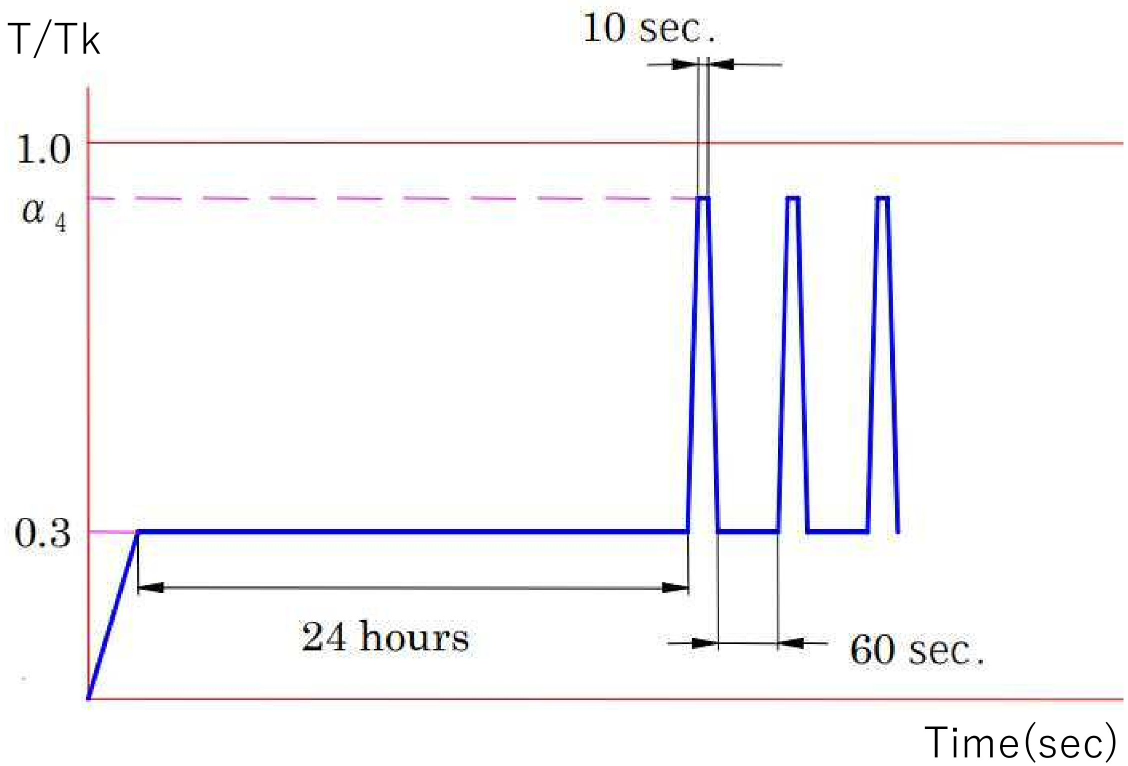
Evaluation of reduction factor

Action combination	Reduction factors (○ : Considered)				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	−	−
Permanent action + variable action (train)	○	○	−	−	○
Permanent action + seismic action (L1 seismic ground motion) + secondary variable action	○	○	−	○	−
Permanent action + seismic action (L2 seismic ground motion) + secondary variable action	○	○	−	○	−
During construction	−	○	−	−	−

α_1 : Reduction factor considering alkaline resistance
α_2 : Reduction factor related to damage during construction
α_3 : Reduction factor related to creep
α_4 : Reduction factor for momentary load
α_5 : Reduction factor related to train load



Test to evaluate reduction factor a4 (Effect of momentary load)

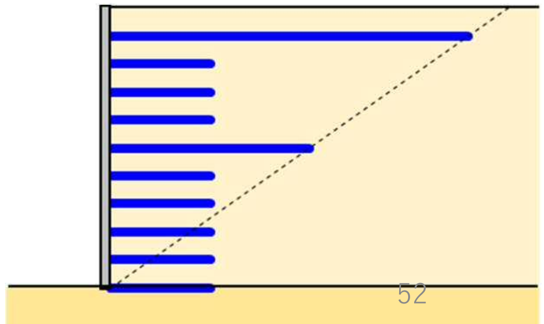


The impact loading reduction factor（α４）corresponds to the maximum load level（Ｔｅ／TK）for which 3 specimens do not exhibit failure nor exceed 15% tensile strains.

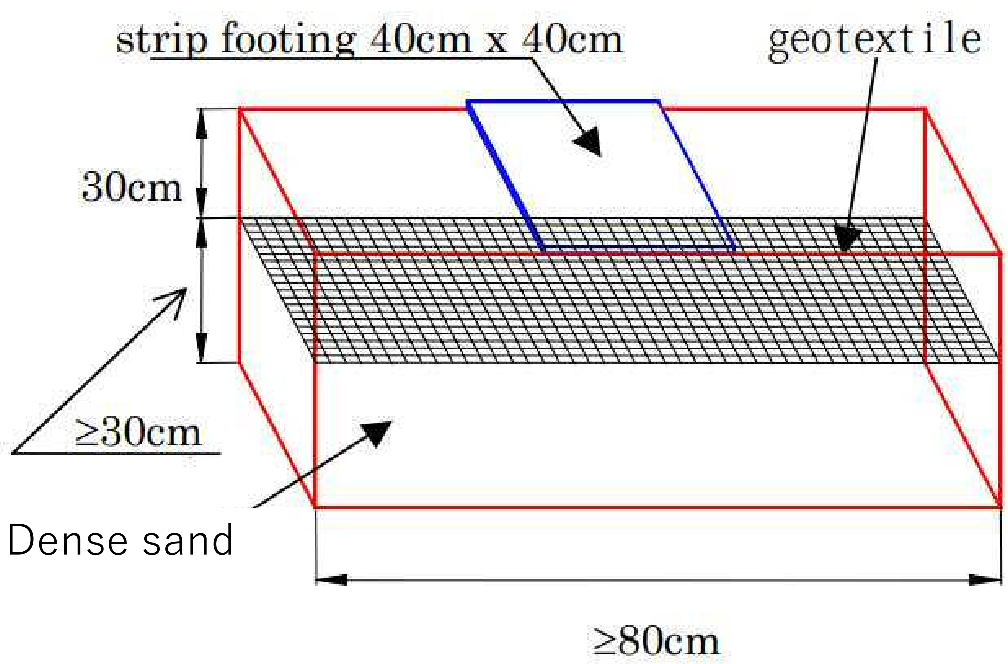
Evaluation of reduction factor

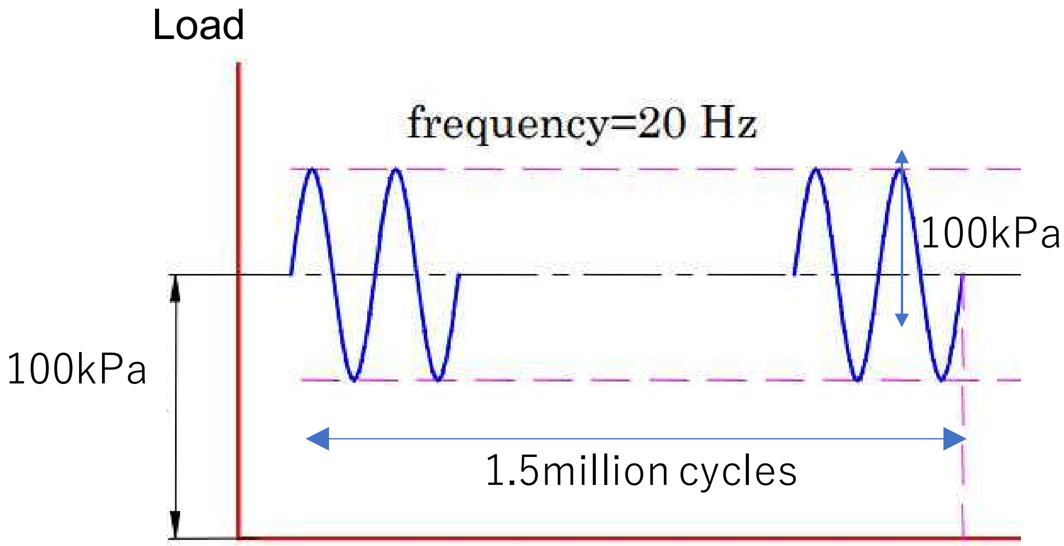
Action combination	Reduction factors (○ : Considered)				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	―	―
Permanent action + variable action (train)	○	○	―	―	○
Permanent action + seismic action (L1 seismic ground motion) + secondary variable action	○	○	―	○	―
Permanent action + seismic action (L2 seismic ground motion) + secondary variable action	○	○	―	○	―
During construction	―	○	―	―	―

α_1 : Reduction factor considering alkaline resistance
α_2 : Reduction factor related to damage during construction
α_3 : Reduction factor related to creep
α_4 : Reduction factor for momentary load
α_5 : Reduction factor related to train load



Test to evaluate reduction factor a5 (Effect of cyclic train load)

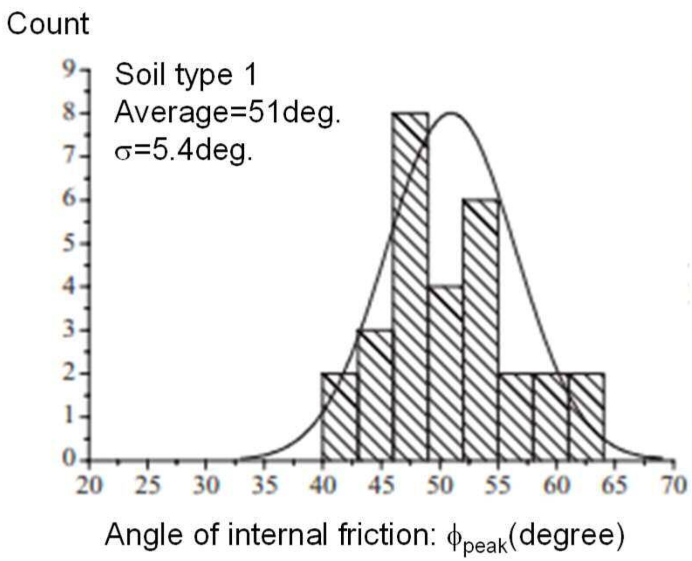


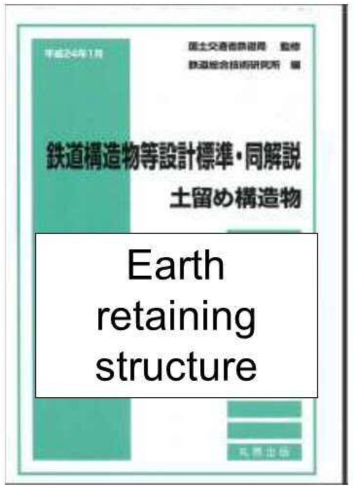


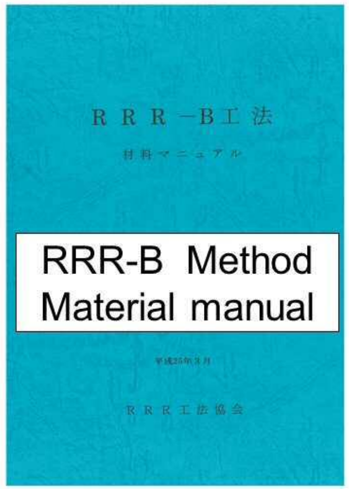
- ✓ The reinforcement are placed beneath the strip footing with cover soil thickness of just 30cm.
- ✓ After application of cyclic load, the reinforcement is extracted and tested to obtain the value of Tk after cyclic load.
- ✓ Reduction factor a5 is expressed as the ratio of Tk after cyclic load to Tk without cyclic load.

Summary 2

1. Railway design standard for earth retaining structures, earth structures, and material manuals for RRR-GRS structures regulates the applicable materials and embankment compaction management for RRR-GRS structures.
2. Based on the triaxial compression test result, design soils strength are set depending on the soil type, while the effect of compaction achieved by the construction is reflected.
3. Applicable embankment material and compaction management value are regulated depending on the performance rank and part of the structures.



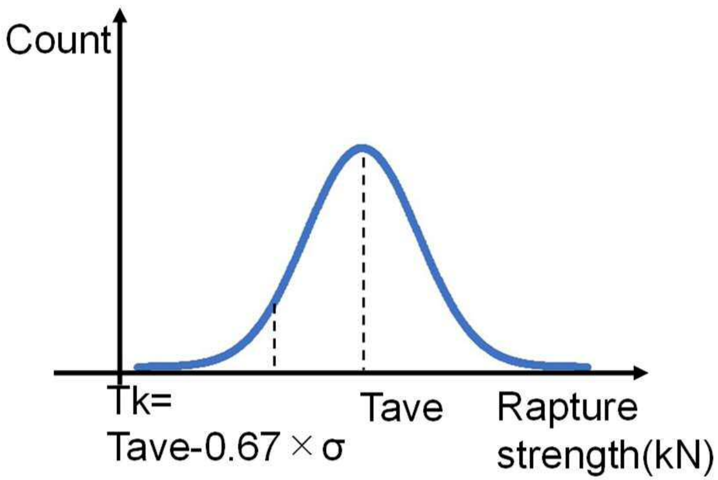




PF rank	Upper part of embankment
I	〔A〕 Stabilized〔B〕 Recycled material
II	〔A〕〔B〕 Stabilized〔C〕〔D1〕〔V〕 Recycled material
III	〔A〕〔B〕 Stabilized〕〔D1〕〔V〕 Recycled material

Summary 2 (contd.)

1. Reinforcement materials applicable to the use of RRR-GRS structures are regulated by material manual.
2. Standard tensile strength Tk is set based on material variation, while additional safety margin of 20 % is also considered to set the characteristic design value Ta.
3. Reduction factors a1 to a5 are also considered based on the combination of action to achieve design tensile strength.
4. Test procedures to obtain reduction factors are briefly introduced, for the detail, please refer to the design manual for RRR-GRS structures (ed. RRR association).



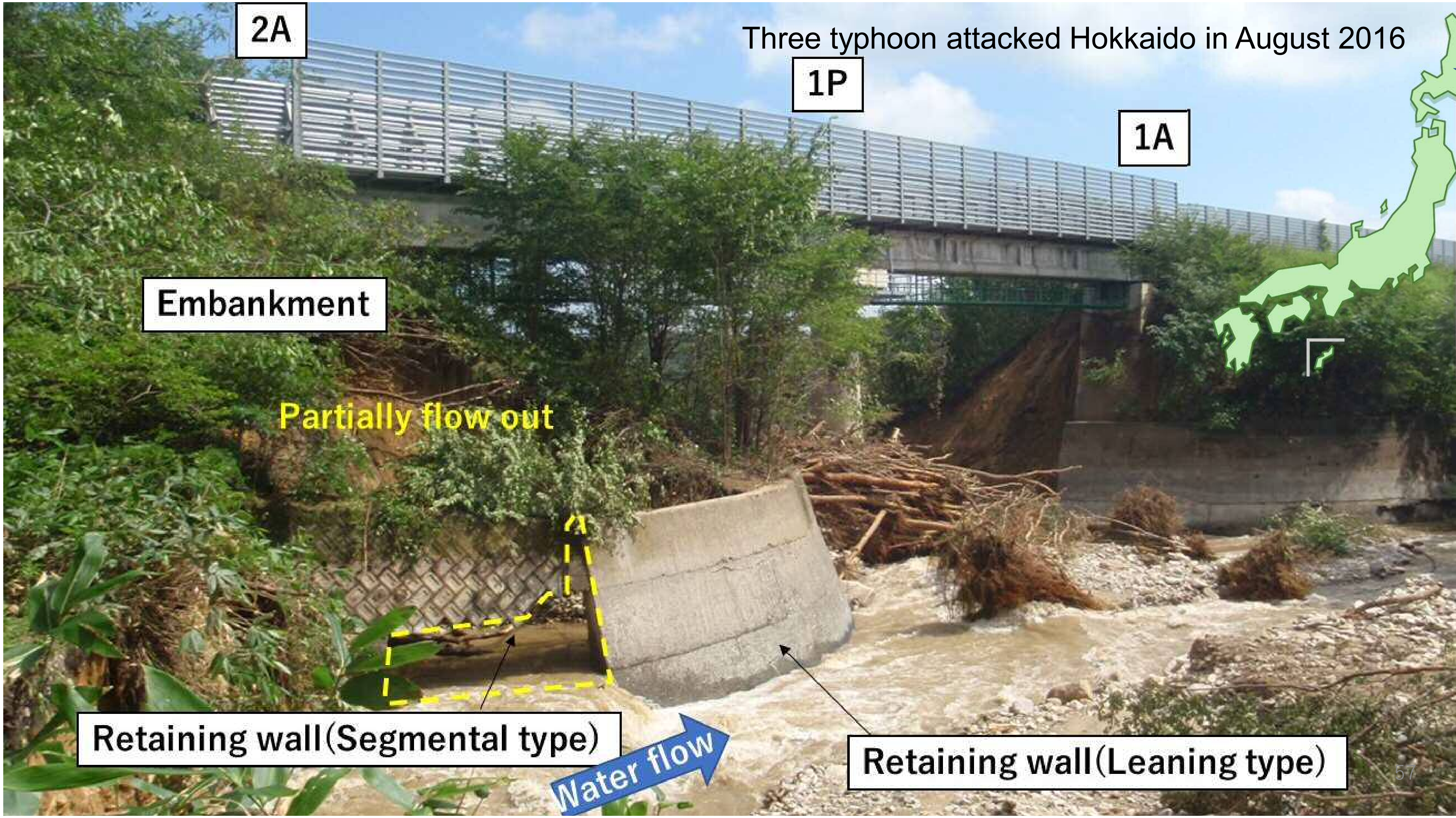
Action combination	Reduction factors (○ : Considered)				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	−	−
Permanent action + variable action (train)	○	○	−	−	○
Permanent action + seismic action (L1 seismic ground motion) + secondary variable action	○	○	−	○	−
Permanent action + seismic action (L2 seismic ground motion) + secondary variable action	○	○	−	○	−
During construction	−	○	−	−	−

OUTLINE

1. Design standard of Japanese railway
2. Material regulation and construction of GRS retaining wall
3. Recent application for disaster retrofitting
4. Summary
5. Appendix to introduce applied project outside of Japan.

Case of retaining wall damaged by river water flow

Case1

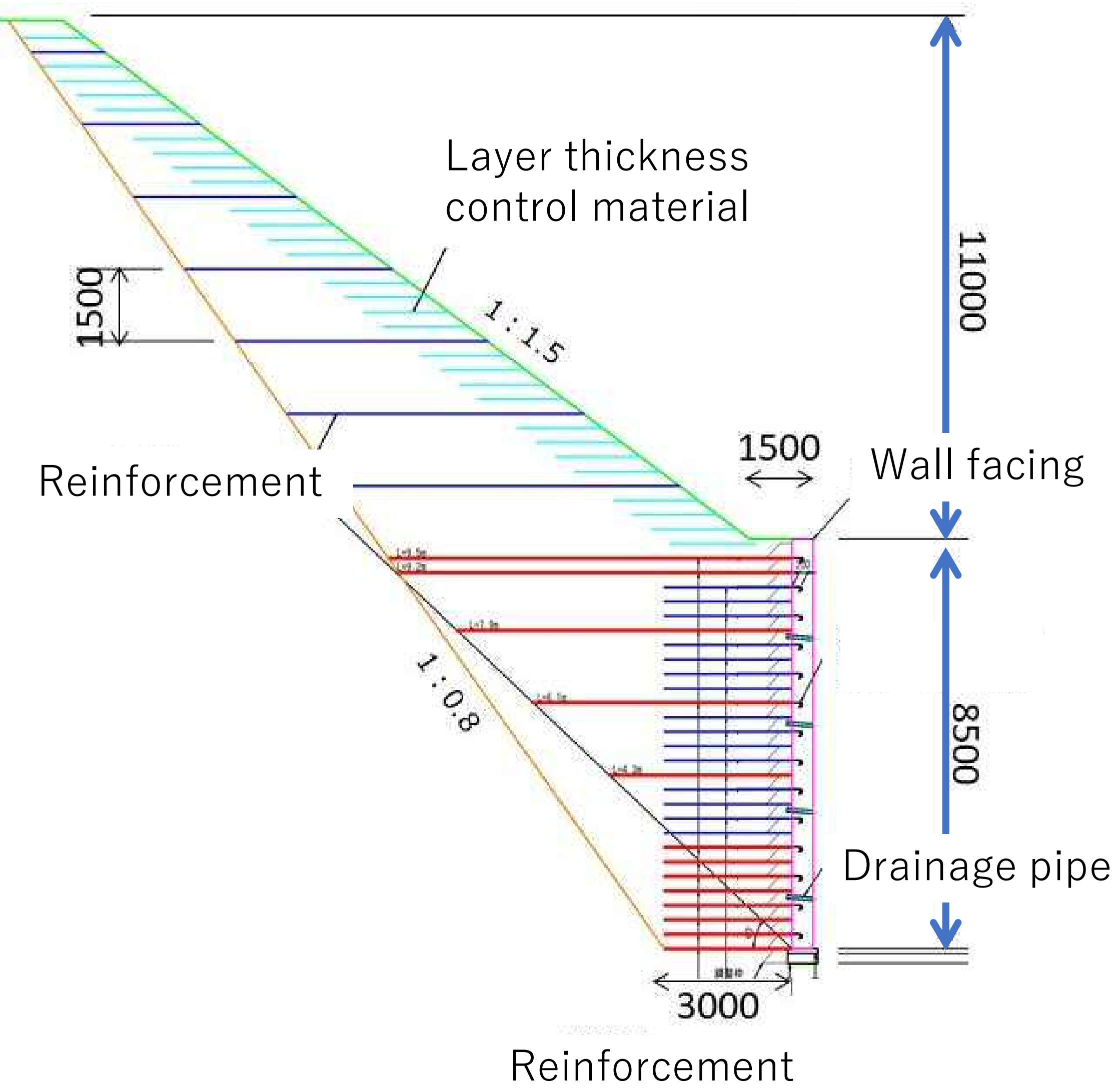


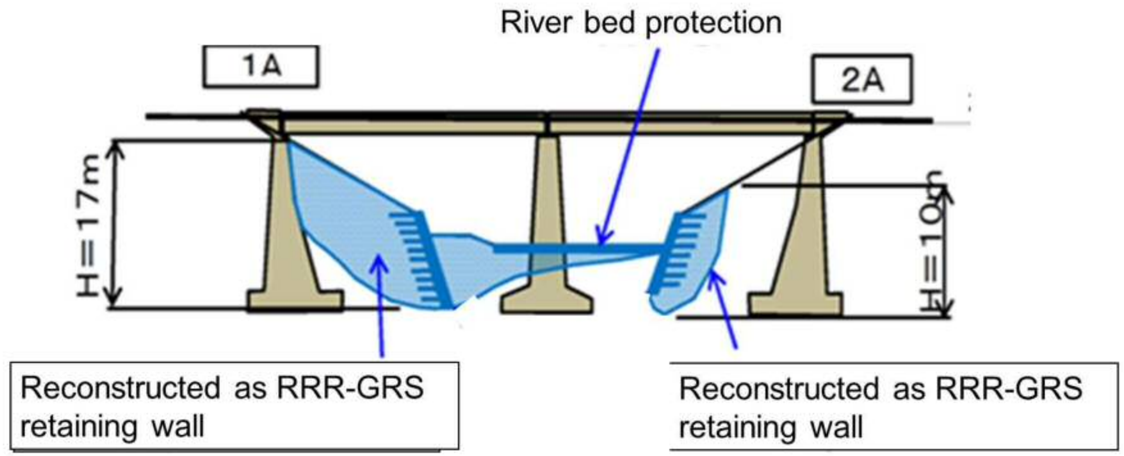
Case of retaining wall damaged by river water flow

Case1

Case of retaining wall damaged by river water flow

Case1





- Reinforcement length L is 3.0m.
- Every 1.5 m, the reinforcement is extended to the active failure angle of 40 degree.
- Design tensile strength is 60 kN/m (Red) and 30 kN/m (Blue).

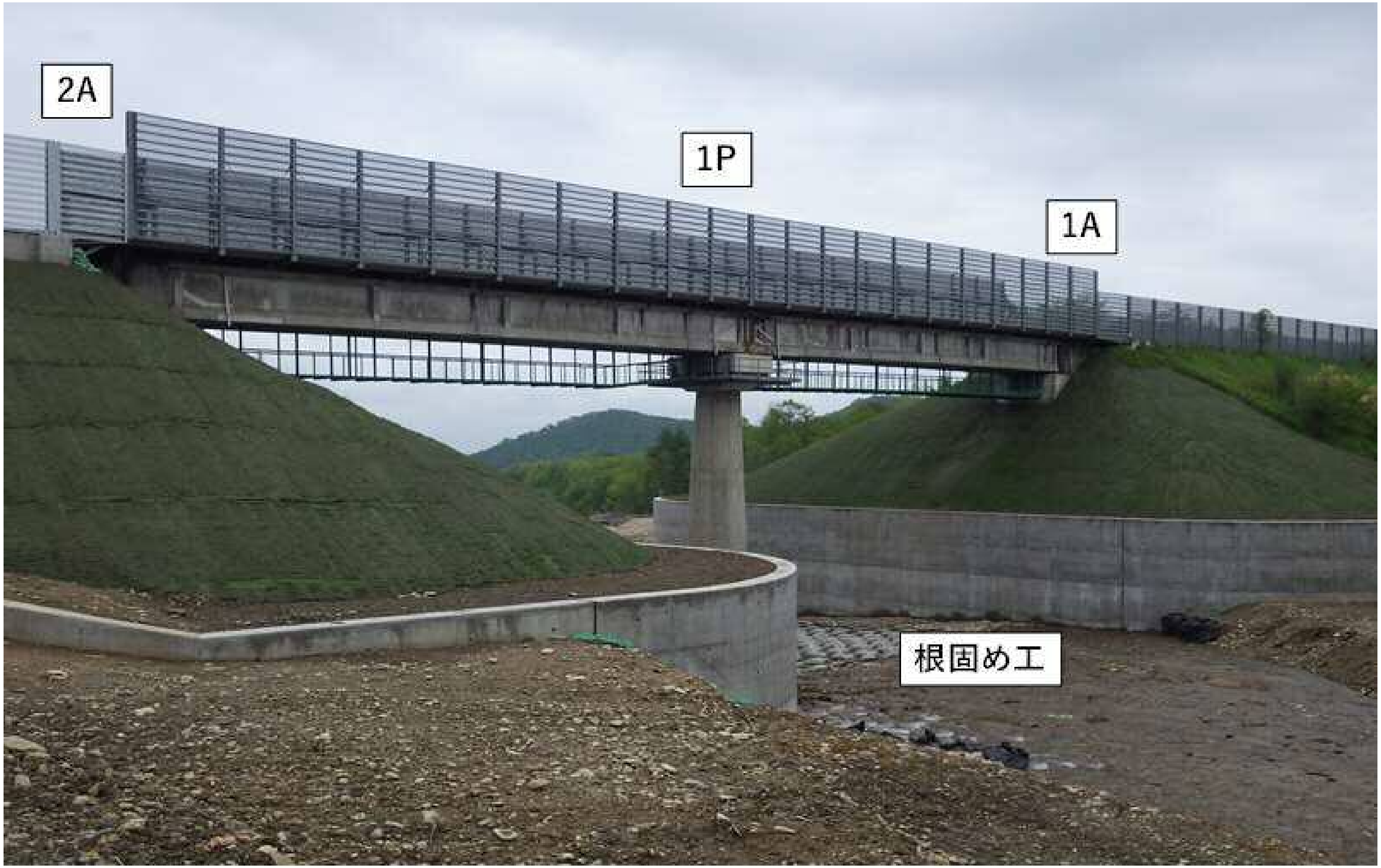
Case of retaining wall damaged by river water flow

Case1

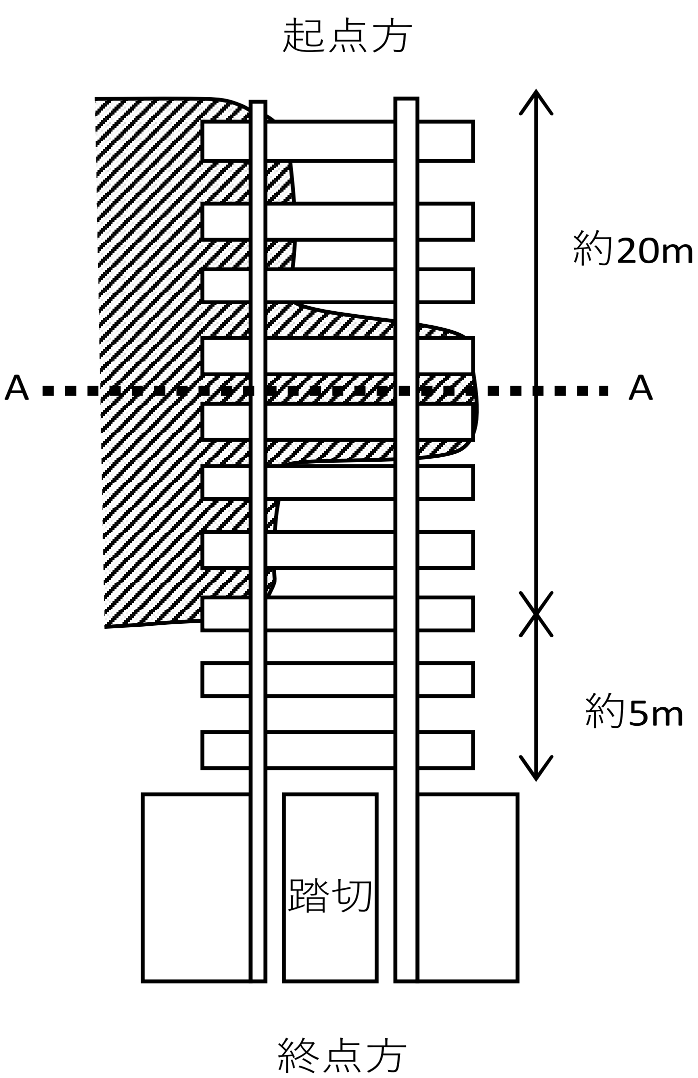
- Backfill compaction ： Dc=90%, K_{30}=70MN/m^3

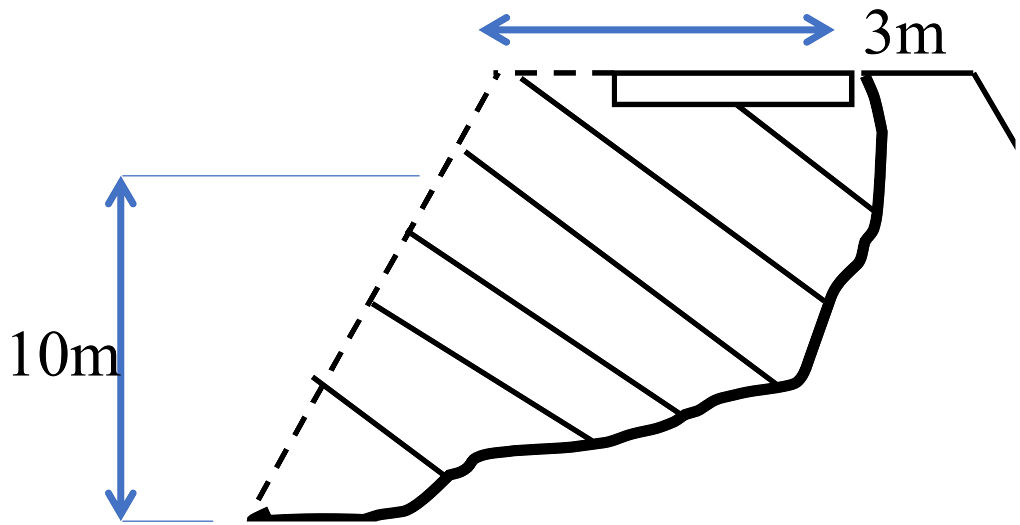
Case of retaining wall damaged by river water flow

Case1

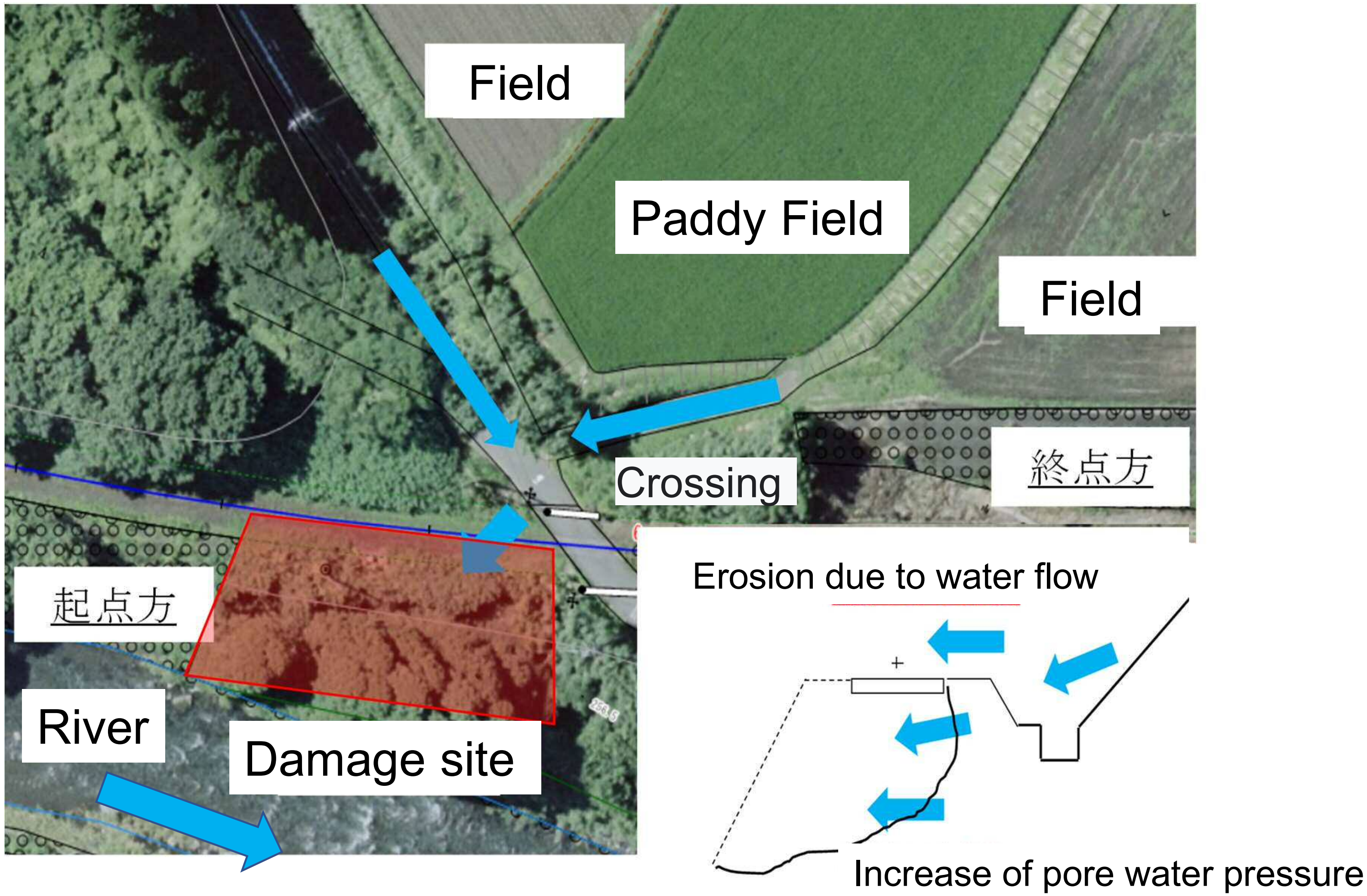


Case of retaining wall damaged by heavy rain fall Case2





Case of retaining wall damaged by heavy rain fall Case2



Case of retaining wall damaged by heavy rain fall Case2

- Height extends 10m.
- There was a land restriction.

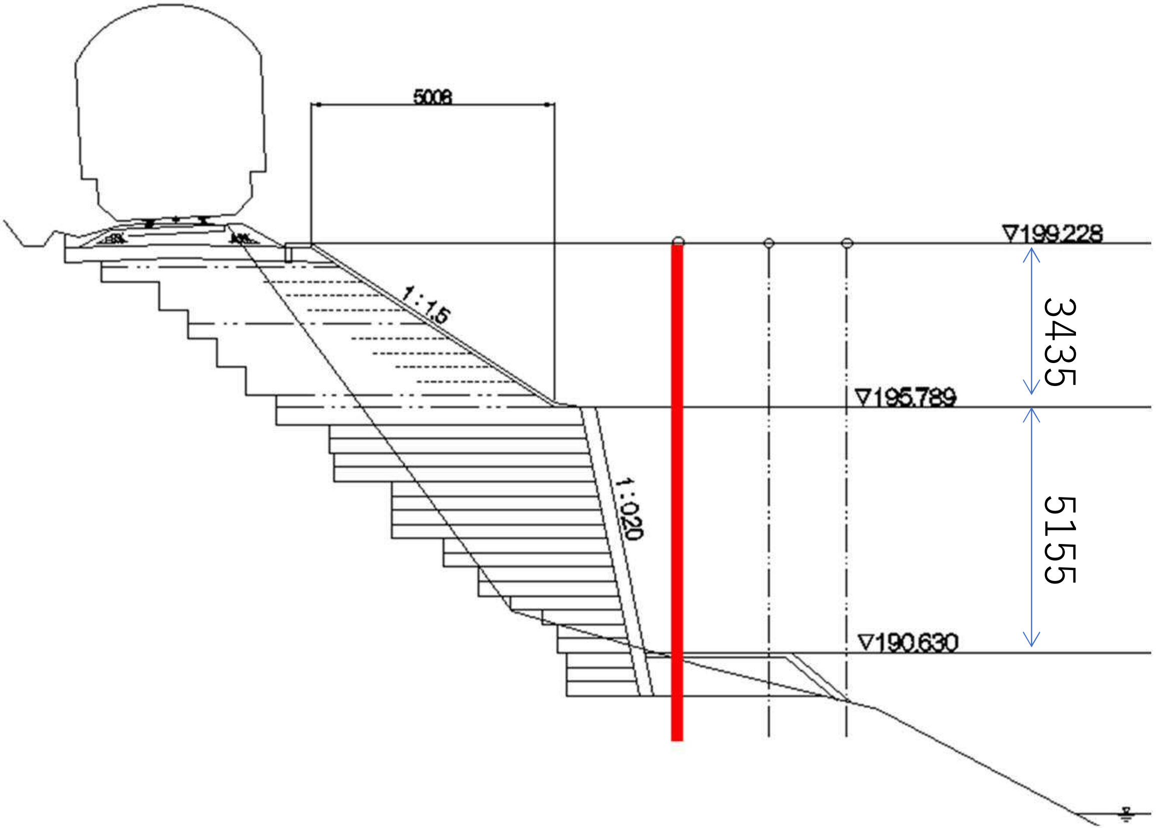
⇒Application of RRR-GRS wall.

- Due to coordination with relevant local governments and requests from residents along the line, it is necessary to resume operation in mid-August(1.5 month for reconstruction work).

The normal construction process does not satisfy the above requirement.

⇒Specifications for temporally RRR-GRS wall is adopted for the service supply before completion of RC facing.

Case of retaining wall damaged by heavy rain fall Case2



Specification of temporally RRR-GRS wall

- ✓ Inclination of wall facing (1:0.2)
- ✓ All reinforcement is extended to existing embankment

Embankment material

- ✓ To enhance the drainage, crushed stone (C-40) is used as embankment material.

A-group material

Case of retaining wall due to heavy rain fall

Case2

1. Up to reopening service supply

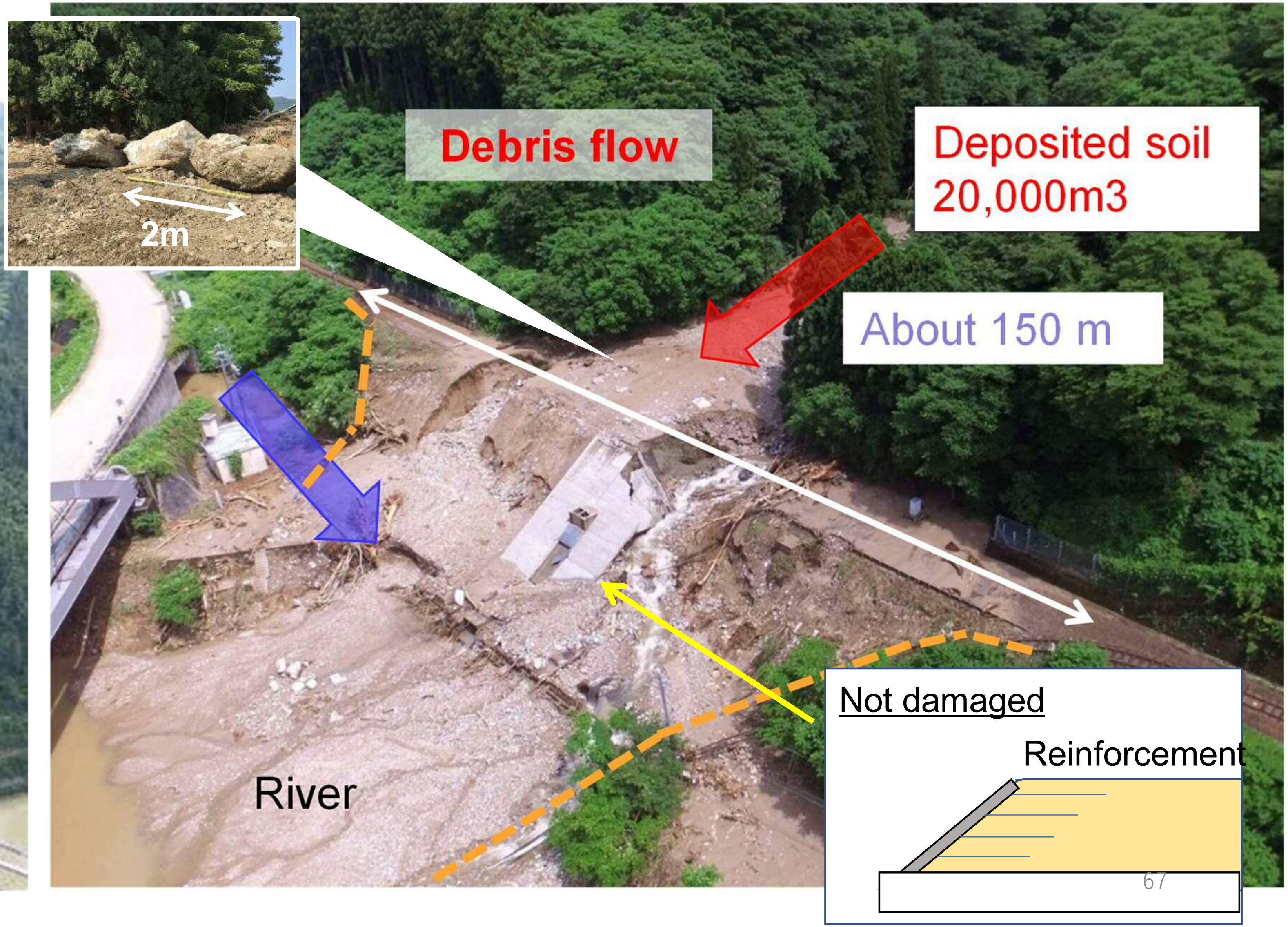



2. Wall facing and slope protection work after reopening service supply

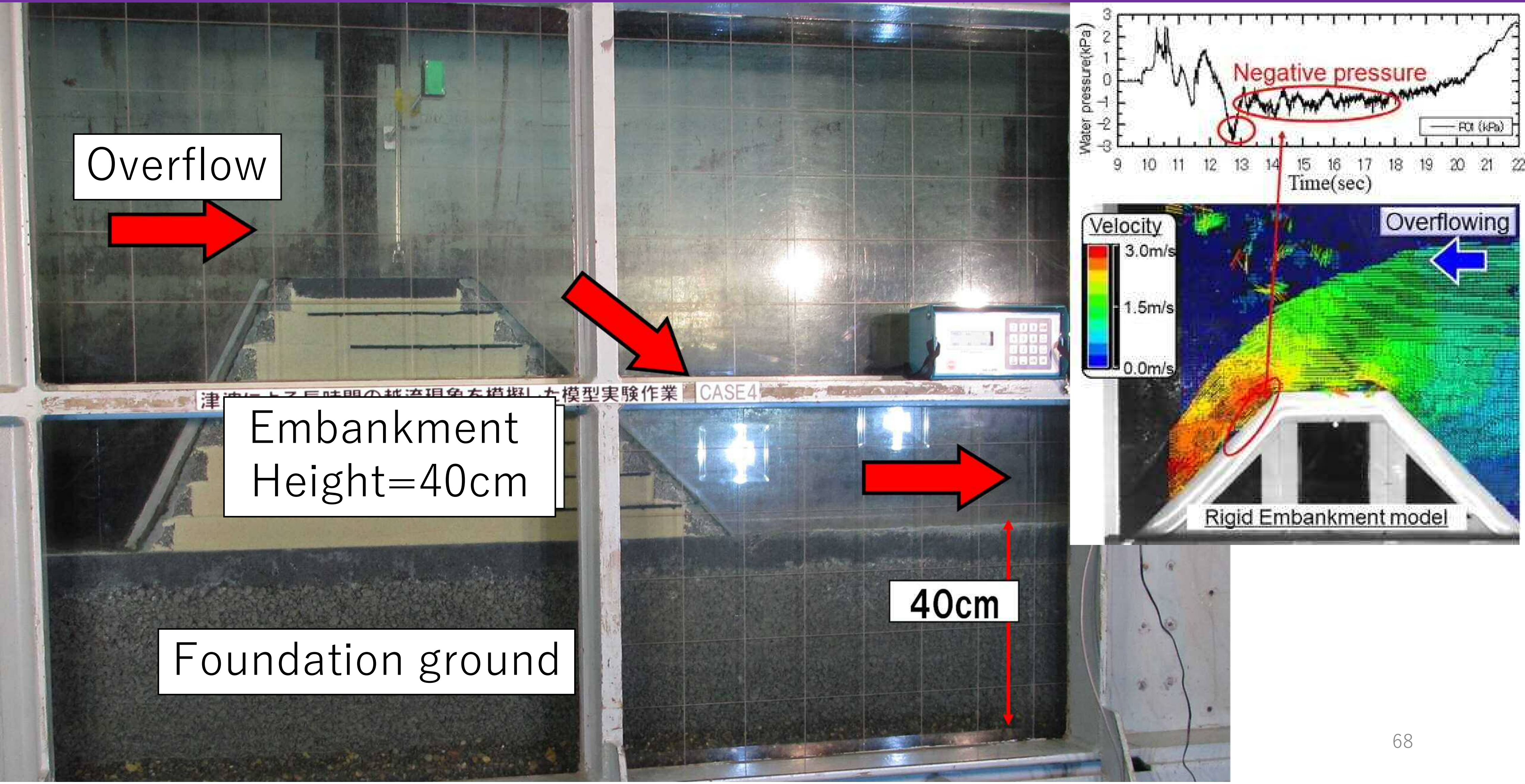



Case of embankment damaged by outflow

Case3

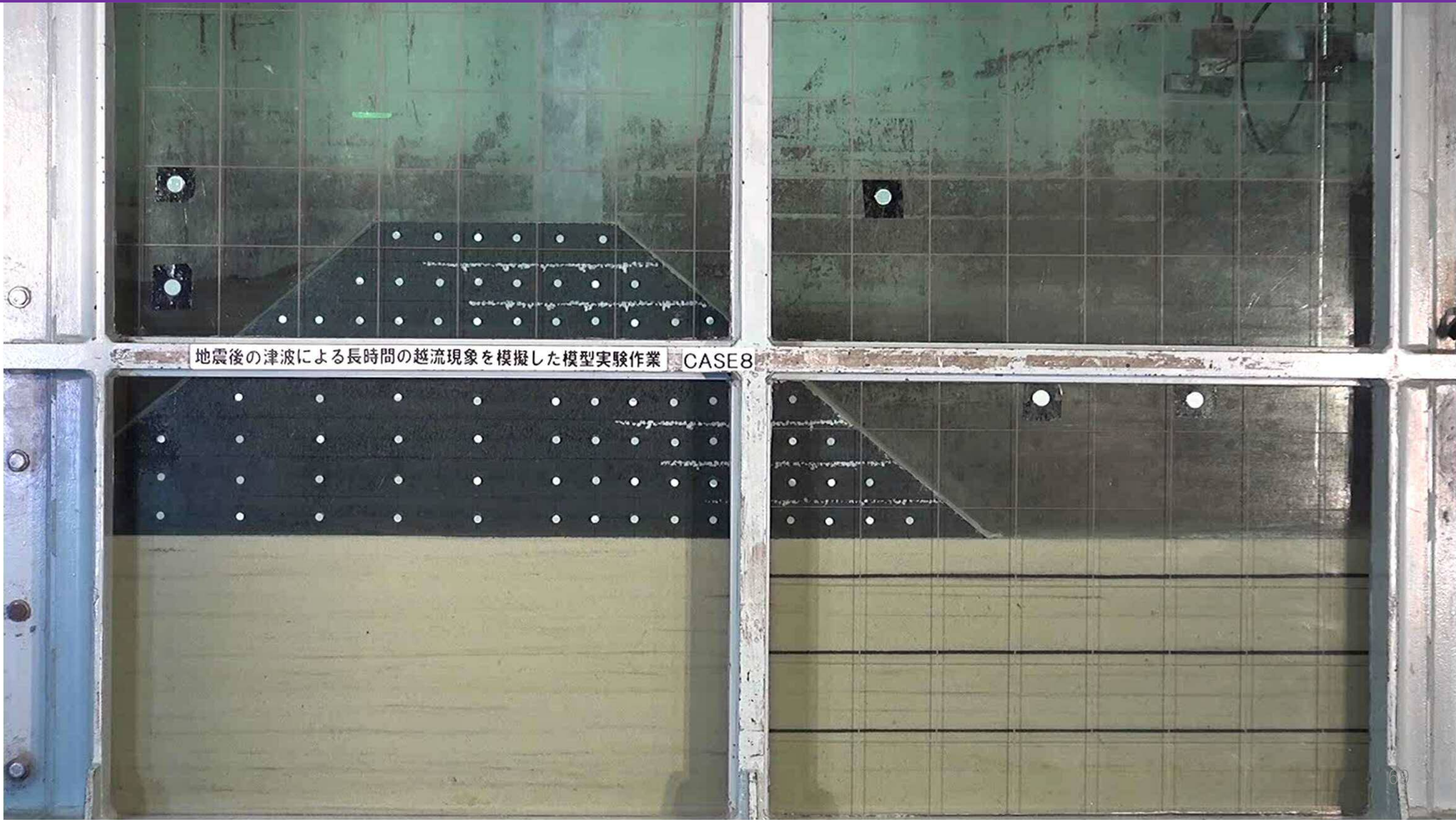


Case of embankment damaged by overflow



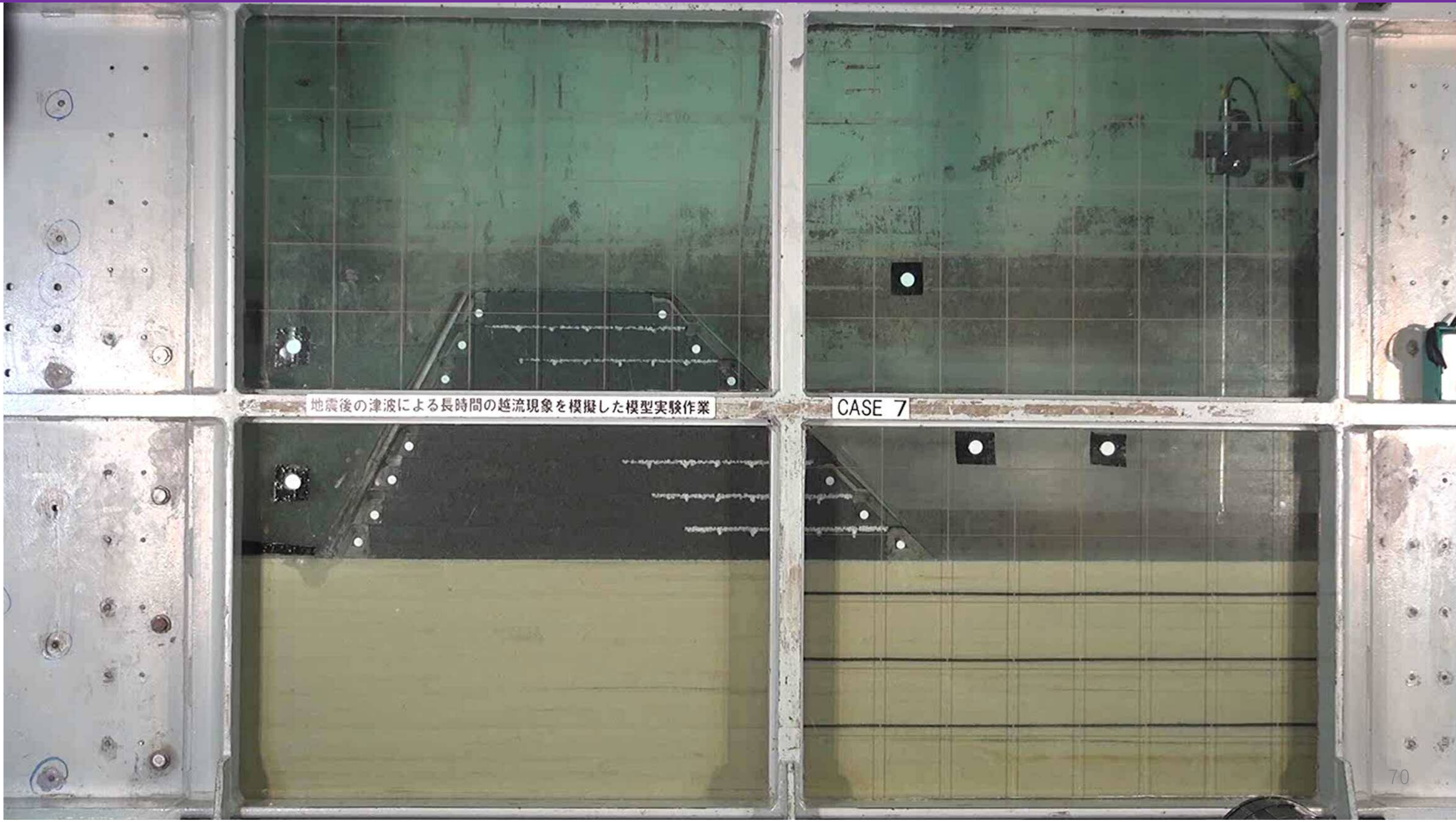
Case of embankment damaged by overflow

Case3



Case of embankment damaged by overflow

Case3



Case of embankment damaged by outflow

Case3

■ Specification of embankment

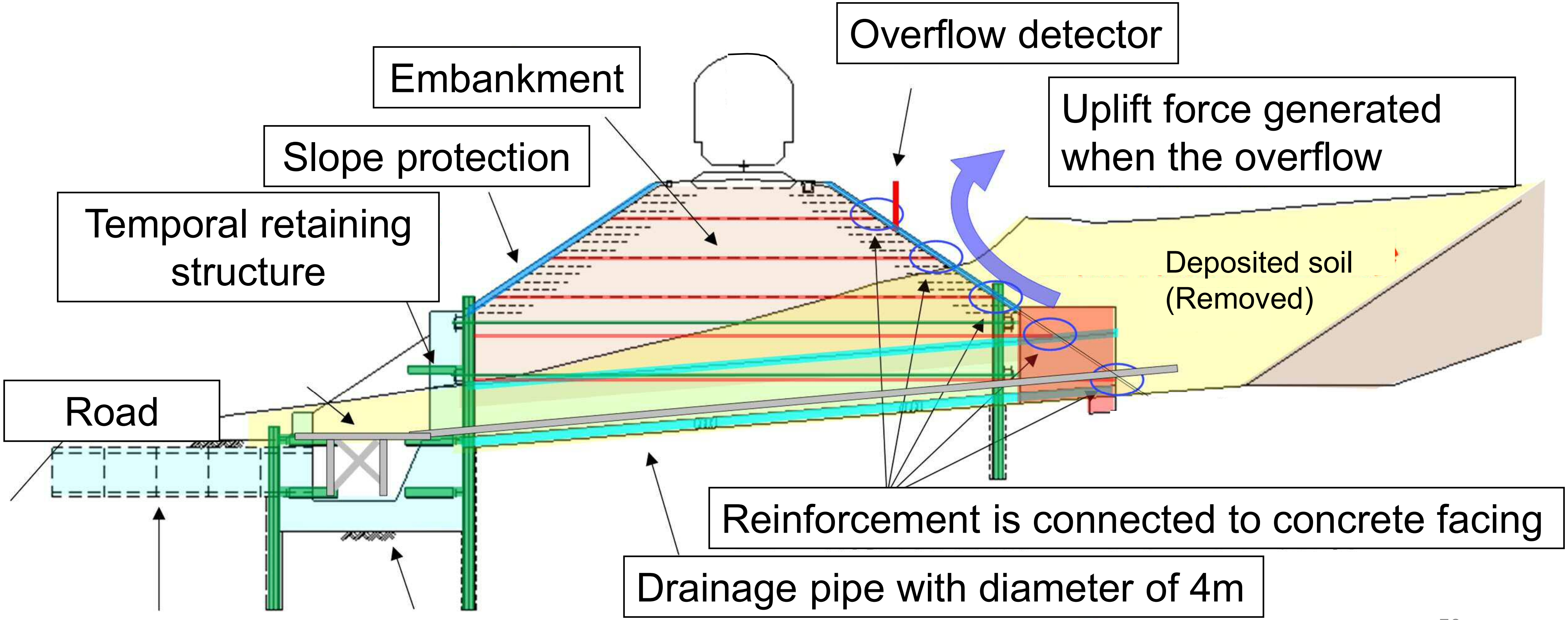
- Drainage pipe with diameter of 4 m is adopted to achieve drainage at the occurrence of debris flow while the 100-year rainfall probability is considered.
- The arrangement of the reinforcement is set by following the specification of performance rank Ⅰ,while the performance rank of embankment is Ⅲ.

■ Specification of slope protection

- Cast in place concrete facing is adopted to protect the embankment from the erosion.
- Reinforcement is anchored to the concrete facing to resist the uplift force induced by the outflow.

Case of embankment damaged by outflow

Case3

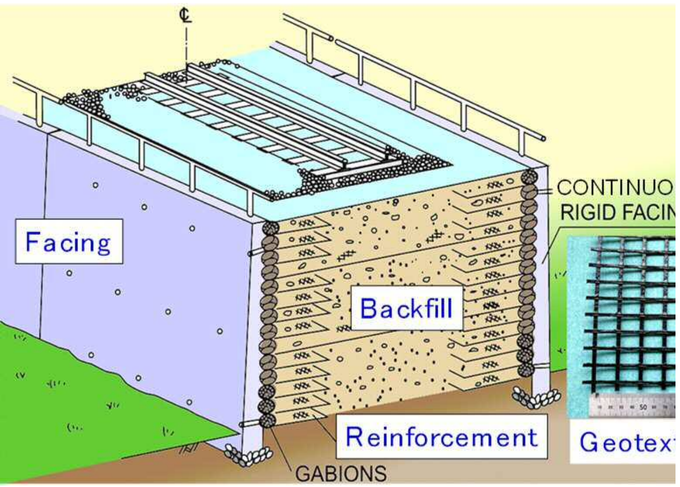


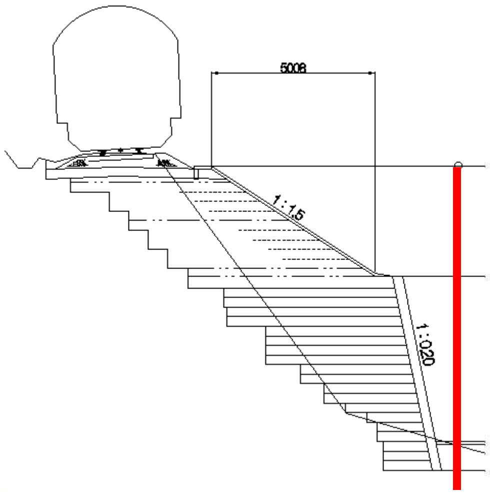
Case of embankment damaged by overflow

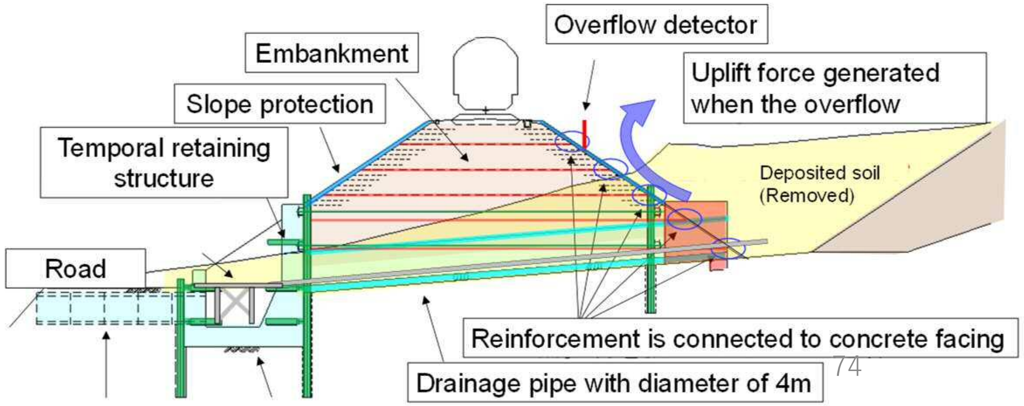
Case3

Summary 3

1. In Japan, many soil structures have been damaged by recent heavy rain disasters, and RRR-GRS structures have been adopted for restoration.
2. The adoption of RRR-GRS structures makes it possible to stabilize the damaged structures against heavy rains and earthquakes without the need for structural changes to bridges, etc., and by utilizing staged construction method, it is possible to resume train operations before construction is completed.
3. Strong connection between reinforcement and concrete facing is effective to resist the uplift force generating by the overflow.







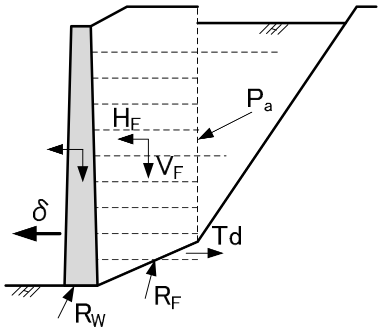
OUTLINE

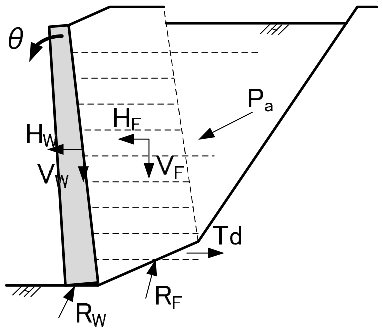
1. Design standard of Japanese railway
2. Material regulation and construction of GRS retaining wall
3. Recent application for disaster retrofitting
4. Summary
5. Appendix to introduce applied project outside of Japan.

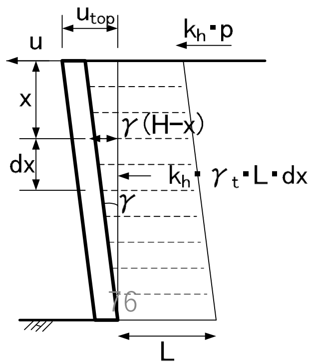
Summary

1. Railway structures adopt a performance-based design system. Structural evaluation is possible with the same index as concrete structures and tunnels.
2. Structure modeling and verification items in design are set according to the characteristics of the structure.
3. RRR-GRS structures have a performance rank that indicates the required level of required performance.
4. Analytical methods for overall stability, stability of reinforced earth bodies, and damage to reinforcement materials and walls have been developed.
5. The analytical model is verified by the slightly damaged RRR-GRS retaining wall, and the amount of residual displacement and deformation mode agreed with the measured one.



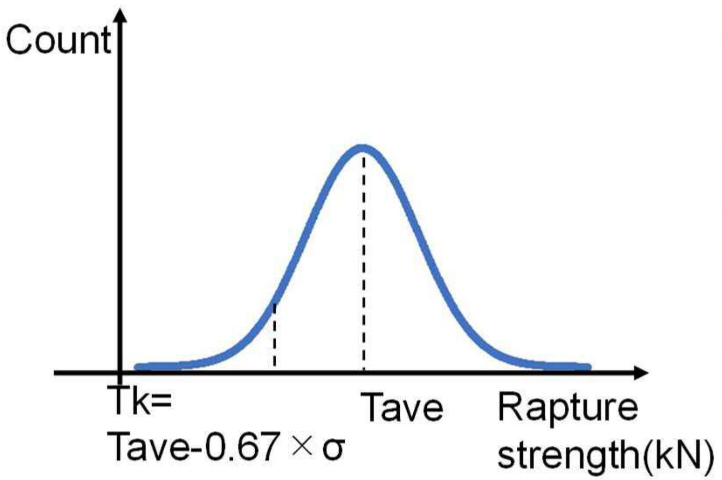






Summary contd.

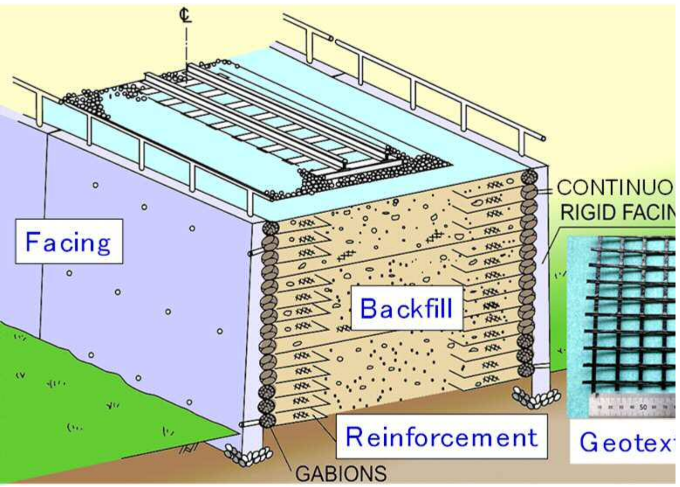
6. Reinforcement materials applicable to the use of RRR-GRS structures are regulated by material manual.
7. Standard tensile strength Tk is set based on material variation, while additional safety margin of 20 % is also considered to set the characteristic design value Ta.
8. Reduction factors a1 to a5 are also considered based on the combination of action to achieve design tensile strength.
9. Test procedures to obtain reduction factors are briefly introduced, for the detail, please refer to the design manual for RRR-GRS structures (ed. RRR association).

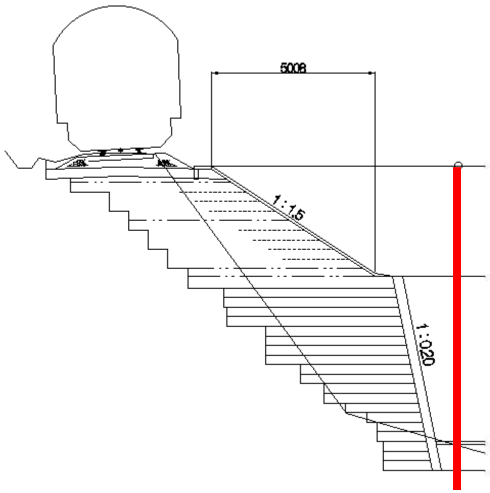


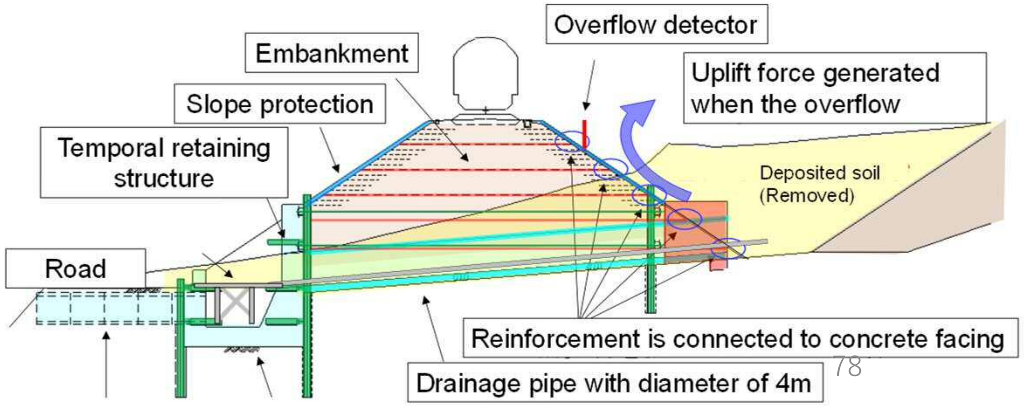
Action combination	Reduction factors (○: Considered)				
	α_1	α_2	α_3	α_4	α_5
Permanent action	○	○	○	–	–
Permanent action + variable action (train)	○	○	–	–	○
Permanent action + seismic action (L1 seismic ground motion) + secondary variable action	○	○	–	○	–
Permanent action + seismic action (L2 seismic ground motion) + secondary variable action	○	○	–	○	–
During construction	–	○	–	–	–

Summary 3

10. In Japan, many soil structures have been damaged by recent heavy rain disasters, and RRR-GRS structures have been adopted for restoration.
11. The adoption of RRR-GRS structures makes it possible to stabilize the damaged structures against heavy rains and earthquakes without the need for structural changes to bridges, etc., and by utilizing staged construction method, it is possible to resume train operations before construction is completed.
12. Strong connection between reinforcement and concrete facing is effective to resist the uplift force generating by the overflow.







OUTLINE

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RRR construction method overseas railway project

	Country	Projects	Section	Design Company
1	India	High-speed railway projects	Mumbai ～ Ahmedabad	JIC (TATA・L＆T)
2	Philippines	North-south commuter extension line	Depot	OCG
3	Indonesia	Java north trunk semi-high-speed railway projects	Jakarta ～ Surabaya	Chodai
4	Myanmar	High-speed railway projects	Yangon ～ Mandalay	OCG

RRR construction method overseas railway project

	Country	Projects	Section	Design company	Contractor
1	Vietnam	North-South High Speed Rail	Ninh-binh bridge	JTC	Mitsui Zosen etc.
2	Indonesia	Jakarta MRT	Depot	D&B	Tokyu etc.
3	Philippines	North-South Commuter Line	Malolos ～ Tutuban	OCG	Taisei etc.

High Speed Railway Projects on Hanoi - Vinh

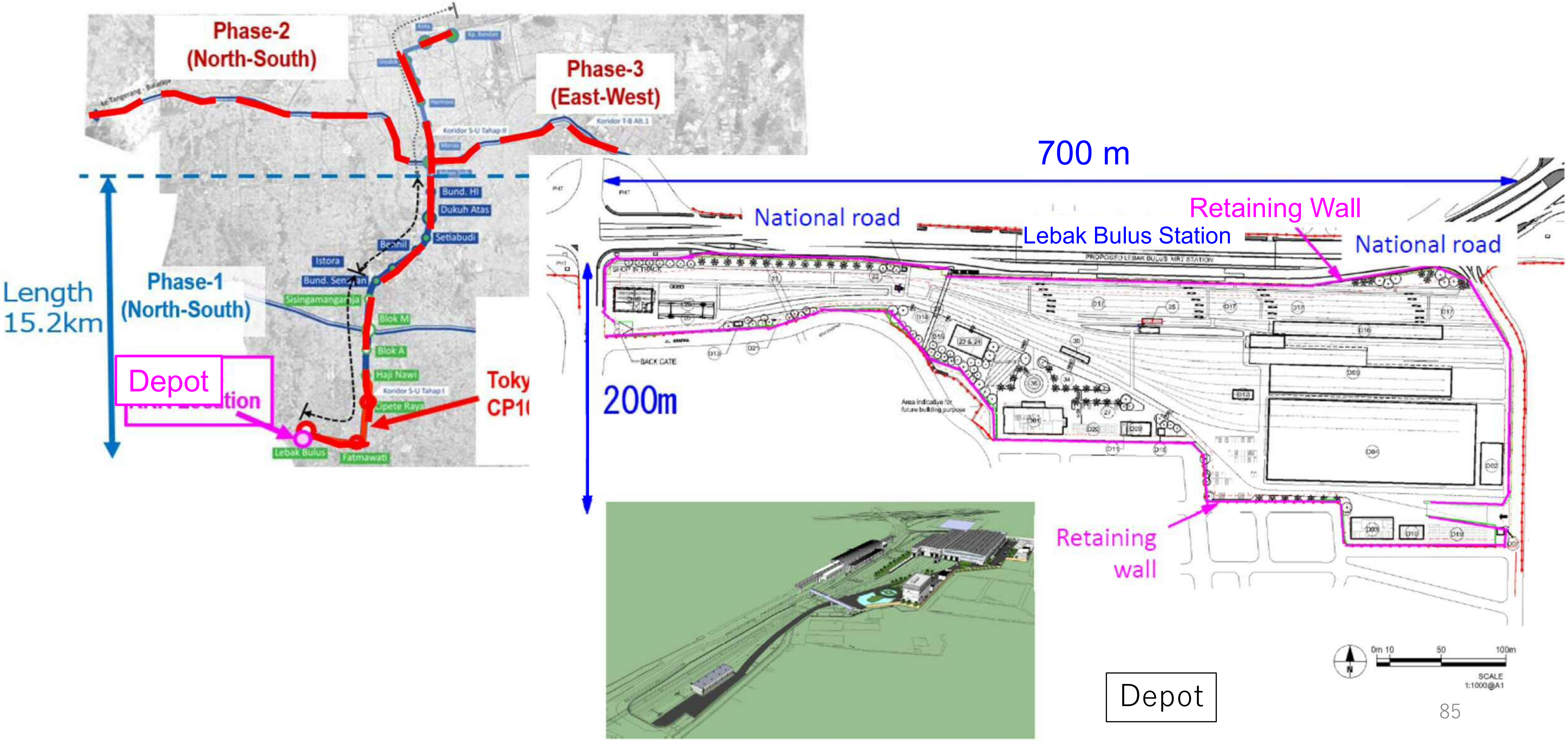
Type	GRS RW
Construction	Mitsui Zosen corp. Rinkai Nissan corp. Taisei corp. Cienco 1(Vietnum)
Height	1.8～5.7 m
Length	1,485 m
Date	2013/July
Reinforcement	60 kN/m 93,000㎡
Design and management	Japan Transportation Consultants

Photo courtesy : Mitsui Chemicals

Photo courtesy : Mitsui Chemicals

MRT (Mass Rapid Transit) Projects in Jakarta - Indonesia

Route map



MRT (Mass Rapid Transit) Projects in Jakarta - Indonesia

Photo-1 geotextile laying

Photo- 2 compaction

Photo-3 geotextile wrapping

Photo-4 roller compaction

Photo-5 small compactor

Photo-6 formwork anchor

Photo courtesy : Tokyu construction

MRT (Mass Rapid Transit) Projects in Jakarta - Indonesia

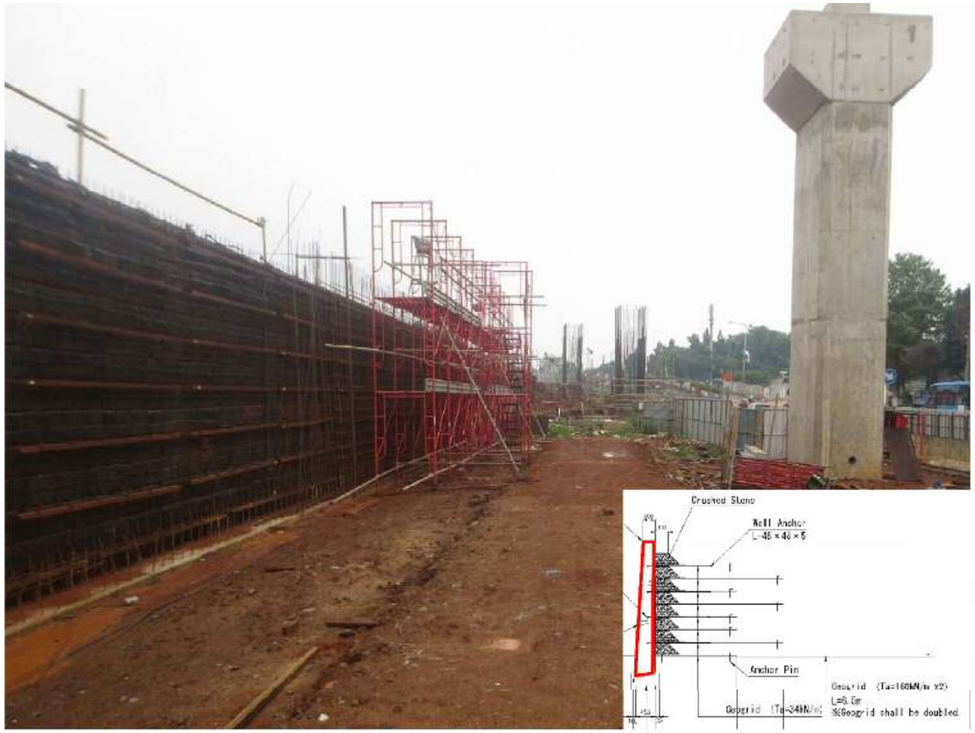
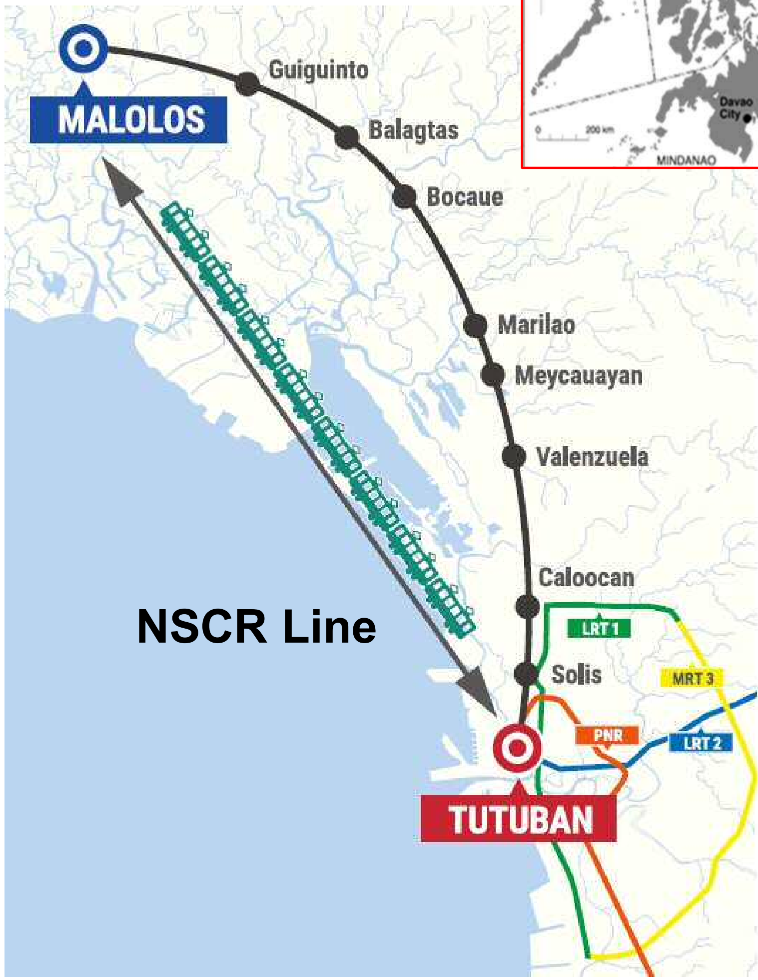


Photo courtesy : Tokyu construction

GRS Structures for the North-South Commuter Railway (NSCR), Manila, Philippines

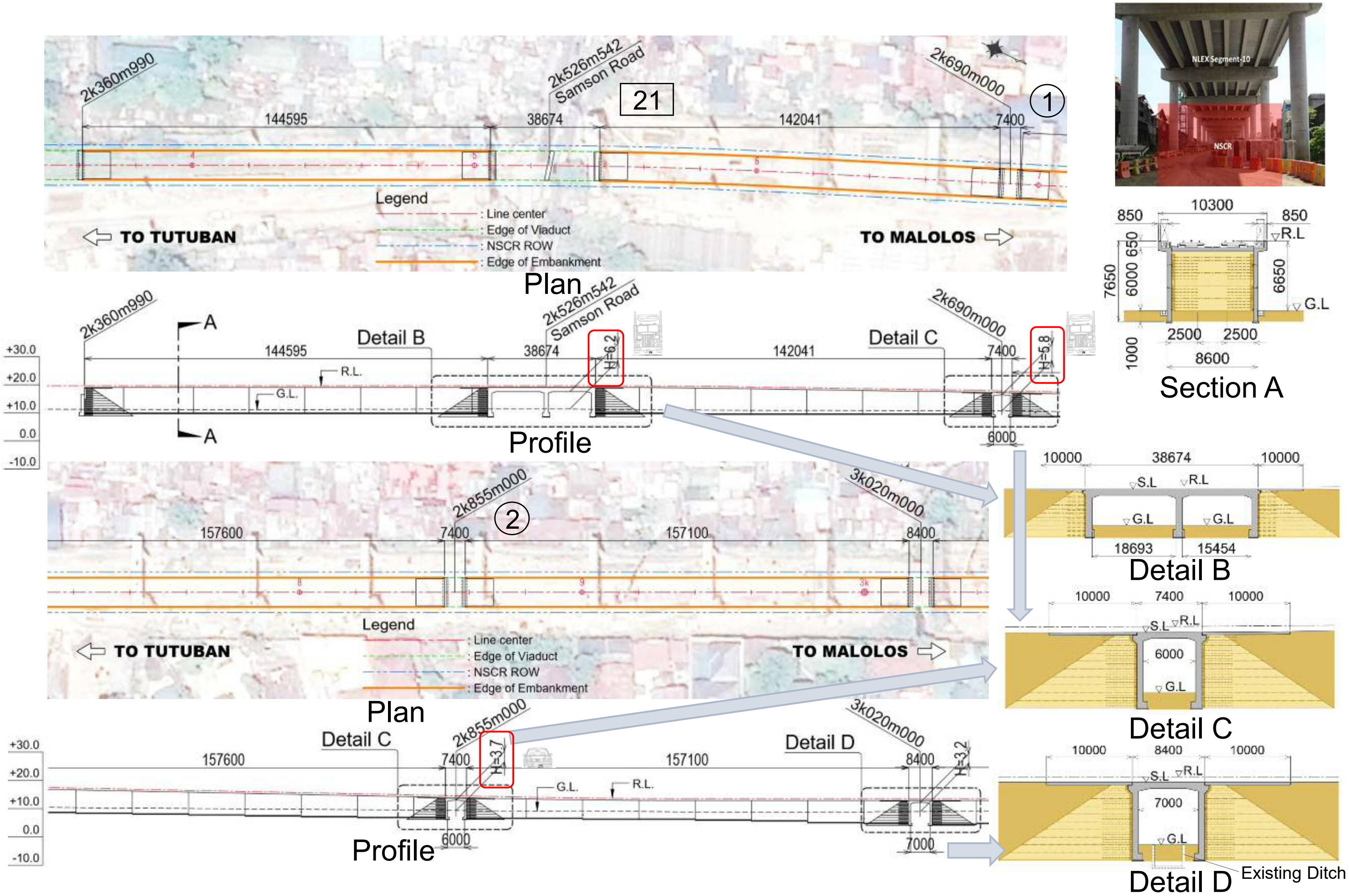
JICA (July 2017): Detailed design of NSCR in the republic of Philippines, Final report

Item	Description
Line	Tutuban – Malolos 37.6 km Double Track Standard Gauge (1,435mm)
Stations	10 stations
Structure	Elevated Viaduct: 35.4 km Embankment: 2.2 km
Depot	Valenzuela
Train	8-car train (DC 1,500V) (2,250 passengers/train) Tutuban – Malolos 35 min. Max speed: 120 km/h Headway: 6 minutes



Segment -10 Section (under construction)

JICA (July 2017): Detailed design of NSCR in the republic of Philippines, Final report



foundation

soil sprinkling

soil leveling

compaction

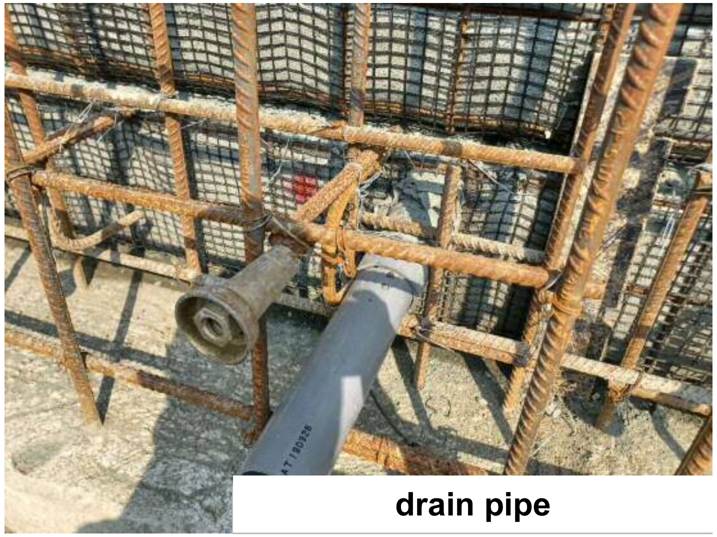
geotextile laying

density test

Photo courtesy : Taisei construction


protection against rain


reinforcing bar


drain pipe


formwork

cast-in-concrete


completion

Photo courtesy : Taisei construction