IGS 40th Anniversary Lecture
Thursday, 9 November 2023, 10AM Tokyo time

Geosynthetic-Reinforced Soil Structures in Japan
- many requirements and the solution -

Fumio TATSUOKA
Professor Emeritus
University of Tokyo and Tokyo University of Science, Japan

Abstract – 1/2:

In parallel with the development of IGS for the last 40 years, in Japan, geosynthetic-reinforced soil (GRS) structures having unique features were developed responding to many requirements. The requirements are basically “high performance & high cost-effectiveness”, specifically; 1. no pile foundation but high stability & small residual deformation; 2. narrow space occupied during & after construction; 3. facing supporting other structures (e.g., bridge abutment); 4. cost-effective stable RWs on slope; 5. high stability against seismic load, scouring, erosion & tsunami; and 6. reliable structures for High Speed Railways.

As the solution, for GRS RWs, after the deformation of geogrid-reinforced backfill & subsoil caused by the construction of the reinforced backfill has taken place sufficiently, full-height rigid (FHR) facing is constructed by casting-in-place fresh concrete directly on the geogrid-wrapped-around wall face in such that the FHR facing is firmly connected to all the geogrid layers.

Abstract – 2/2:

Early 1990's, GRS Bridge Abutment was developed. One end of a simple girder is supported by a fixed bearing arranged at the top of FHR facing of a GRS RW, or both ends of a simple girder are supported by fixed & movable bearings at the top of FHR facings of a pair of GRS RWs. In total 185 have been constructed. Then, GRS Integral Bridge was developed. Both ends of a continuous girder are structurally integrated to the top of FHR facings of a pair of GRS RWs at the last stage of construction. 14 have been constructed.

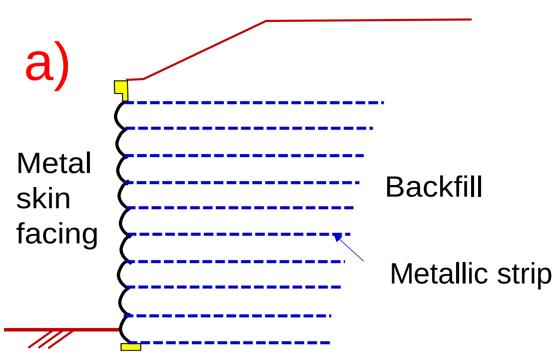
In the meantime, a number of embankments and conventional type RWs & bridges that collapsed by severe seismic load, scouring, erosion or tsunami were reconstructed to these GRS structures.

After 40 years, the total wall length exceeds 200 km. Many GRS structures were constructed for High Speed Railways. All of them have been performing very well with no problematic case during & after construction, while a very high cost-effectiveness with low maintenance cost has been validated.

Various types of mechanically stabilized earth (MSE) RW having different types of facing & reinforcement: 40 years ago

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	

a)



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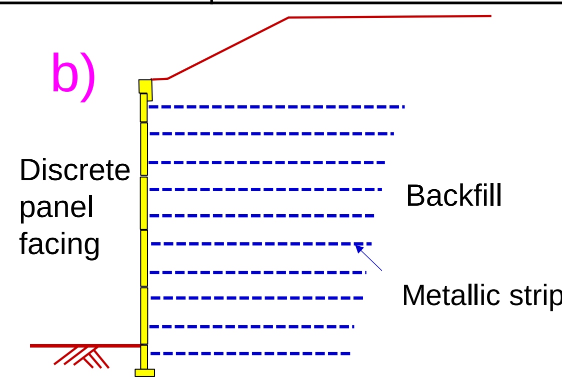

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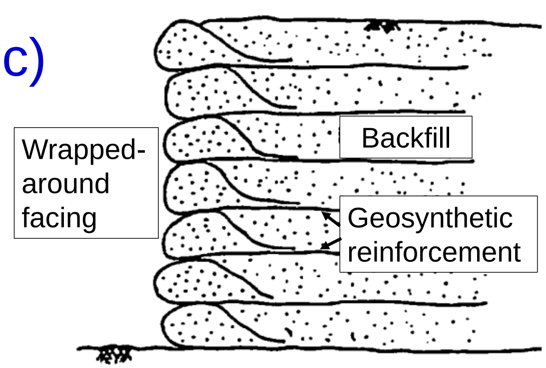


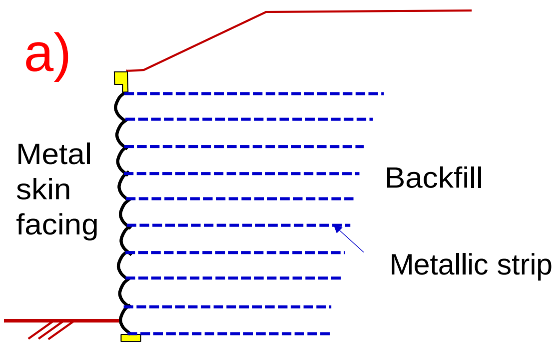
However, the wall face is:
- too deformable;
- not durable; and
- aesthetically not acceptable.

Various types of mechanically stabilized earth (MSE) RW

having different types of facing & reinforcement: in the meantime,

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

a)



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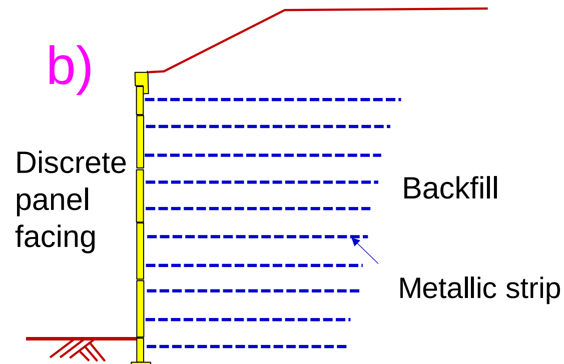

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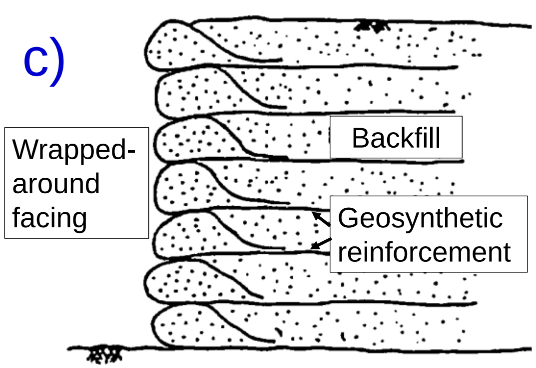
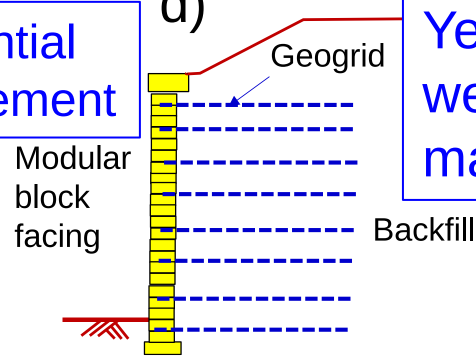


Substantial improvement

d)



Yet, further developments were necessary to respond to many requirements & requests

To the next step

A number of problems with conventional type RWs

- basically, low performance & low cost-effectiveness

Specifically ……

1) Need for a costly pile foundation to ensure sufficient stability.
2) Too large post-construction deformation/settlement.

Furthermore, Japan is congested & narrow with frequent severe natural disasters and a strong need for renewal of many old soil structures. So, we also have the following problems with conventional type RWs…

3) Narrow space available during & after construction.
4) Cost-ineffective construction of facing supporting other structures, including many problems with bridge abutments.
5) Cost-ineffective construction of stable RW on slope.
6) Low stability against severe seismic load, scouring, erosion, tsunami etc.
7) Not reliable for High-Speed Railways.

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1) **Need for a costly pile foundation to ensure sufficient stability.**
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Furthermore, Japan is congested & narrow with frequent severe natural disasters while a strong need for renewal of many old soil structures. So, the following problems should also be solved …

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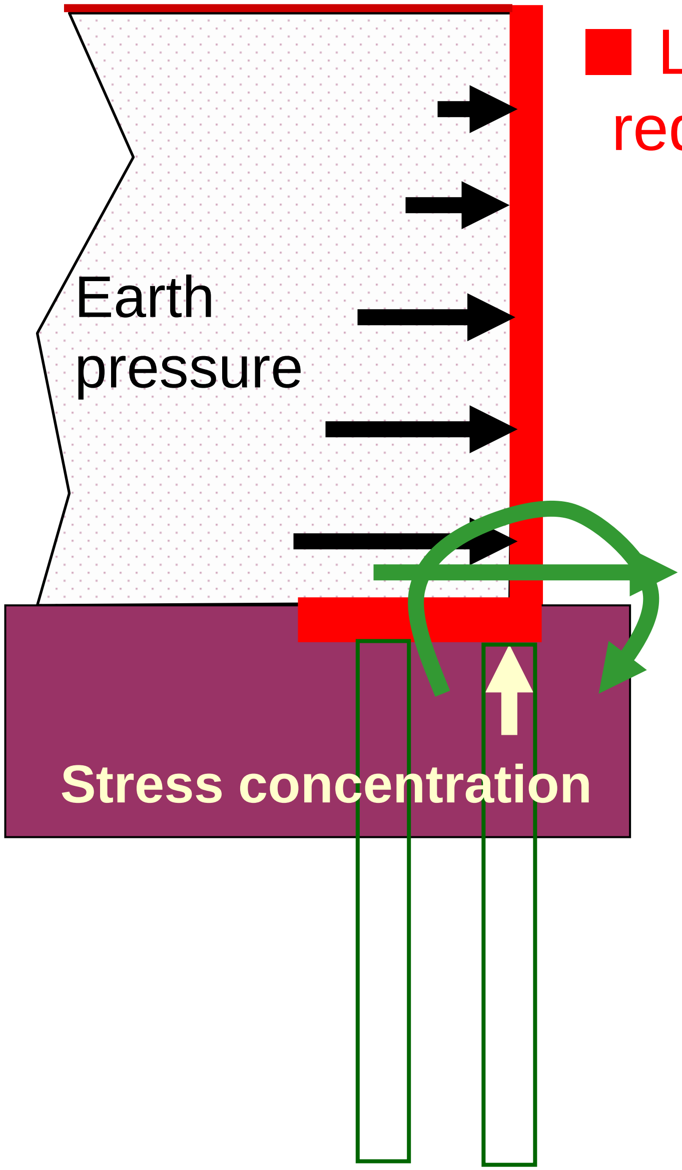
Conventional RW is a cantilever structure!



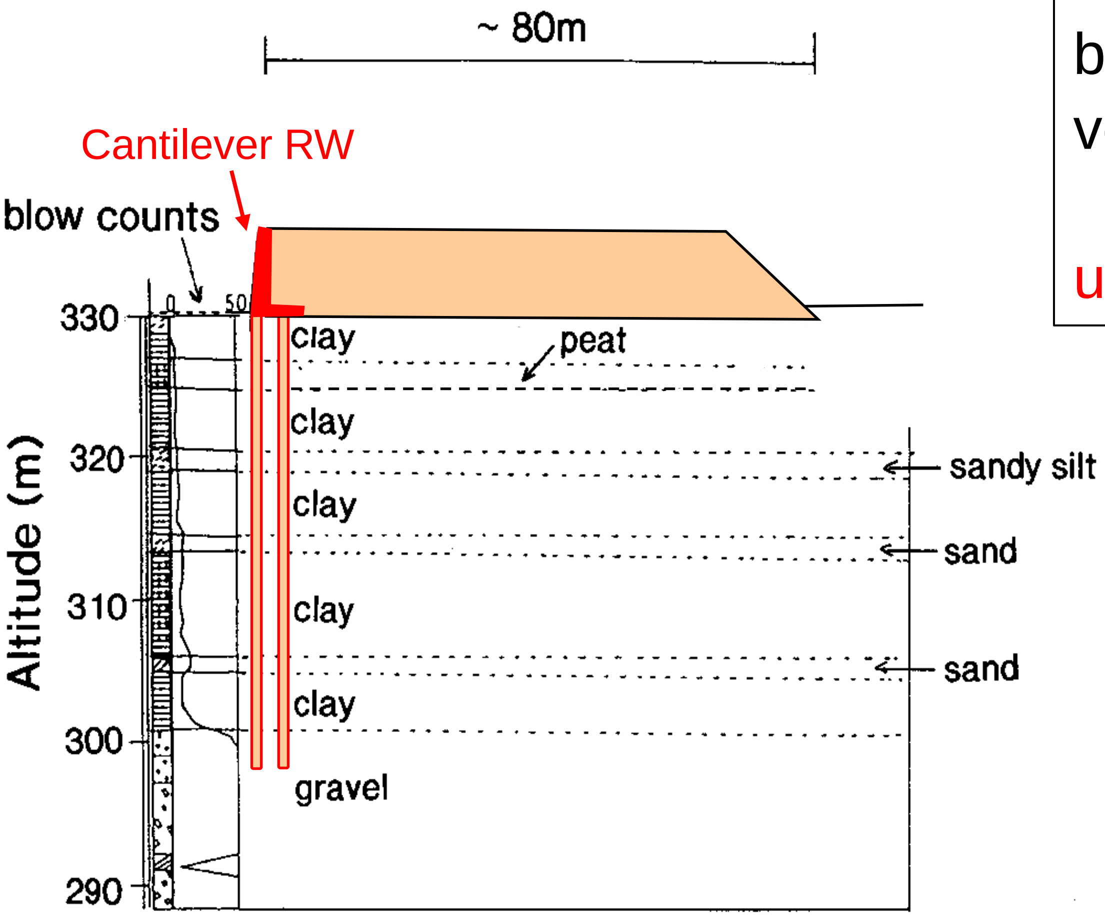
- Large forces in the facing, requiring massive & strong facing

- 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 costly pile foundation is required.

Embankment in Nagano, Japan

- Depot for High Speed Railway (Shinkansen)
- 2.0 m-high & 2 km-long on a very thick clay deposit



RW is necessary,
but canti-lever RW needs a very long pile:

utterly not cost-effective

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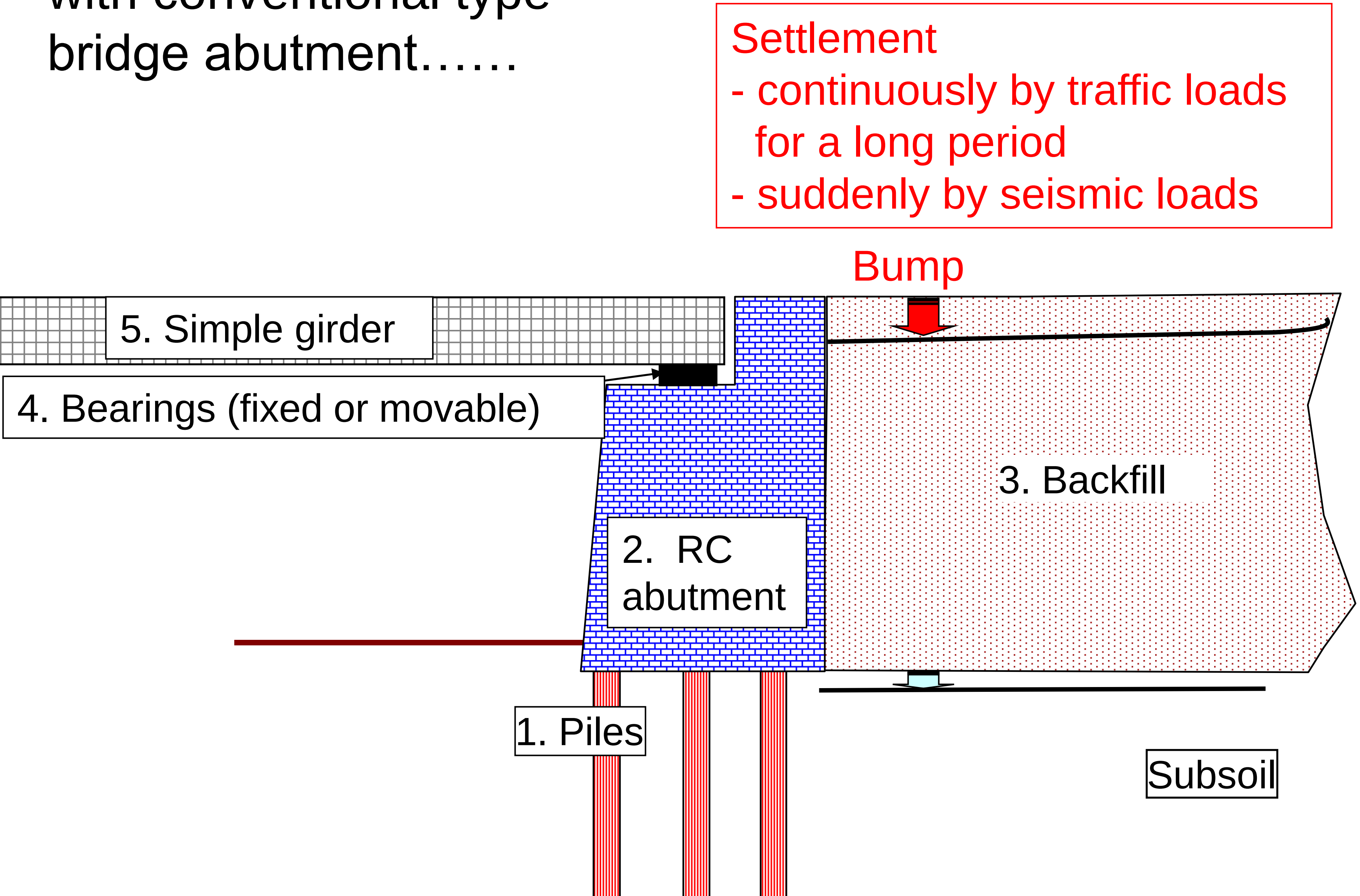
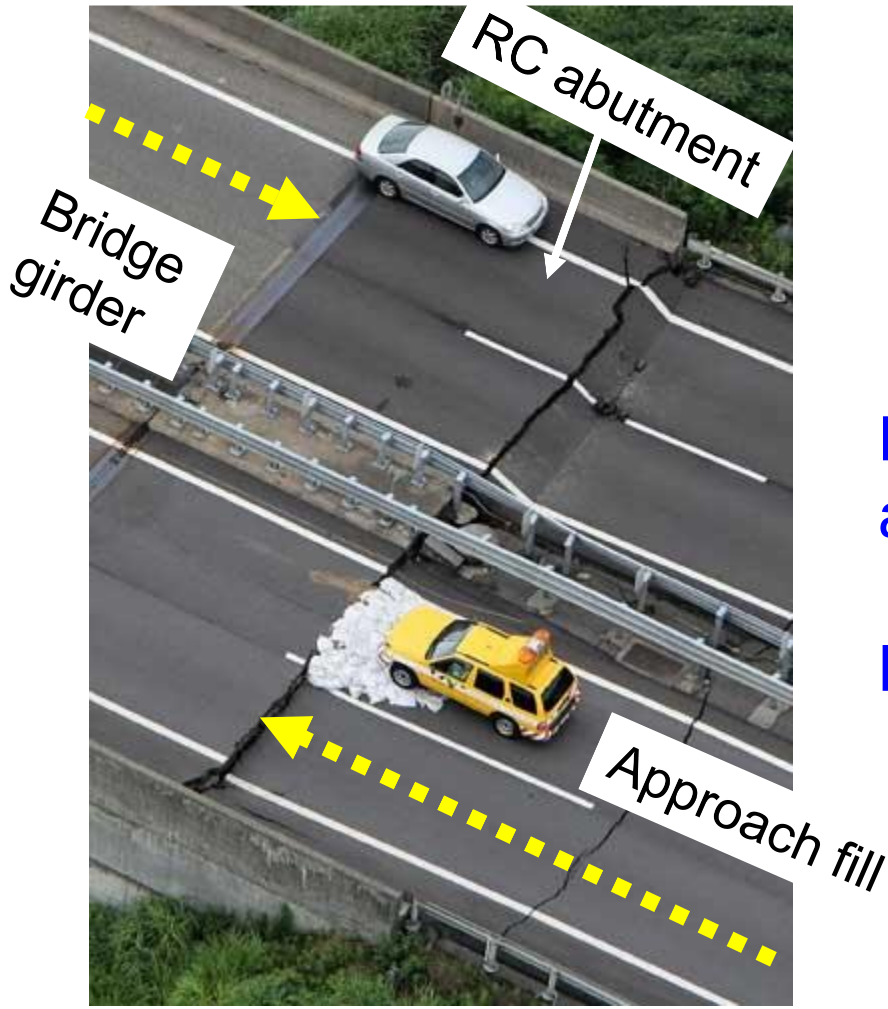
Among several problems with conventional type bridge abutment……



2007 July 16 Niigata-ken Chuetsu-oki E.Q.
Hokuriku Highway



Bump by the settlement of the approach fill behind an abutment

Numerous similar cases…….

1995 Jan. 15 Kobe Earthquake

Settlement in the approach fill behind bridge abutment

Near Shin-Nagata Station, JR Kobe Line

(by the courtersy of Tateyama, M.)

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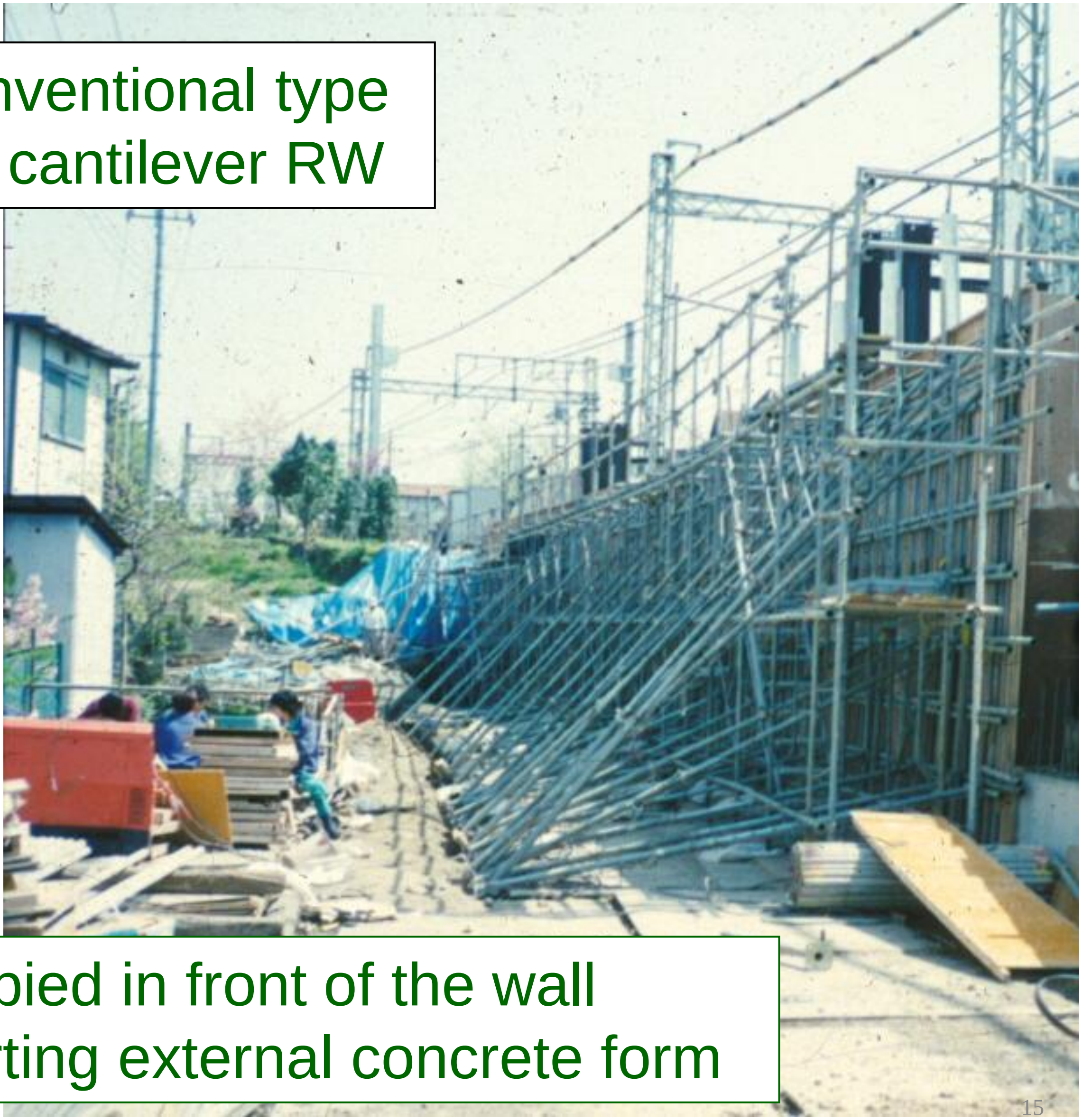
RW for a railway (Keio Line), Hirayama Joshi, Tokyo

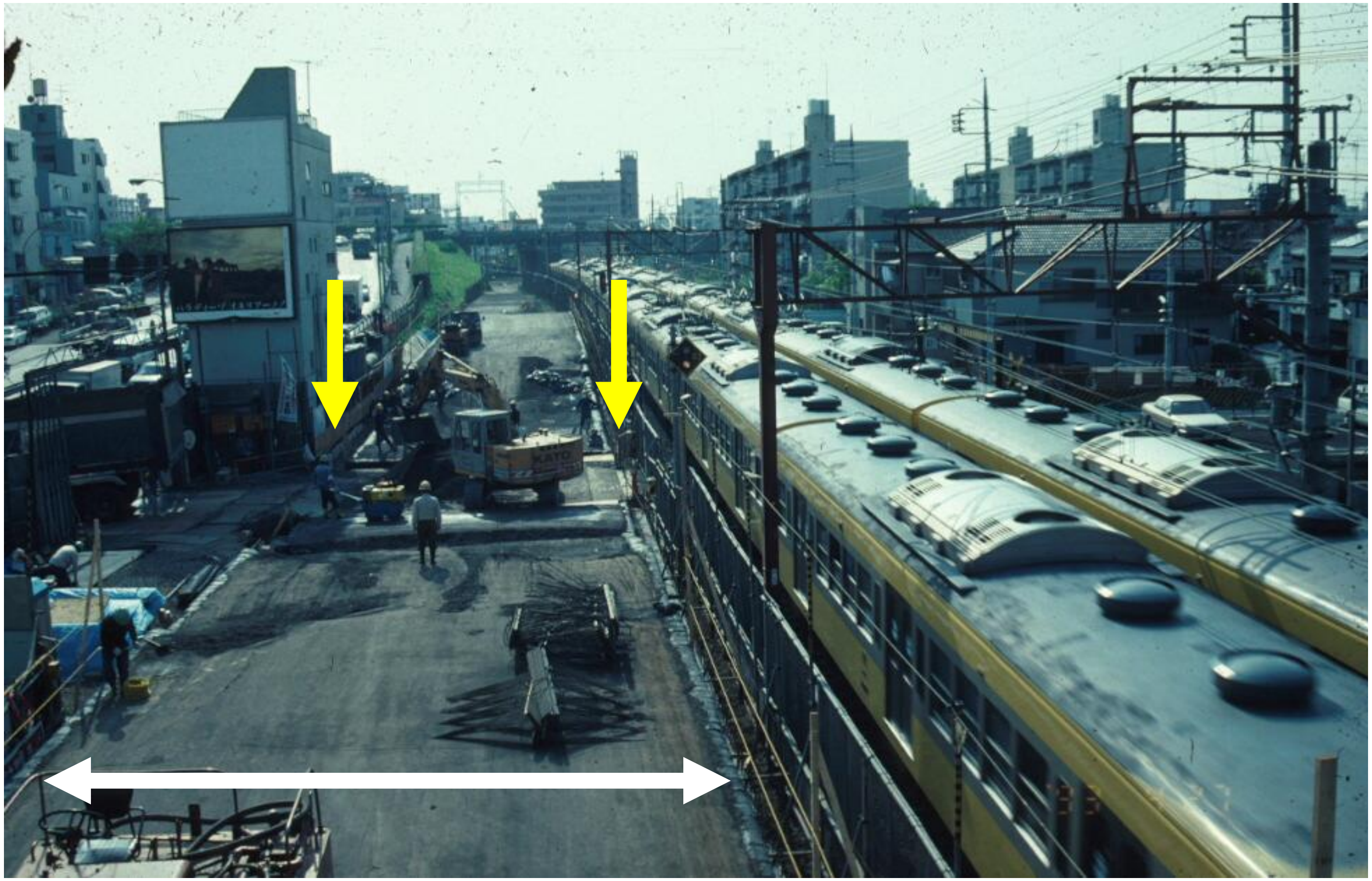


Conventional type
RC cantilever RW

A wide space is occupied in front of the wall
for a propping supporting external concrete form

Seibu Ikebukuro Line, Tokyo, 1993

How to construct the facing in very narrow space available in front of the wall face ?



GRS approach fill with wall faces on both sides (under construction)

A number of problems with conventional type RWs

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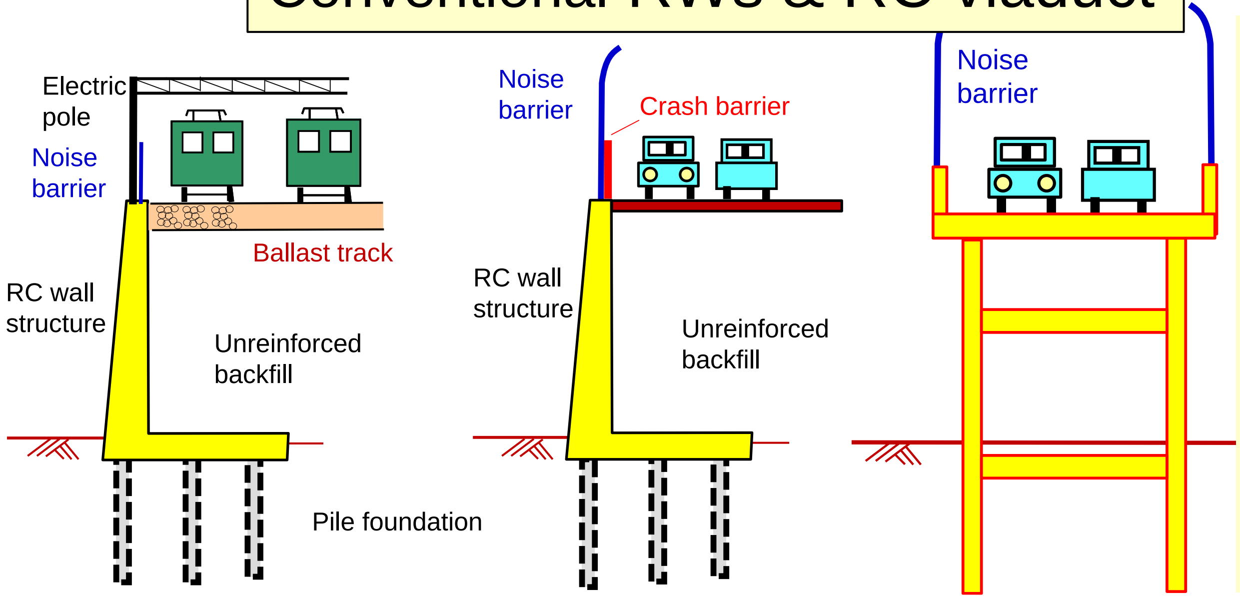
Conventional RWs & RC viaduct



<u>Advantages</u>

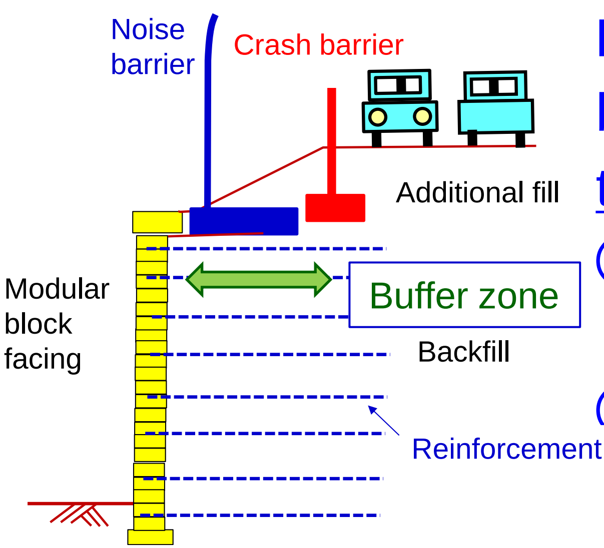
① Limited occupied space

② Ability to support other structures

<u>Disadvantages</u>

Not cost-effective

GRS RWs with facing of modular blocks or discrete panels



Lower construction cost,

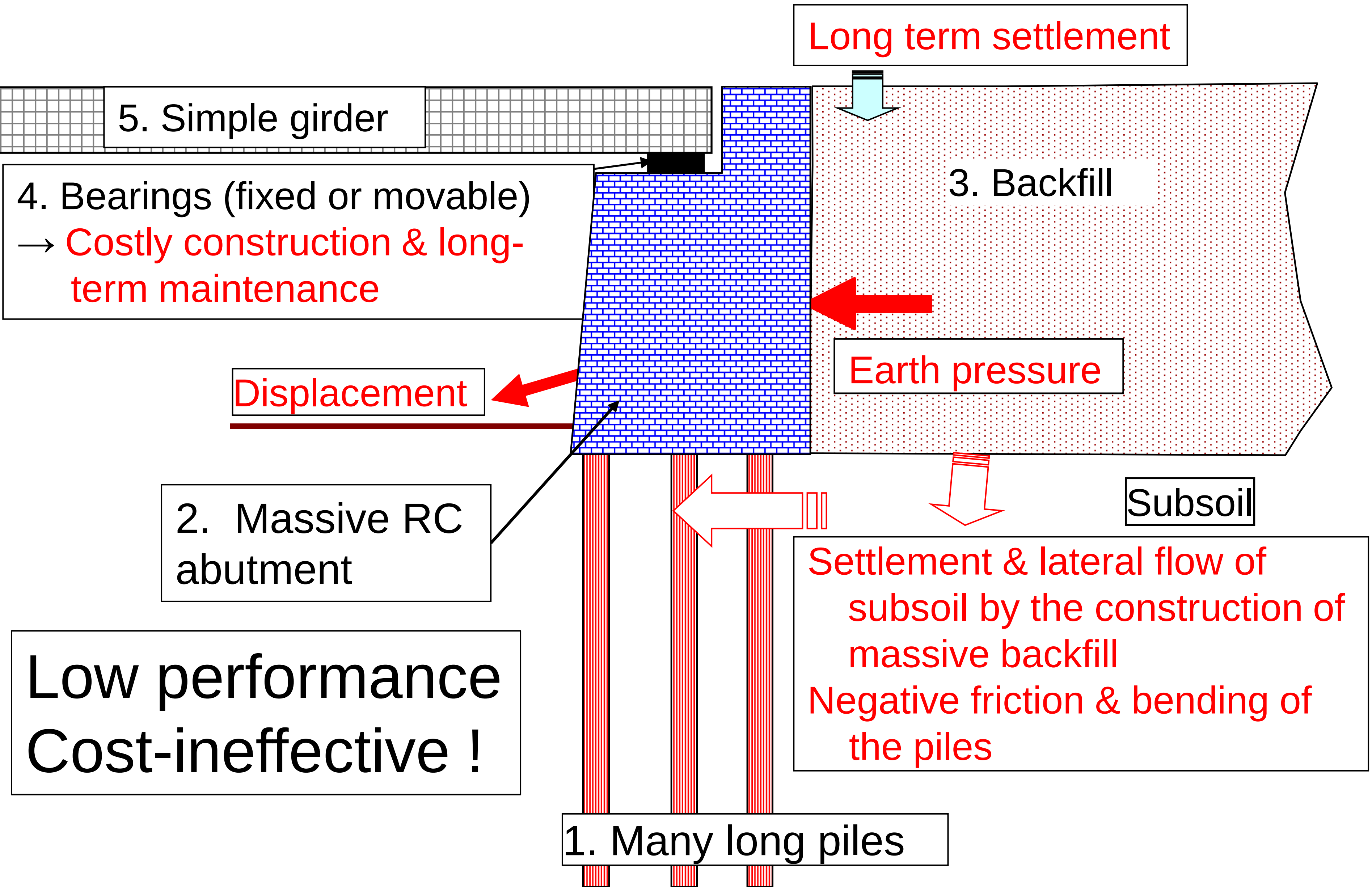
but, <u>unlike conventional RWs & RC viaduct</u>,

<u>the facing is not rigid enough, so,</u>

① a buffer zone is required for safe operation of road & railway, so the occupied space becomes wide; and

② the facing cannot effectively support other structures, so some foundations become necessary.

A number of serious problems with conventional type bridge abutment



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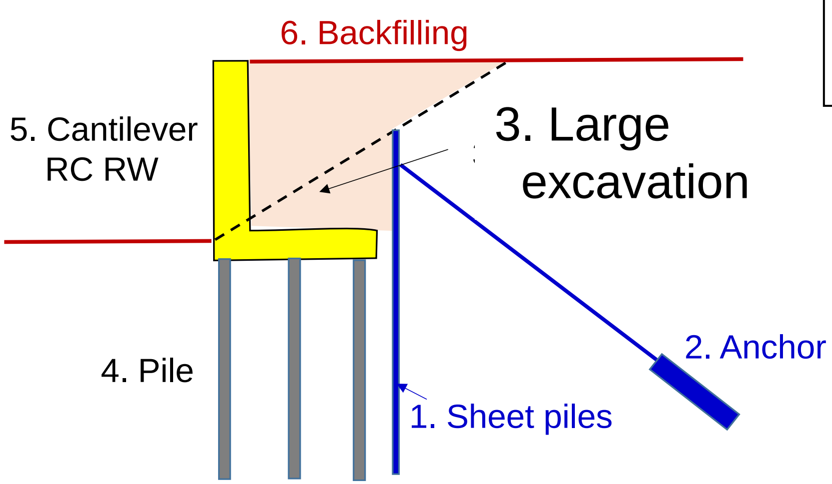
Depot for HSR (Shinkansen) at Biwajima, Nagoya, 1990 - 1991

Need for a vertical wall to widen the crest of the embankment without occupying the space in front of the embankment

- average wall height= 5 m
- total wall length= 930 m

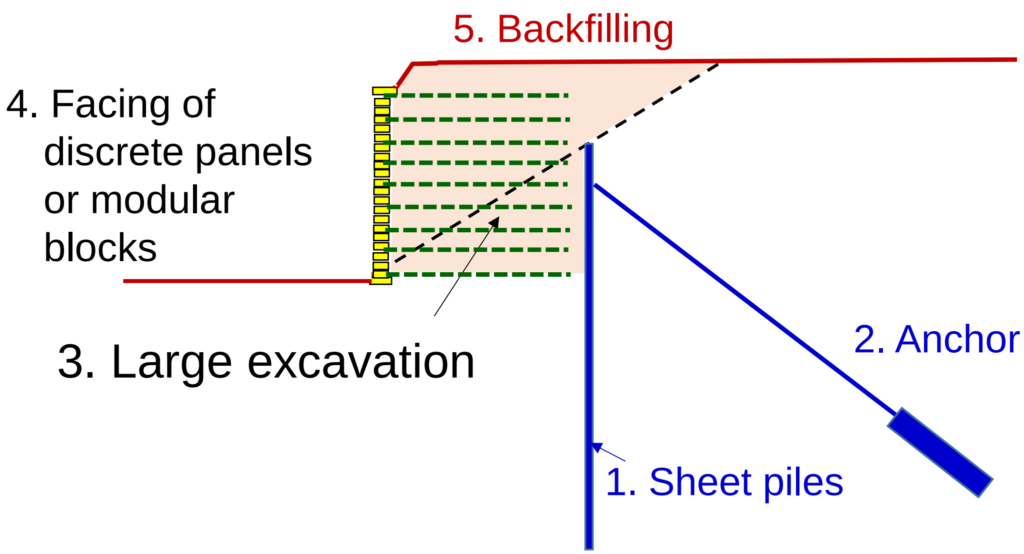
However, large excavation and the use of temporary anchored sheet piles may be required
⇒ an increase in the construction cost & period.

Conventional cantilever RW



A relatively wide base of cantilever RW

MSE RW having facing of discrete panels or modular blocks:
- more cost-effective
- but, geogrid length/wall height L/H ≥ 0.7 for sufficient wall stability



A number of similar cases

A number of problems with conventional type RWs

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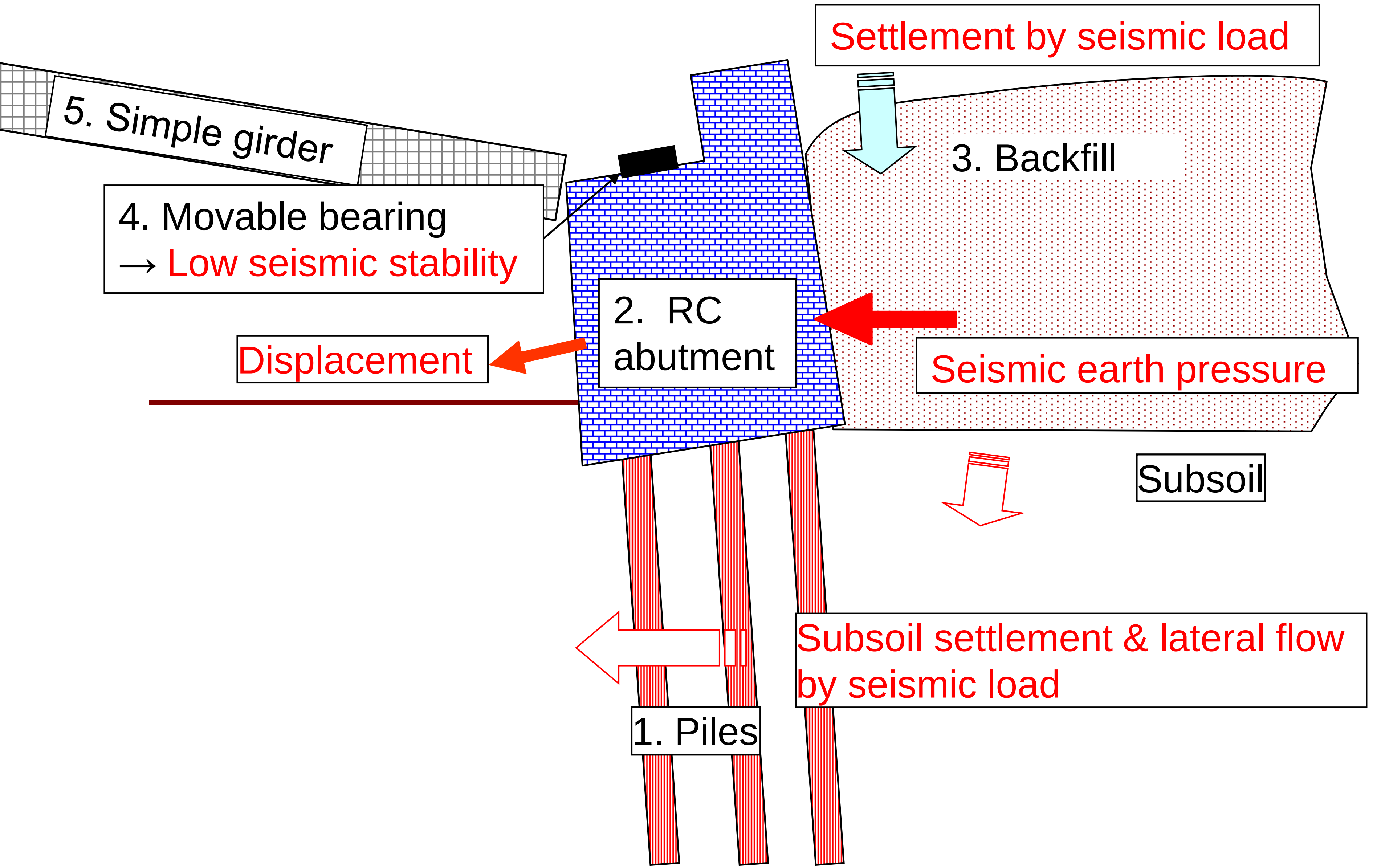
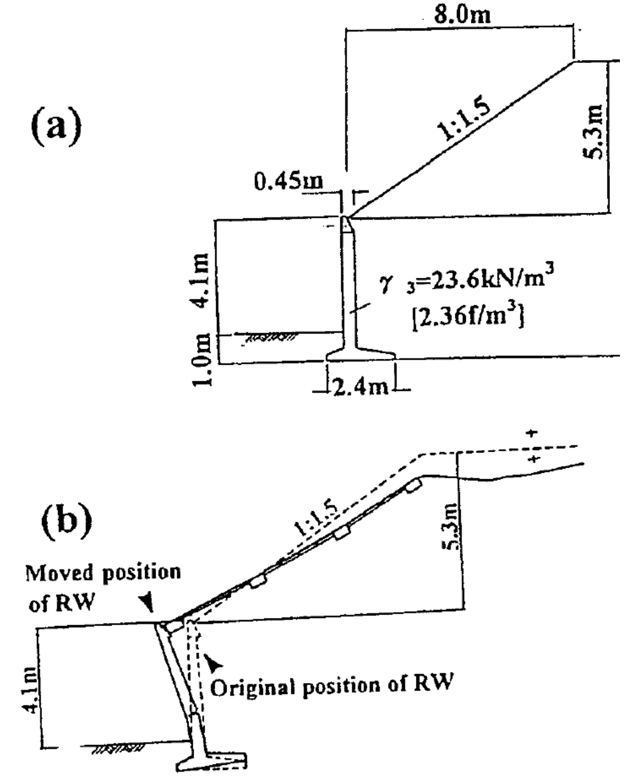
A number of problems by seismic loads



1995 Kobe Earthquake, Kobe Railway Line

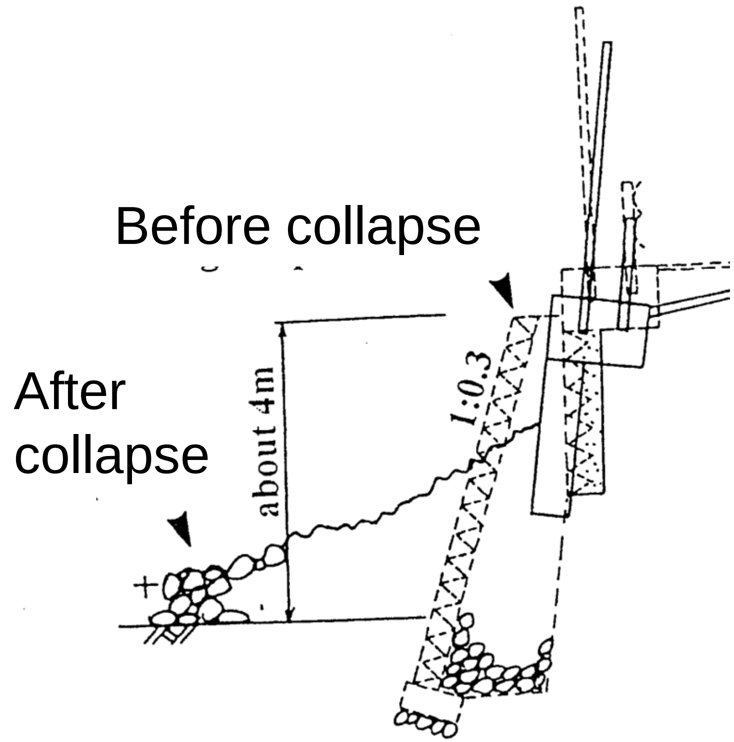
Collapse of RC cantllever RW by the 1995 Kobe EQ

JR Kobe Line
Shin-Nagata Station



Collapse of masonry RW by the 1995 Kobe EQ

JR Kobe line
Mountain-side
Between Setsu-Motoyama and
Sumiyoshi Stations

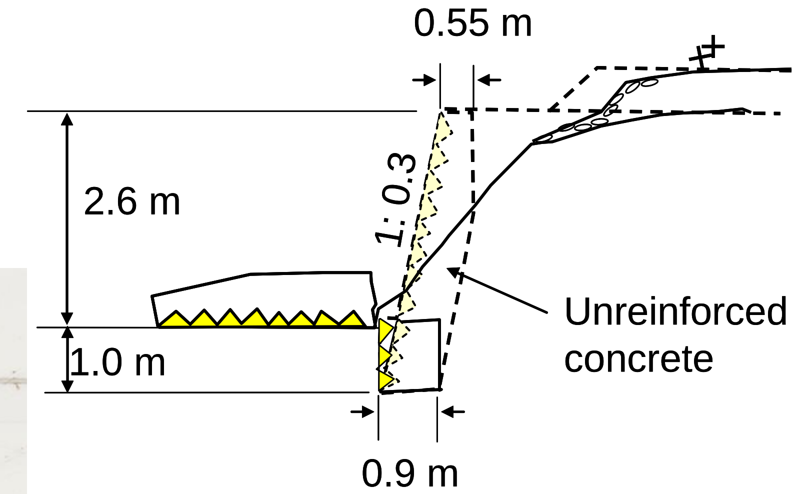


1995 Jan 24, Tatsuoka

Collapse of gravity RW by the 1995 Kobe EQ

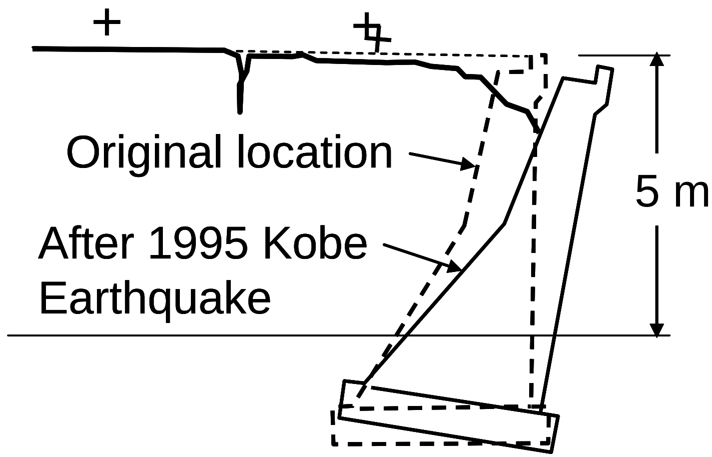
Between Setsu-Motoyama and Sumiyoshi Stations

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



1995 Jan 24, Tatsuoka

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



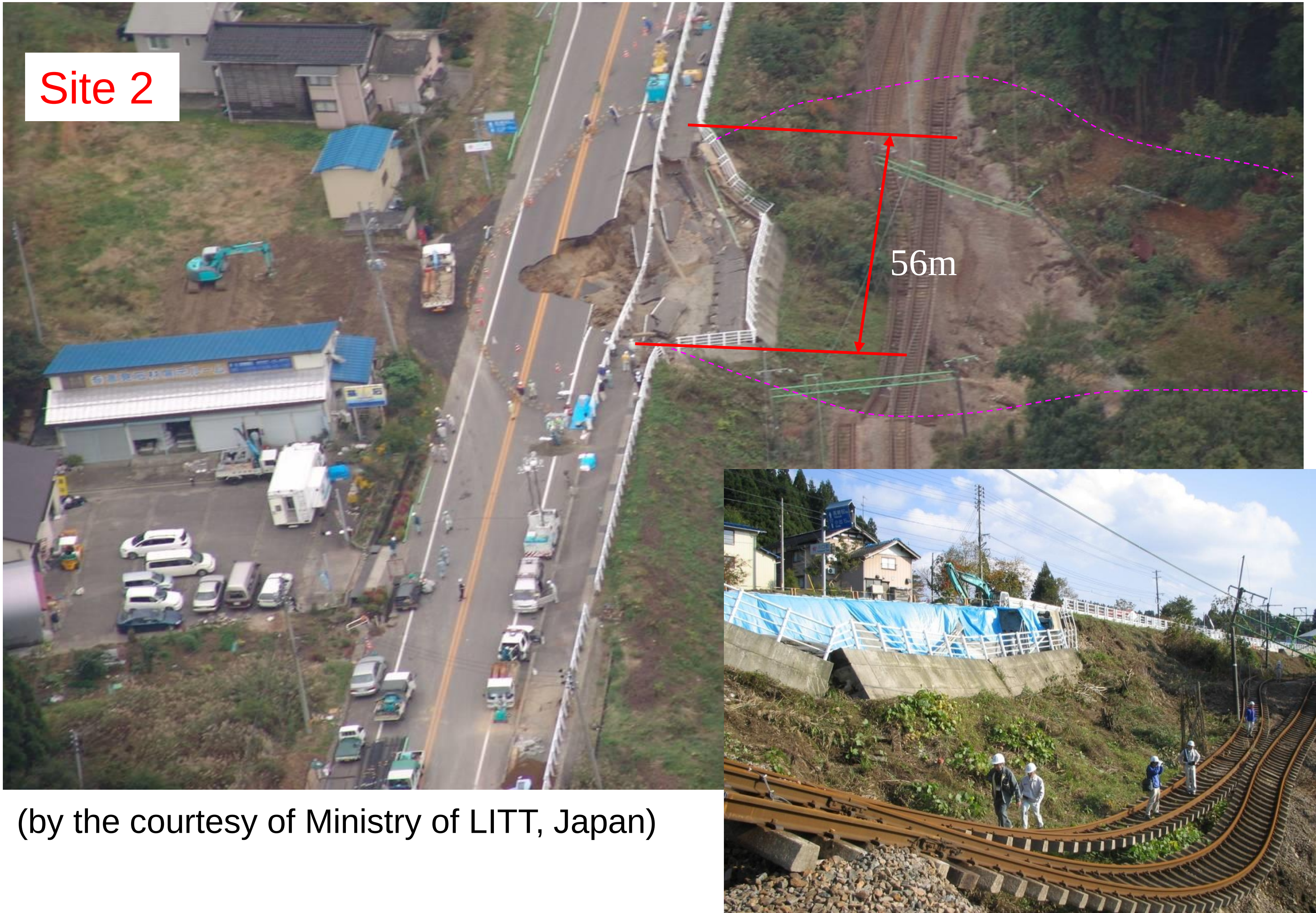
Very dense gravelly subsoil, no pile

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

2004 Niigata-ken Chuetsu EQ, October 2004



(by the courtesy of Ministry of LITT, Japan)

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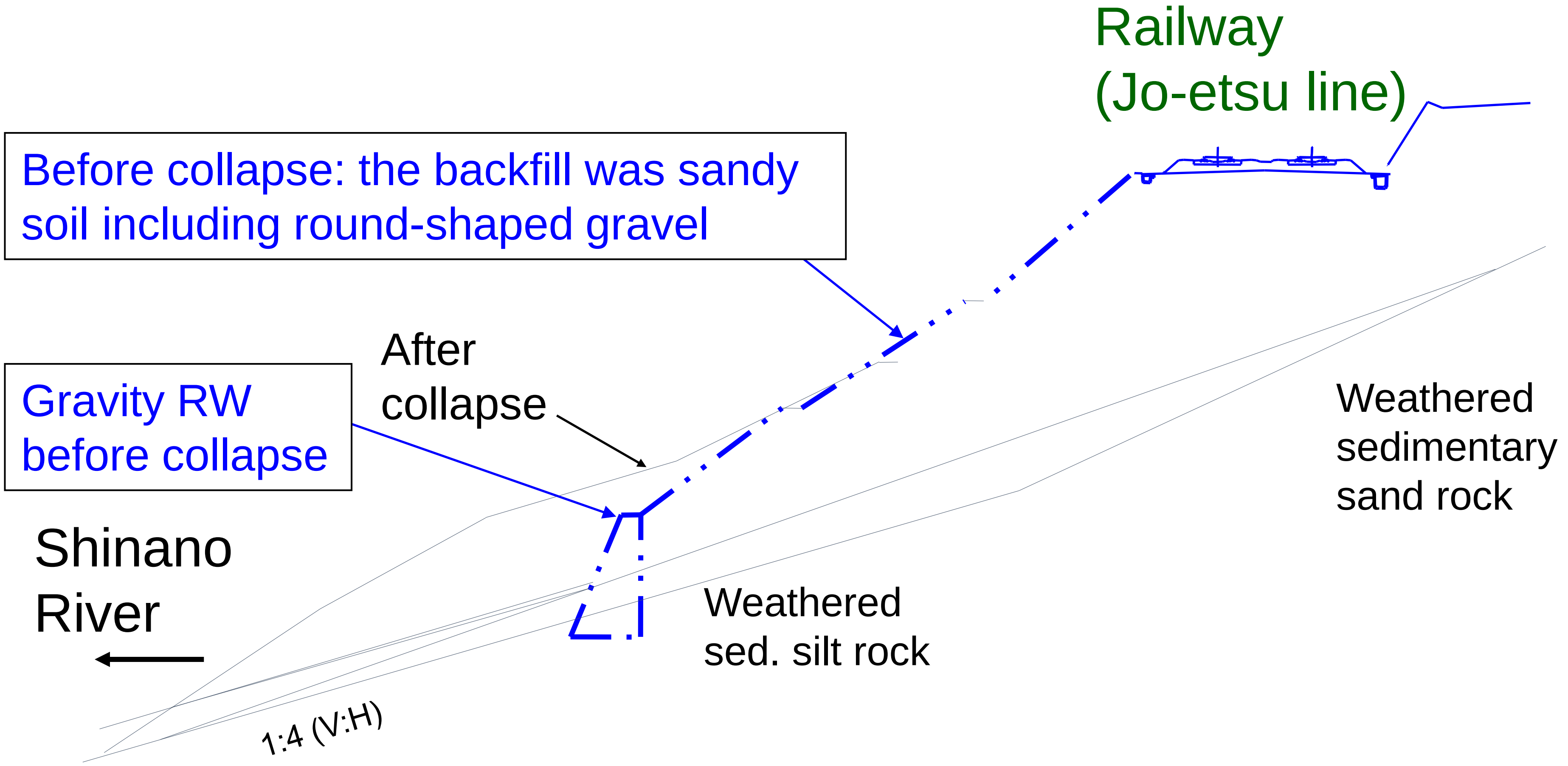
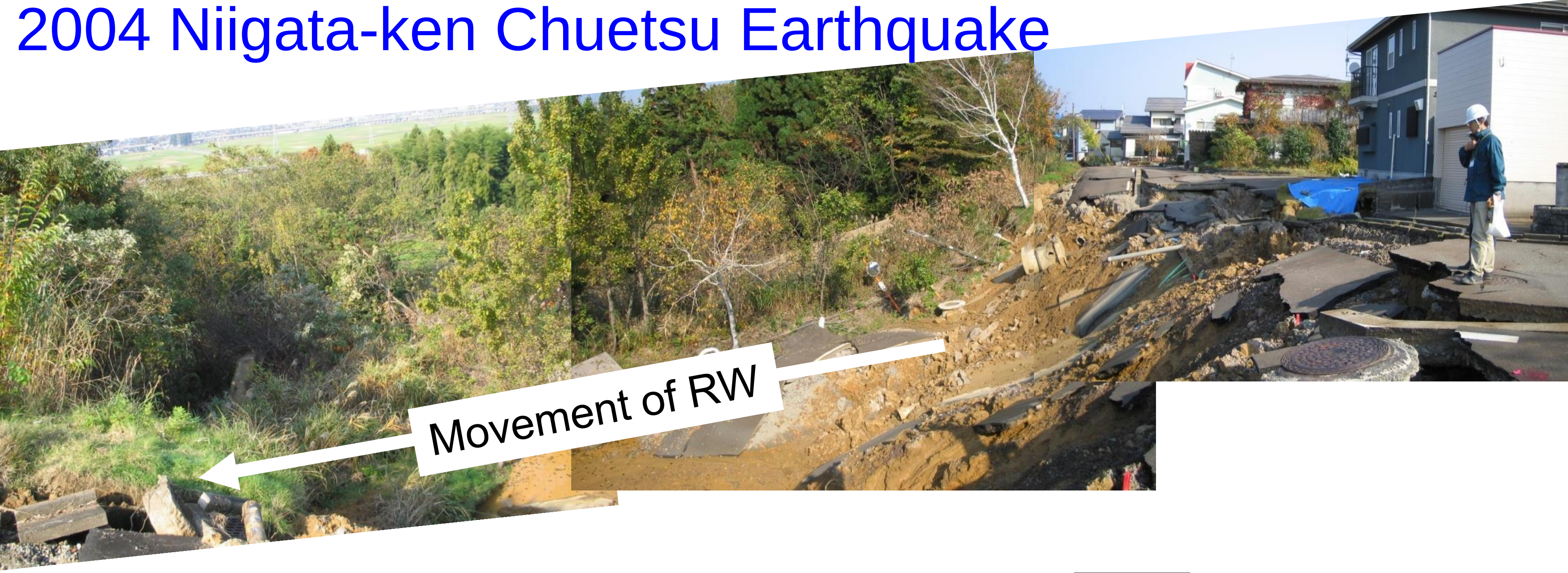
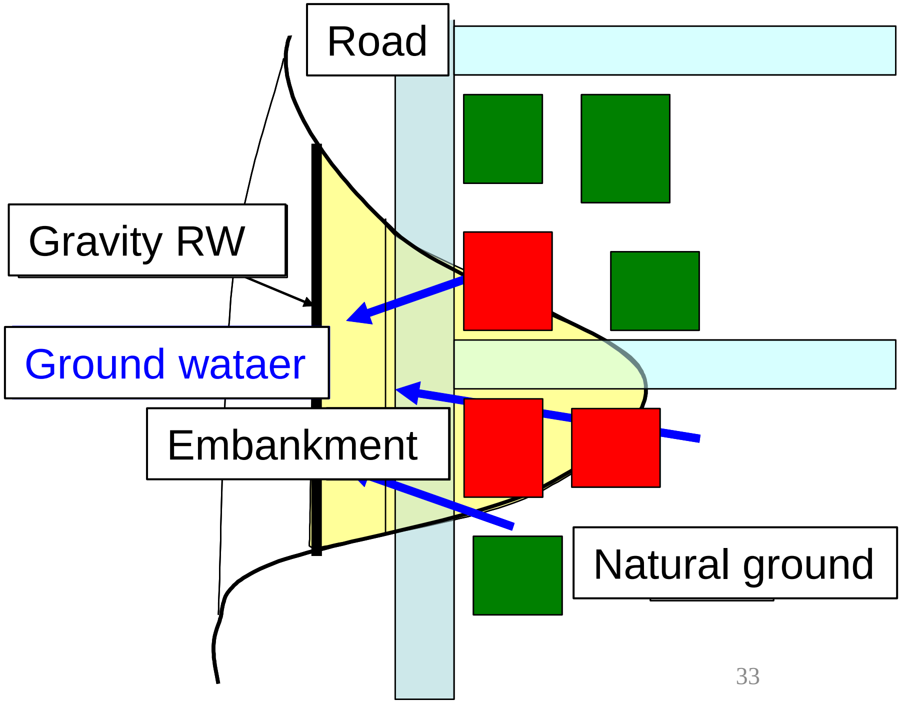


Site 2


Site 3

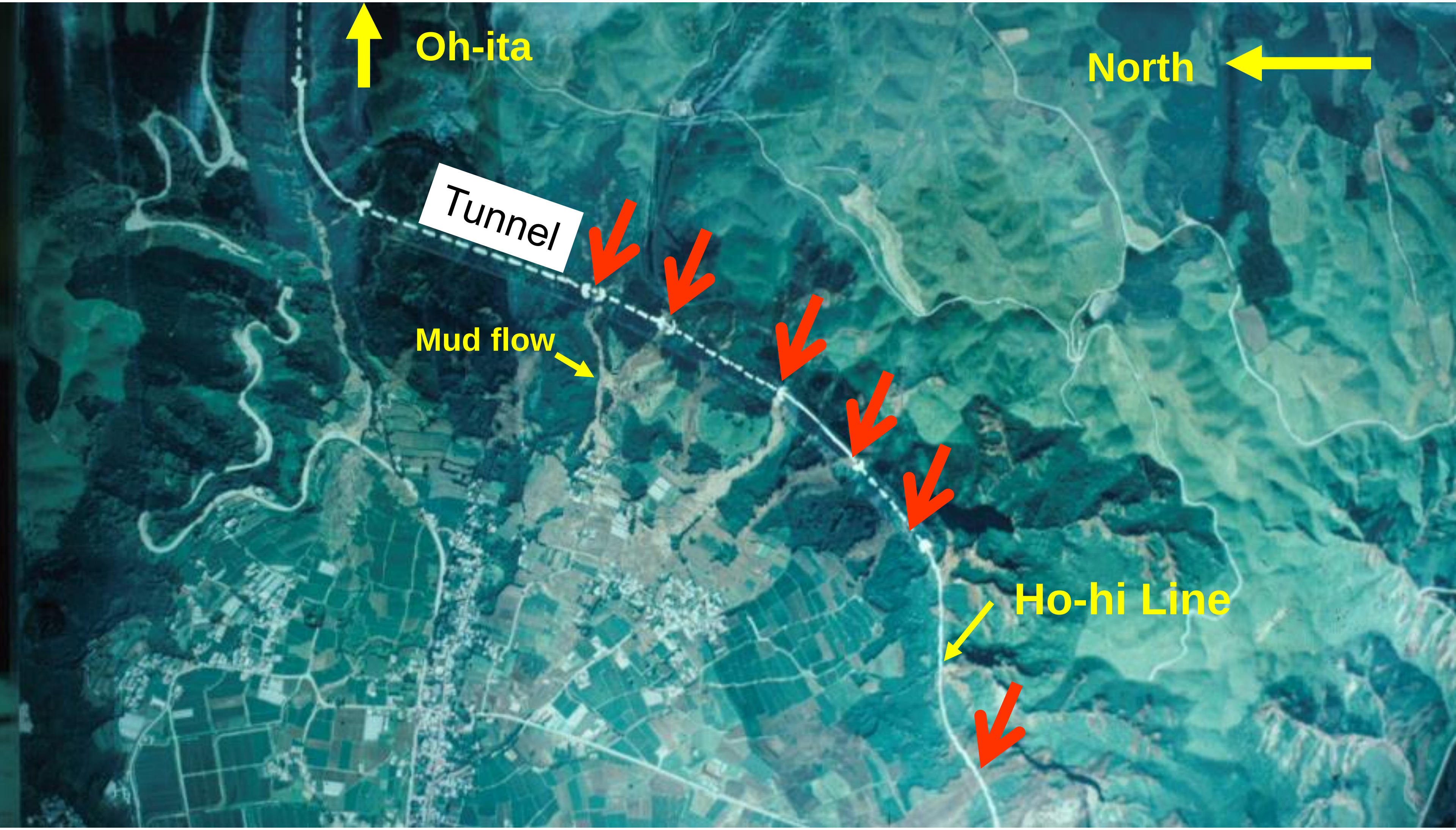
2004 Niigata-ken Chuetsu Earthquake



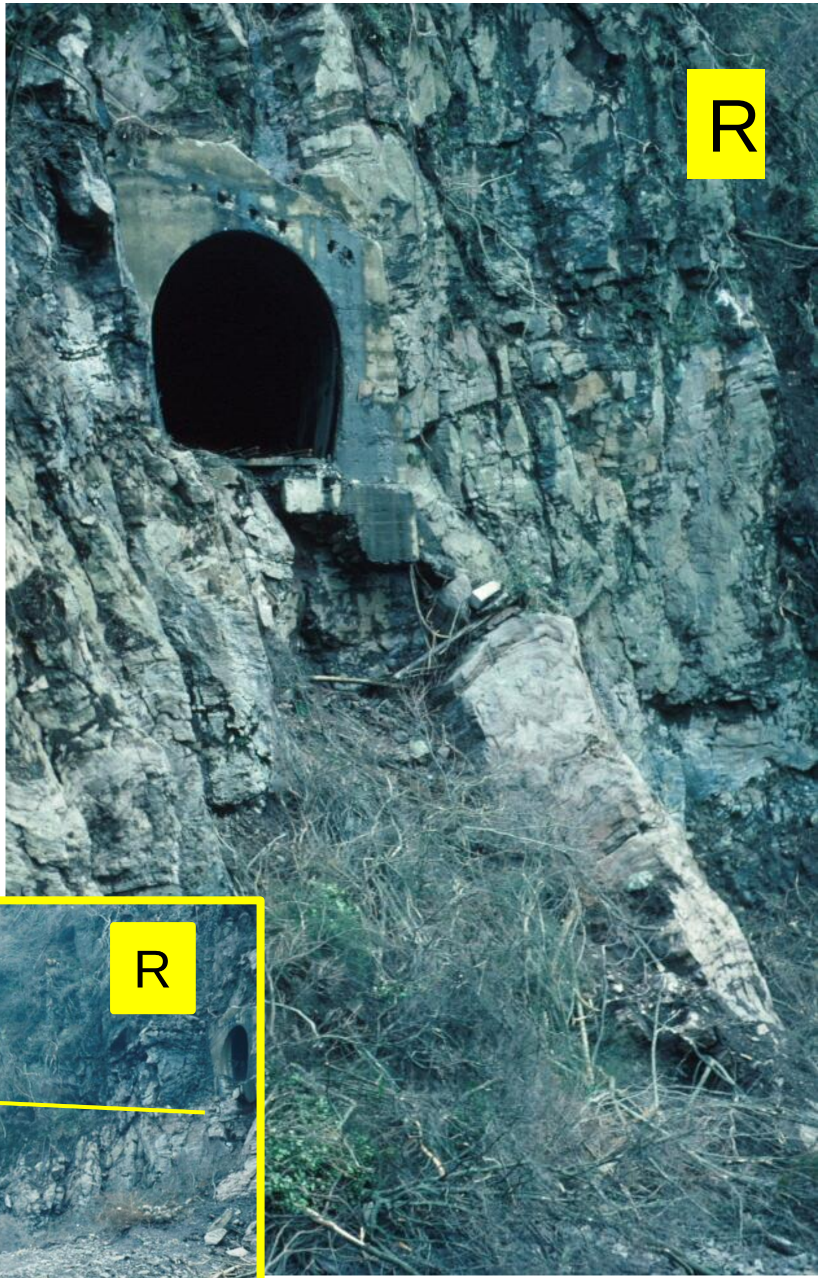


2004 Niigata-ken Chuetsu Earthquake

Embankments for Railway (Ho-hi Line) collapsed by flood in1990
Mt. Aso area, Kyushu, Japan

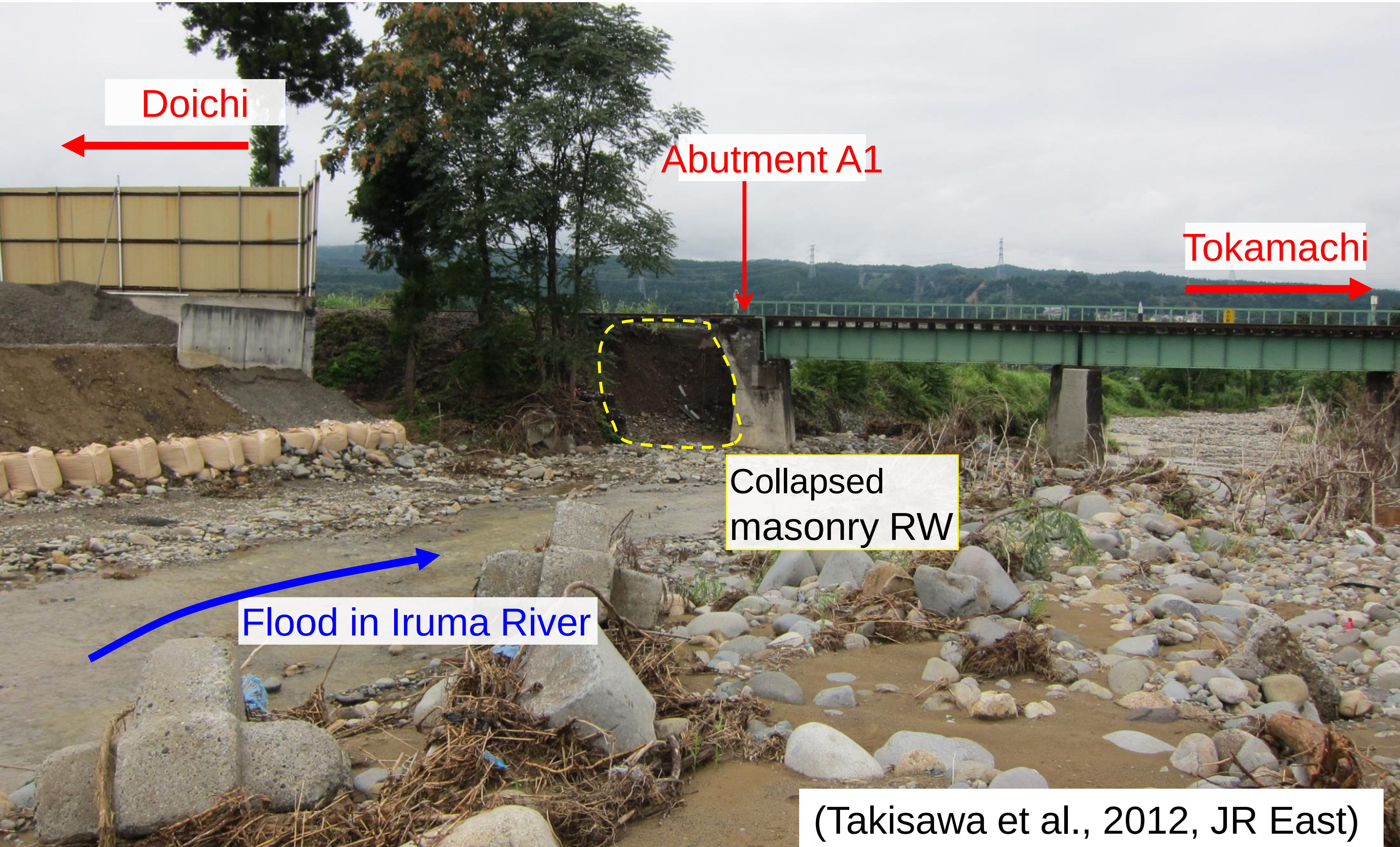


A small-diameter drain pipe crossing the embankment was clogged by flowing timbers. Then, a natural reservoir was formed. The embankment was fully eroded by over-topping flood.



Site 2

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

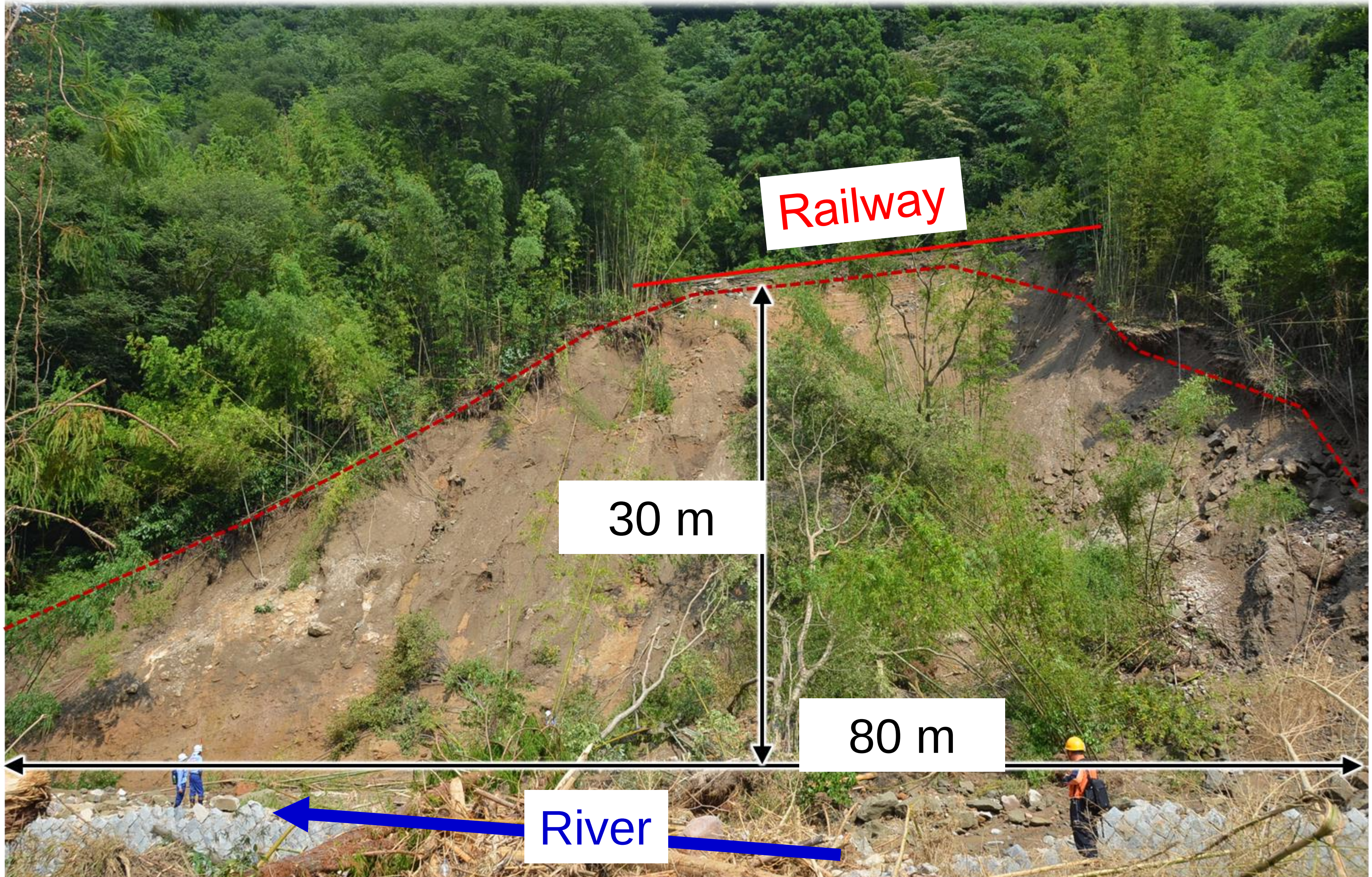


Collapse of a masonry wing RW for a RC bridge abutment by scouring in the subsoil and erosion of the backfill by river flood, Iiyama Line (JR East), July 2011

(Takisawa et al., 2012, JR East)

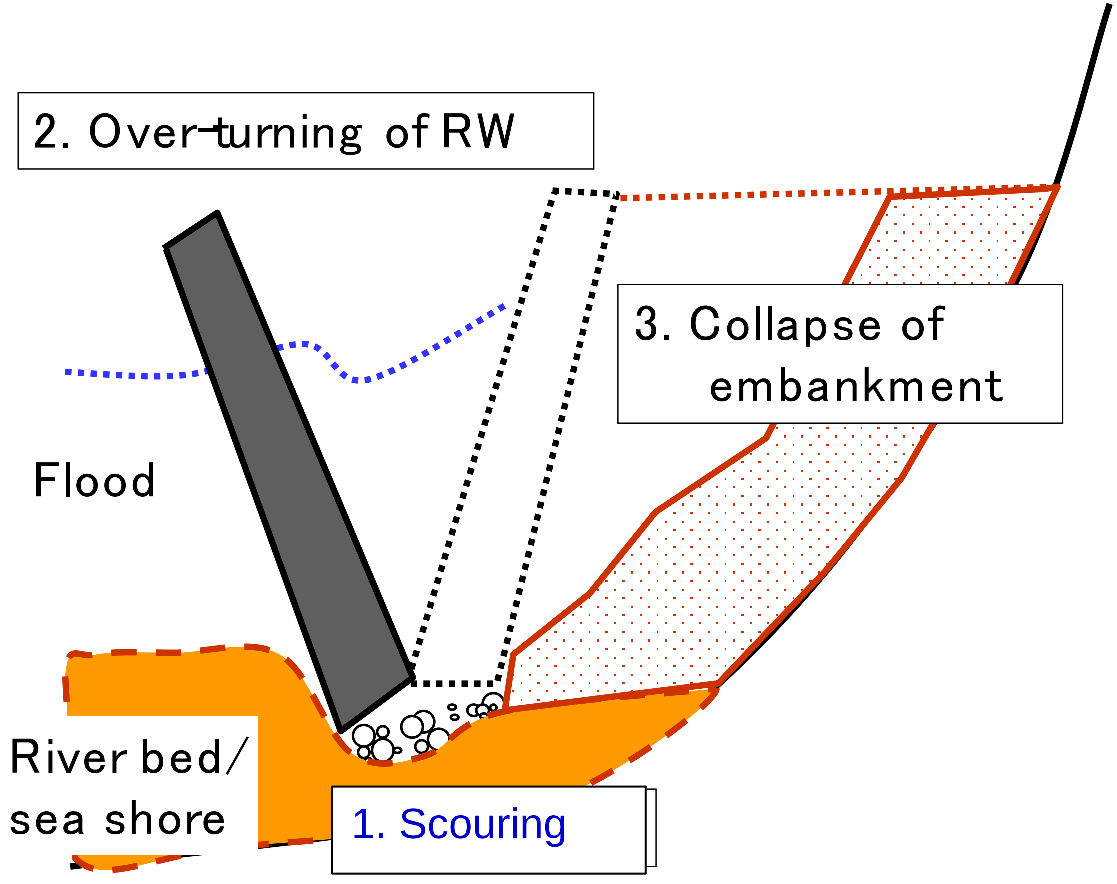
Collapse of railway embankment by scouring at the toe of embankment by river flood (28 July 2013)

JR West



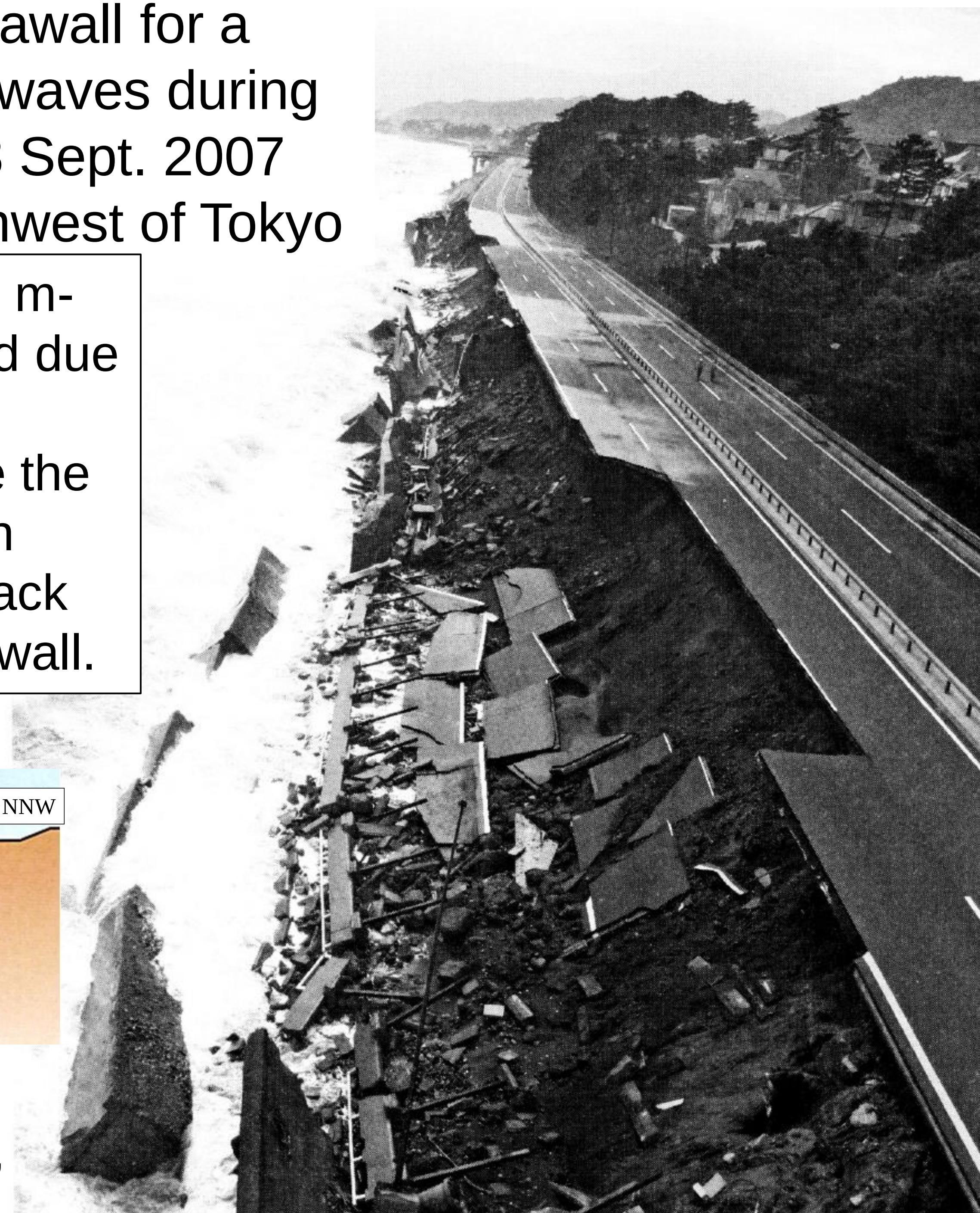
Conventional type cantilever RW

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

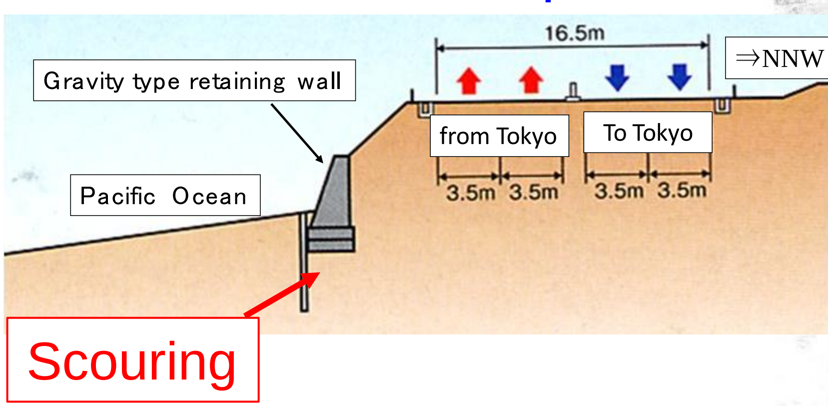


Collapse of gravity-type seawall for a length of 1.5 km by ocean waves during a storm (Typhoon No. 9), 8 Sept. 2007 National Road No. 1, southwest of Tokyo

In front of the wall, about 100 m-wide sand beach disappeared due to erosion by coastal current during the last 60 years since the completion of this road, which resulted in frequent direct attack of storm ocean waves to the wall.



Before collapse:



(by the courtesy of Ministry of LITT, Japan)

Shima-no-koshi Station, Sanriku Railway

Before the 2011 (11 March) Great East Japan Earthquake

Collapse of RC viaduct by tsunami

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

Tsunami

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

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

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6) Low stability against severe seismic load, scouring, erosion, tsunami etc.
7) Not reliable for High-Speed Railways.

⇒ For the last 40 years, continuous efforts to develop the GRS structures that can alleviate these problems …….

The solution by three technical breakthroughs:

1) The use of full-height rigid (FHR) facing for changes:

a) from low earth pressure to high earth pressure on the facing; &

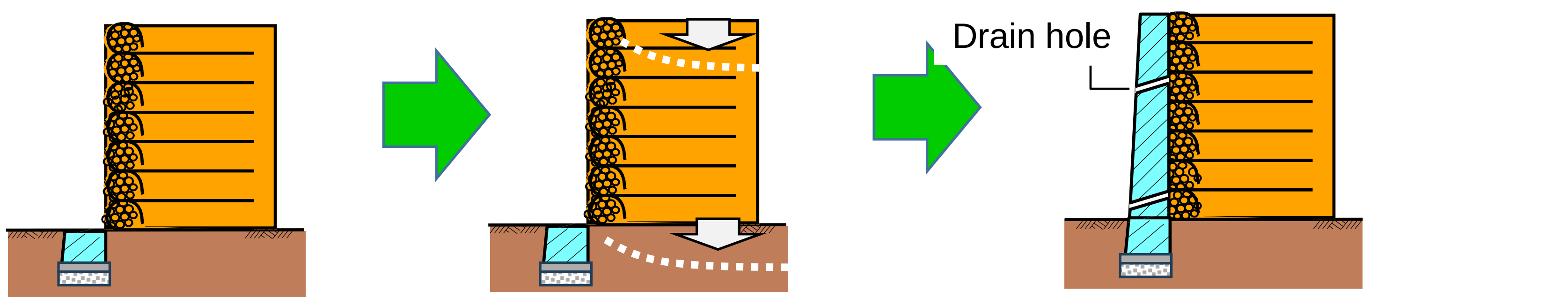
b) from the facing as a secondary non-structural component to the facing as a primary structural component.

2) Structural integration of:

a) **the FHR facing to the reinforced backfill**; &

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.

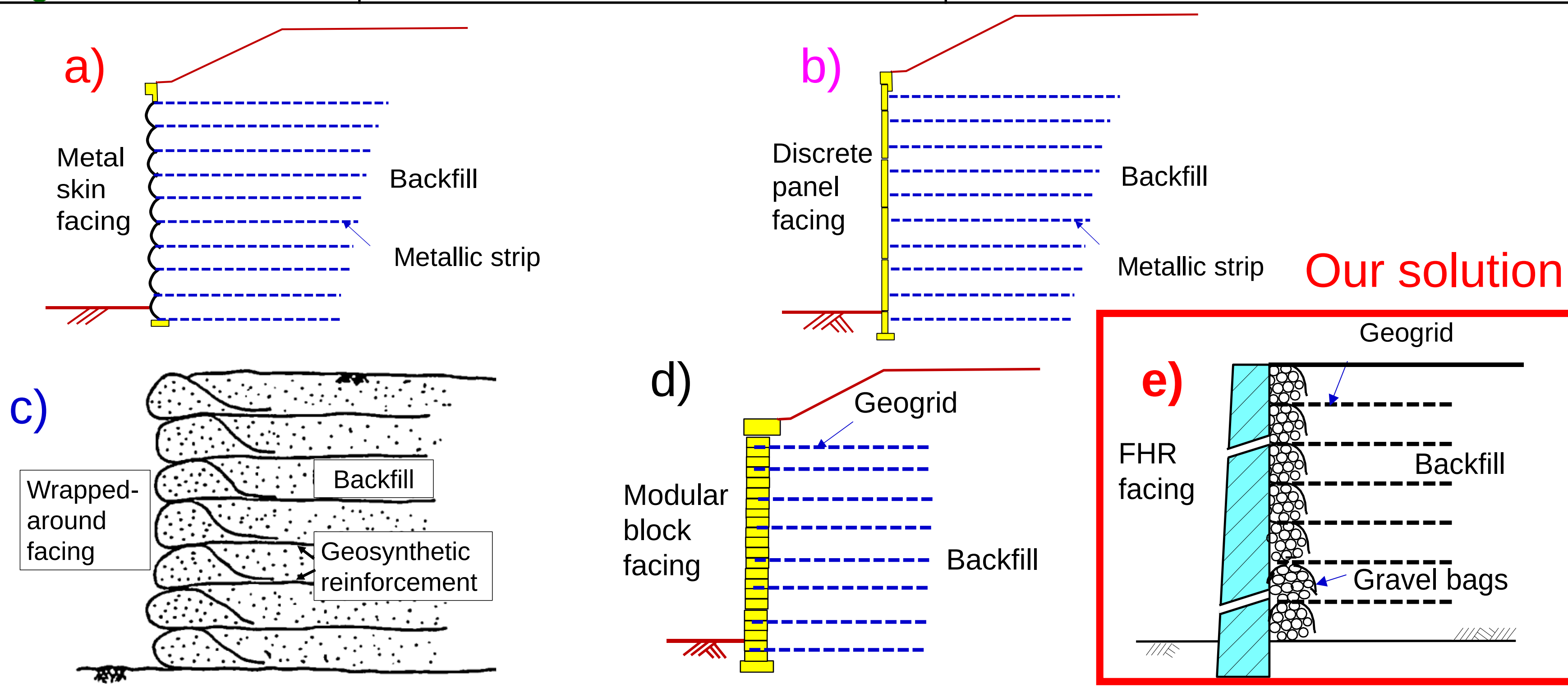
3) Staged construction for a change of construction sequence: from the facing before the backfill to the facing after the backfill.



Deformable facing | Settlement | Full-height rigid facing

Various types of mechanically stabilized earth (MSE) RW having different types of facing and reinforcement- after 40 years

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**



Why this solution is relevant ? ….. some reasons

1) The use of full-height rigid (FHR) facing for changes:

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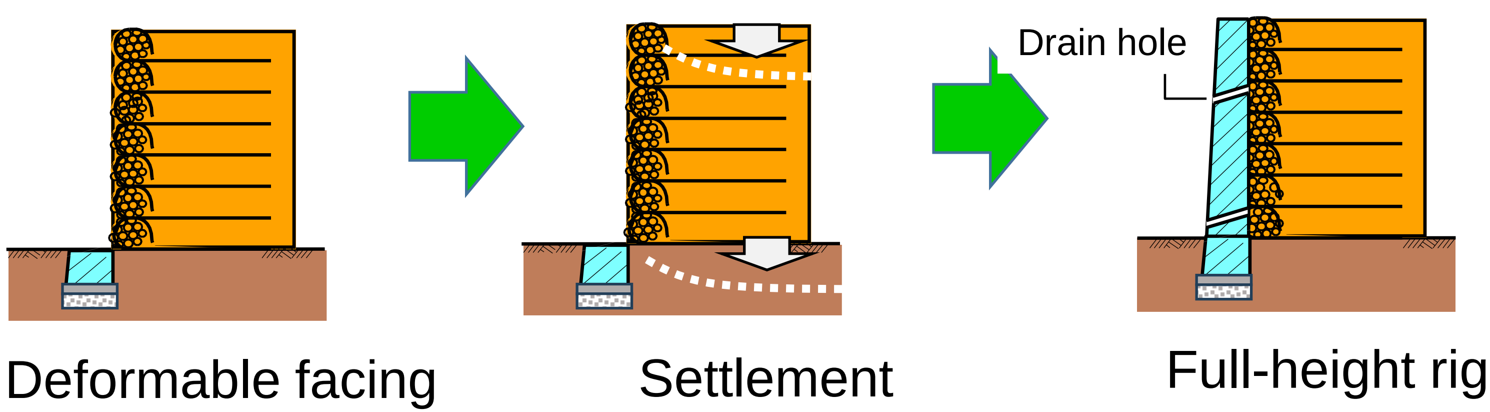
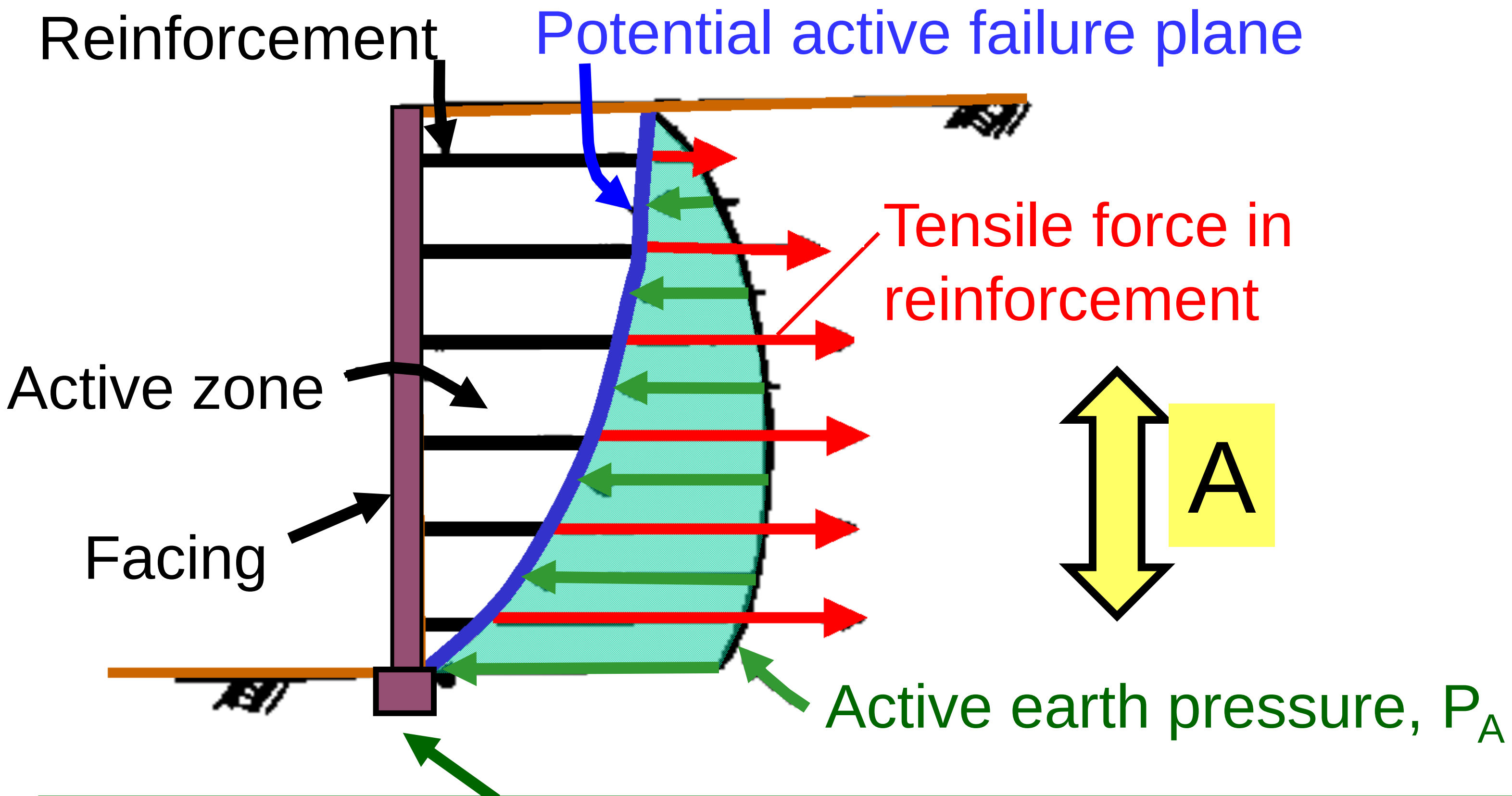
b) **the girder to the FHR facing with GRS Integral Bridge**: for a change from a statically determinate but unstable structure to a statically in-determinate but stable one.

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



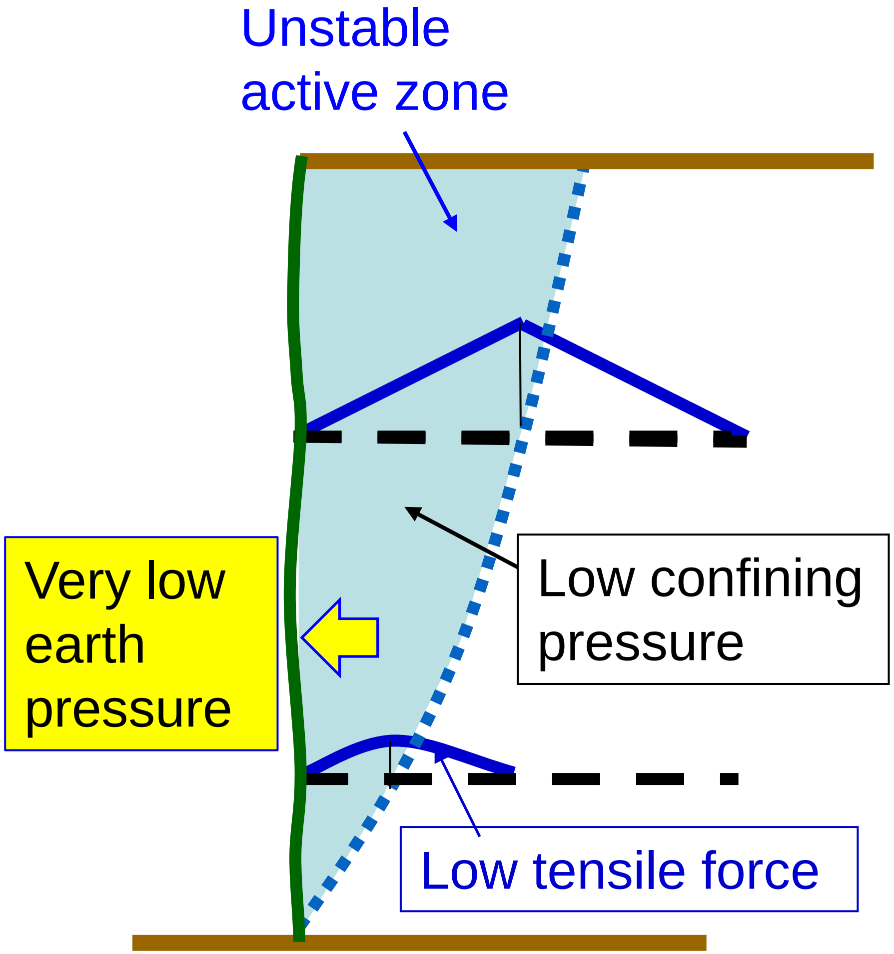
GRS RW is not a cantilever structure- 1 !

Force equilibrium **A** along the potential active failure plane:
- at each level, the active earth pressure is resisted by the tensile reinforcement (unlike a cantilever structure).



Then, small overturning moment & small lateral thrust load
So, usually a costly pile foundation is not required.

However, when the facing is flexible ……….



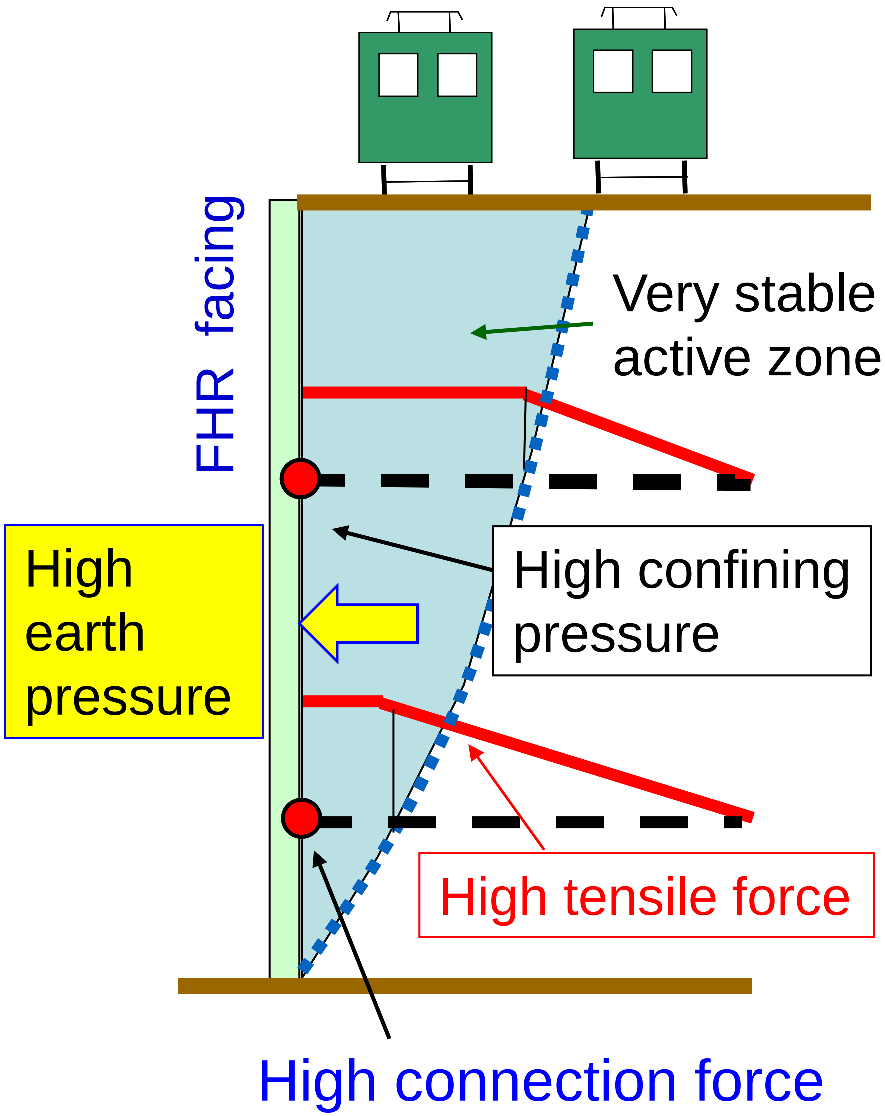
Very low earth pressure on the facing, which results into:

→ 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

On the other hand, when FHR facing is firmly connected to reinforcement....



High earth pressure on the facing, which results into:

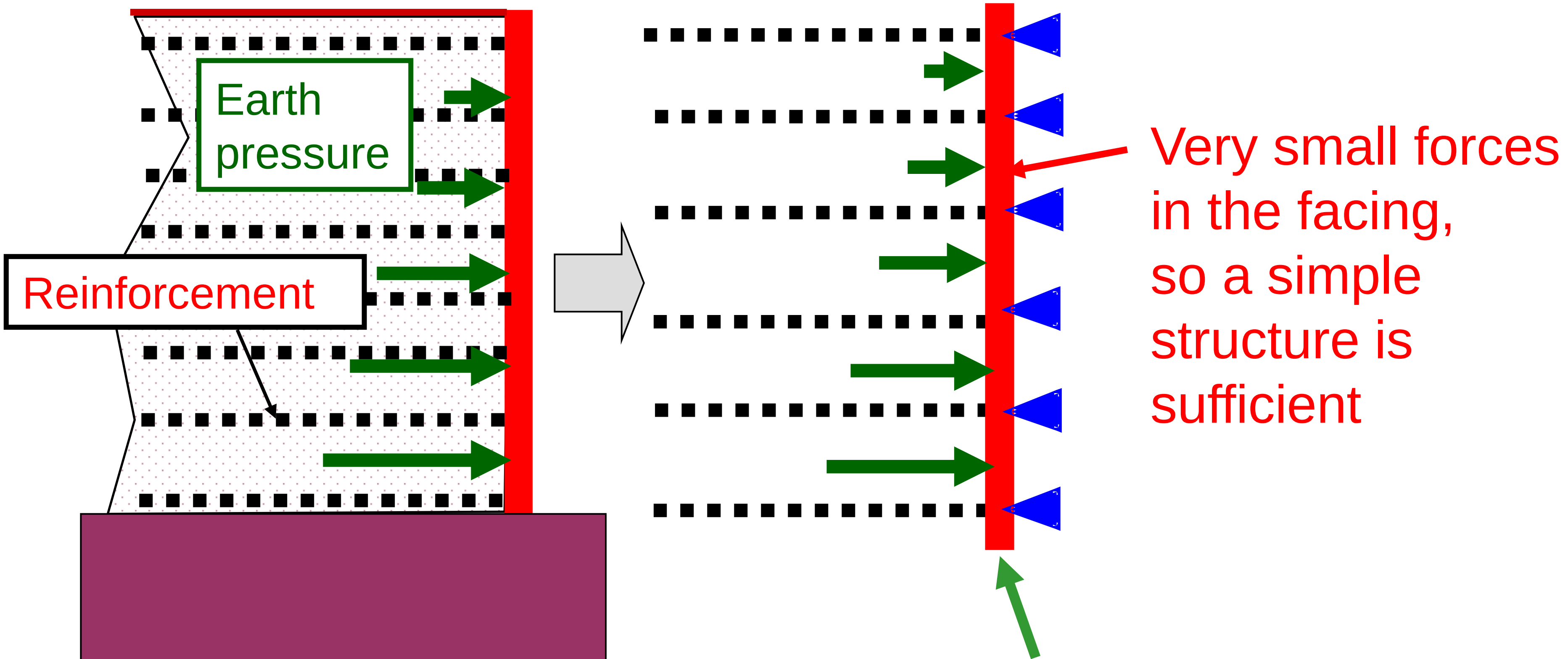
→ High tensile forces in the reinforcement (even at low levels)

→ 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.

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



Then, small overturning moment & small lateral thrust load at the facing base ⇒ a pile foundation is not required, and the wall becomes stable even against severe seismic loads

Why this solution is relevant? ….. some reasons

1) The use of full-height rigid (FHR) facing for changes:

a) from low earth pressure to high earth pressure on the facing; &

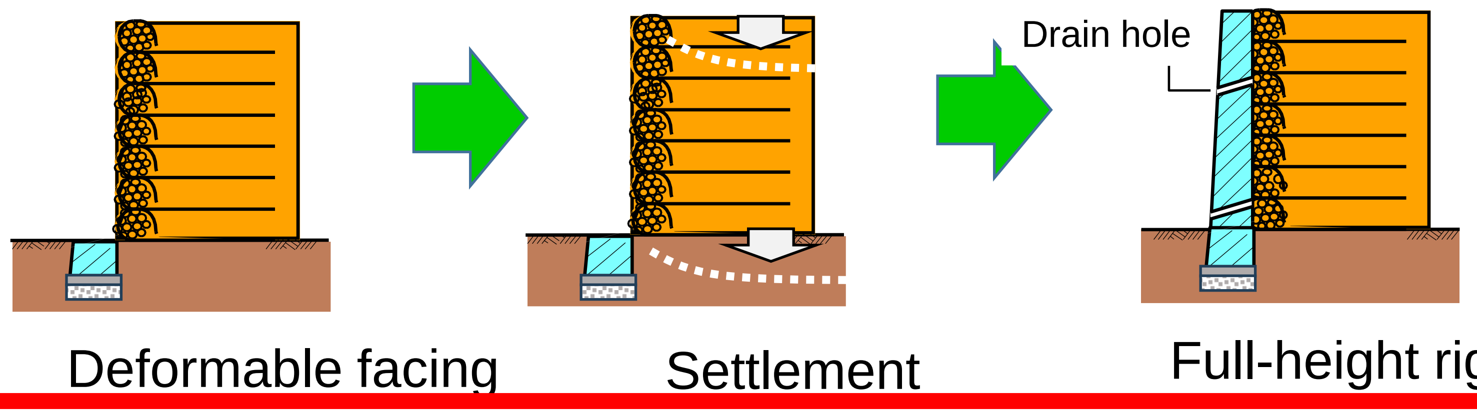
b) from the facing as a secondary non-structural component to the facing as a primary structural component.

2) Structural integration of:

a) **the FHR facing to the reinforced backfill**; and

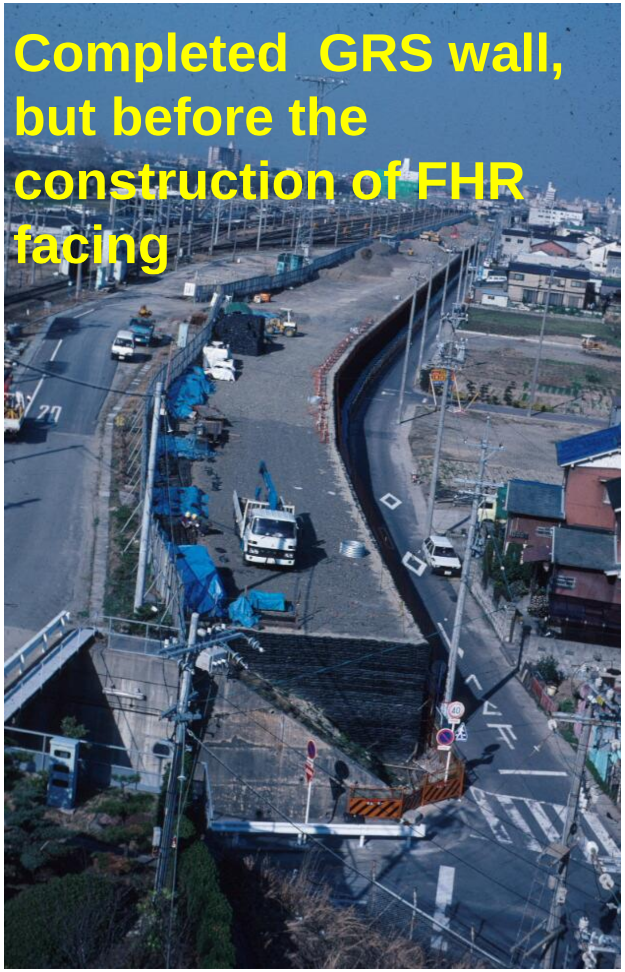
b) **the girder to the FHR facing with GRS Integral Bridge**: for a change from a statically determinate but unstable structure to a statically in-determinate but stable one.

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



Staged construction of GRS RW with FHR facing

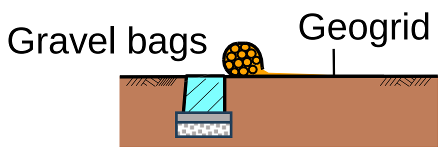
Depot for HSR (Shinkansen) at Biwajima, Nagoya, 1990 - 1991
- average wall height= 5 m & total wall length= 930 m



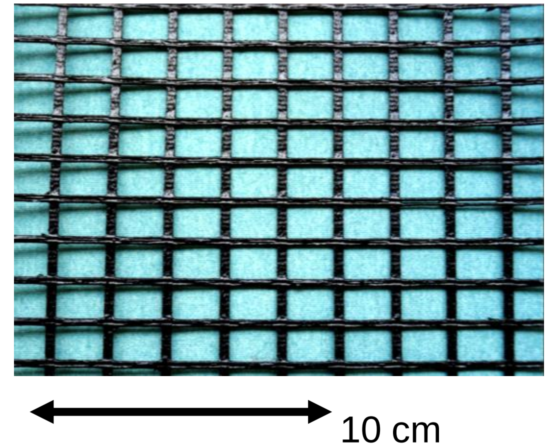
Staged construction: 1) & 2)

- Start of construction

1) Levelling pad & embedded part of FHR facing



2) Placing gravel bags wrapped-around with geogrid

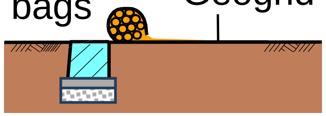


Typical polymer geogrid: bi-axial PVA grid:

Staged construction: 3) & 4)

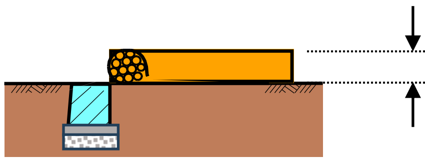
- Compaction of the backfill with a help of gravel bags placed at the shoulder of each soil layer

1) Levelling pad for facing

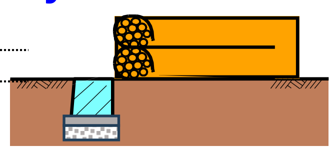


2) Placing gravel bags wrapped-around with geogrid

30 cm= 2 x 15 cm-thick soil layer



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.

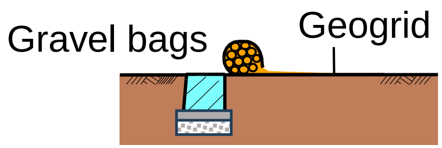
Besides, a small vertical spacing (30 cm) results in:

1) a large contact area between the geogrid and the backfill:
2) then, a high stability of the reinforced backfill as a composite

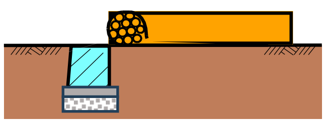
Staged construction: 5)

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

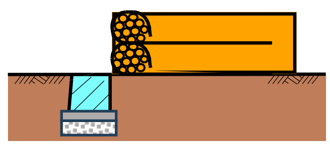
1) Levelling pad for facing



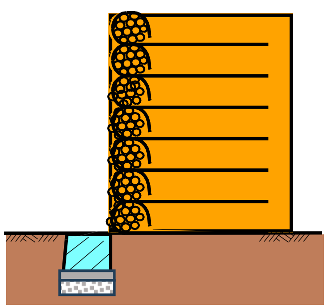
2) Placing gravel bags wrapped-around with geogrid



3) Backfilling & compaction



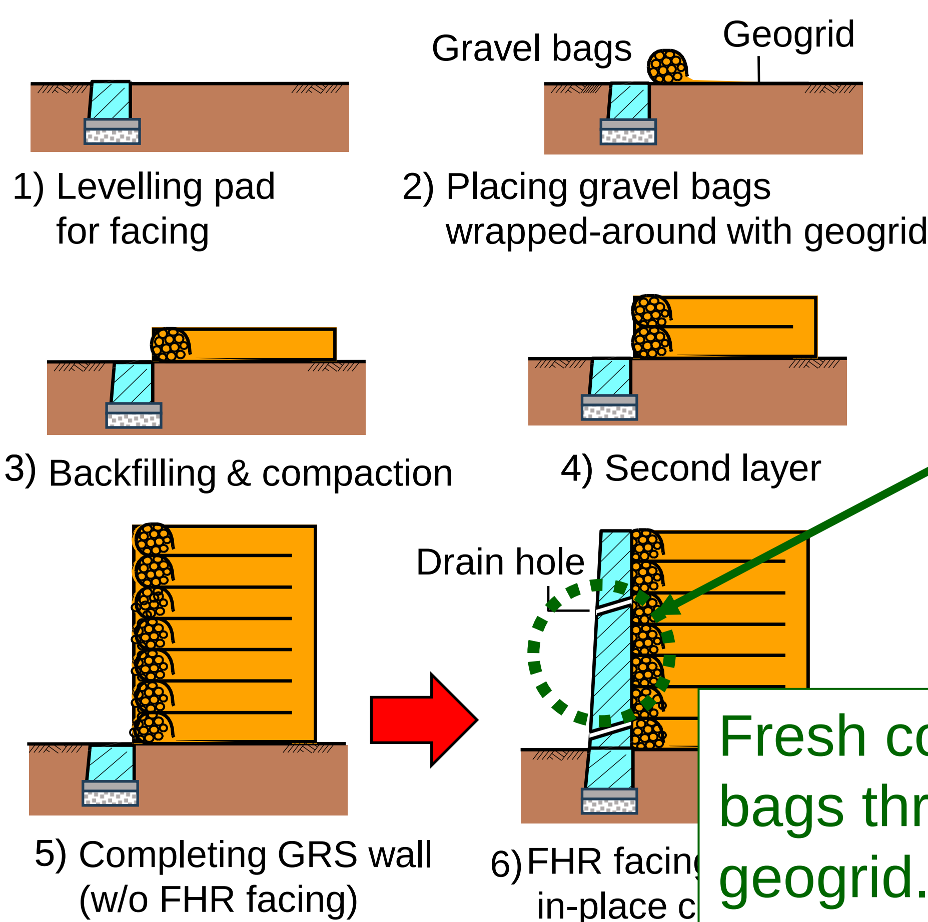
4) Second layer

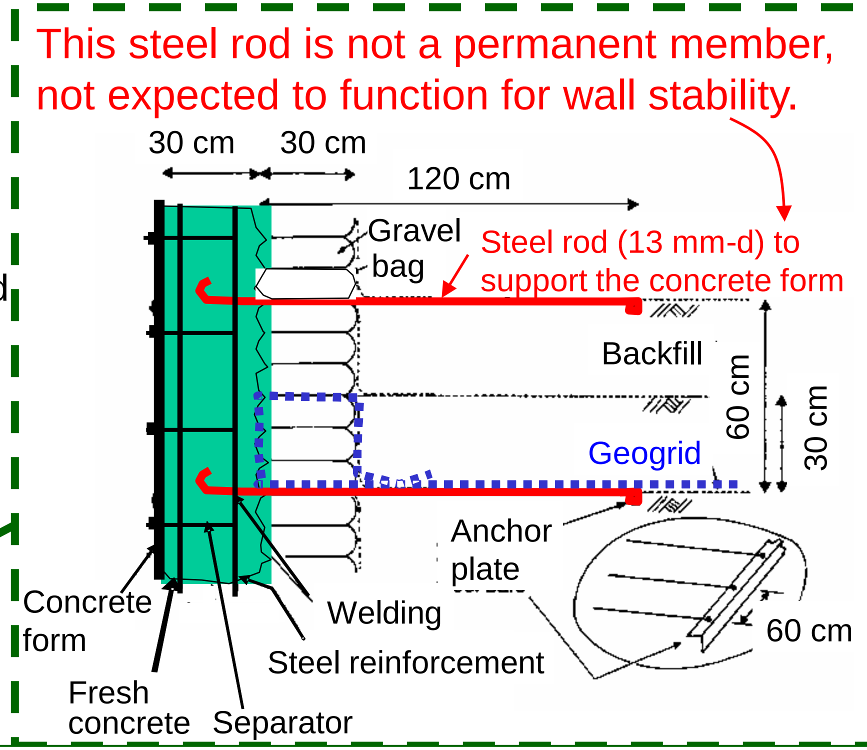


5) Completing GRS wall (w/o FHR facing)

Staged construction from step 5) to step 6):

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



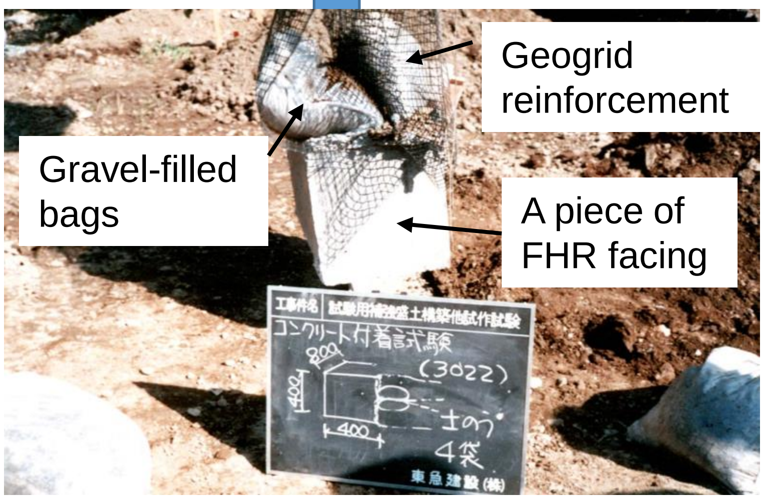


Fresh concrete enters the gravel-filled bags through the aperture of the wrapping geogrid. ⇒ As a result, FHR facing is firmly connected to geogrid layers.

Field & laboratory tests to confirm high separation strength

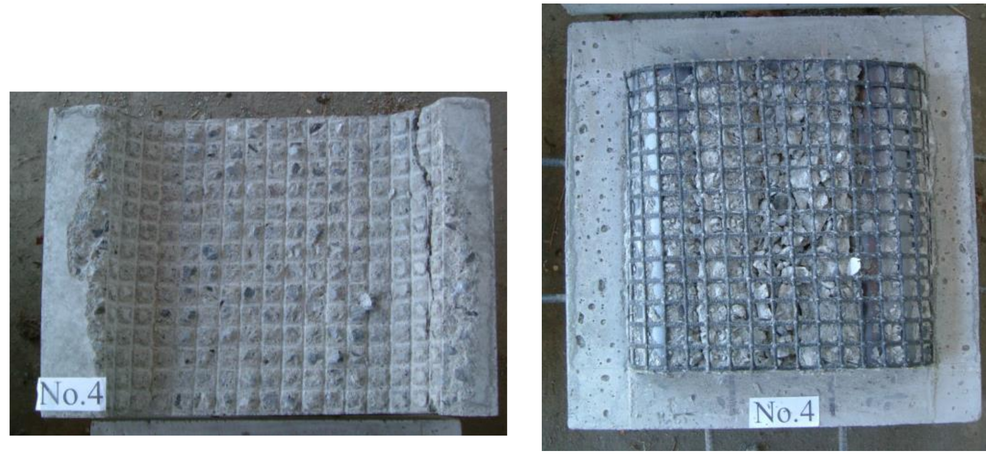
Field separation test

Lift up

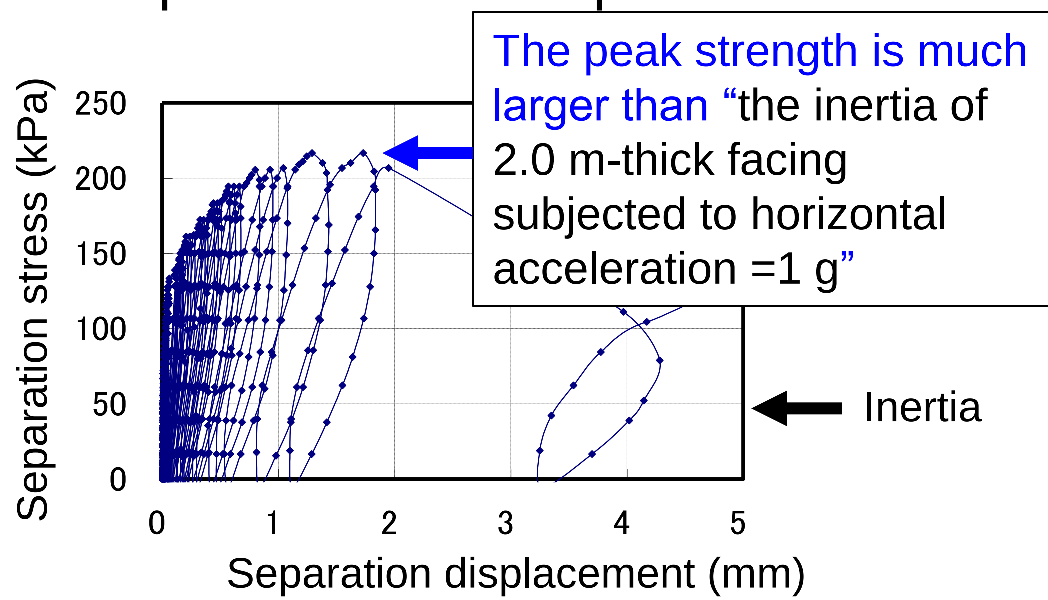


Test specimen (cut out from 40 cm-thick full-scale FHR facing), hung under 1 g:
⇒ no separation

Laboratory separation test

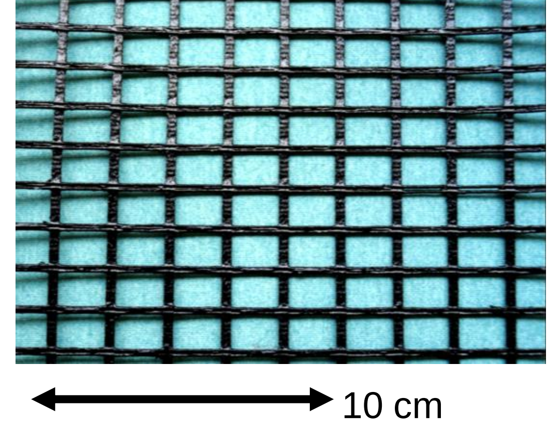


Specimen after separation



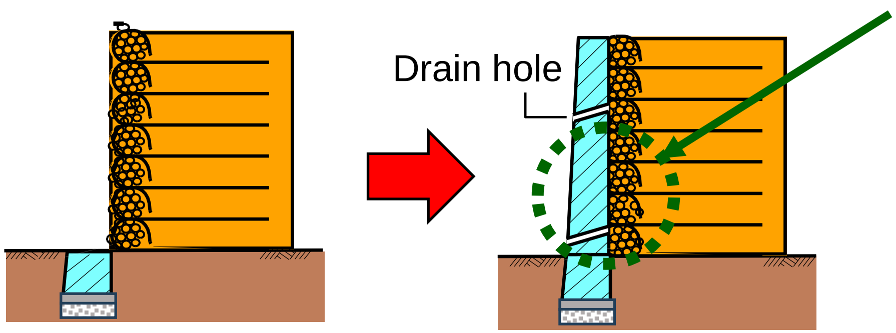
The properties required for the geogrid:

1) Sufficient strength & stiffness with low creep deformation
2) Limited damage during backfill compaction
3) High anchorage strength in concrete & backfill; & good adhesiveness with concrete
4) High long-term resistance against high pH of concrete



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

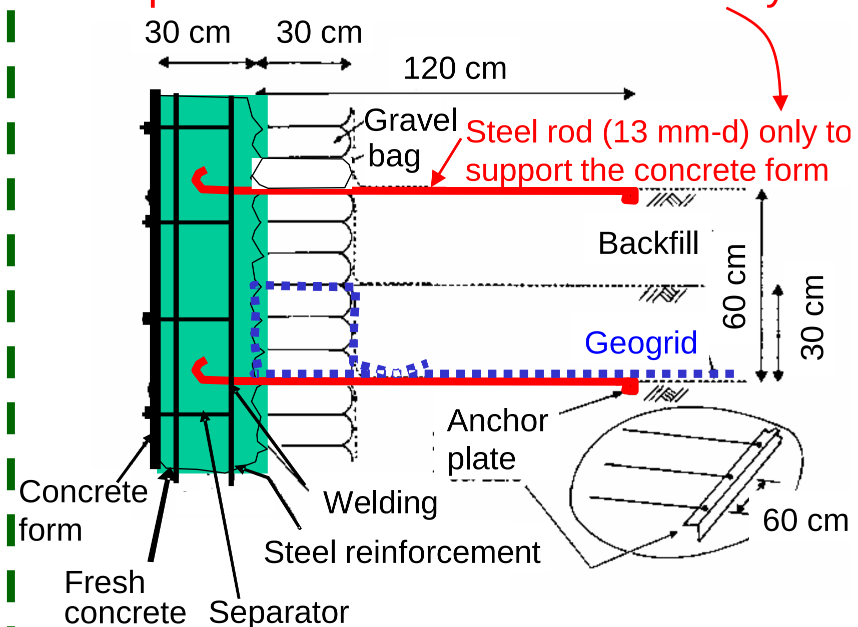
3) & 4) are particularly important, as the geogrid is in direct contact with fresh concrete.



5) Completing GRS wall (w/o FHR facing)

6) FHR facing by casting-in-place concrete

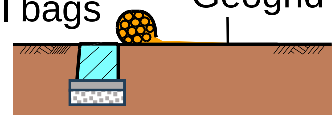
This steel rod is not a permanent member, not expected to function for wall stability.



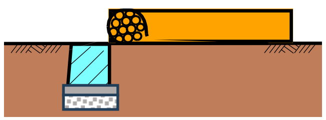
Staged construction: 6)
Completion of GRS RW by the construction of FHR facing

1) Levelling pad
for facing

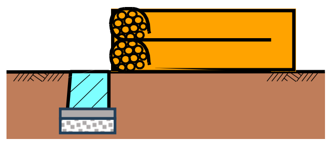
Gravel bags
Geogrid



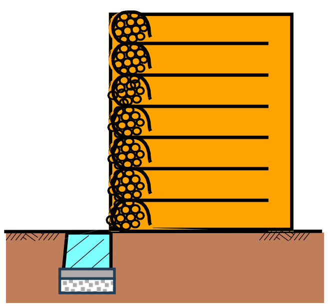
2) Placing gravel bags
wrapped-around with geogrid



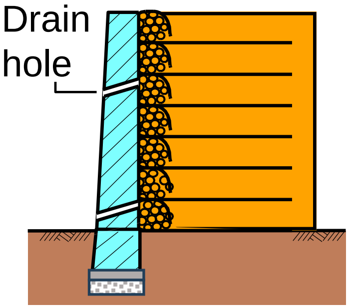
3) Backfilling & compaction



4) Second layer

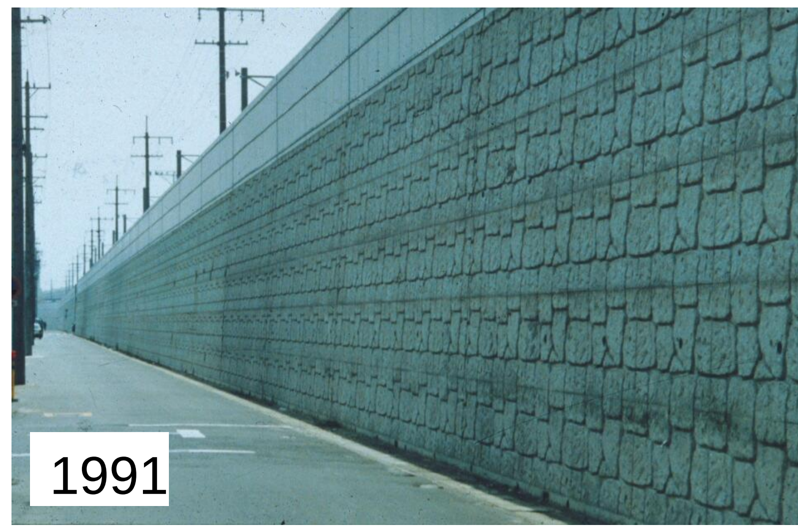


5) Completing GRS wall
(w/o FHR facing)

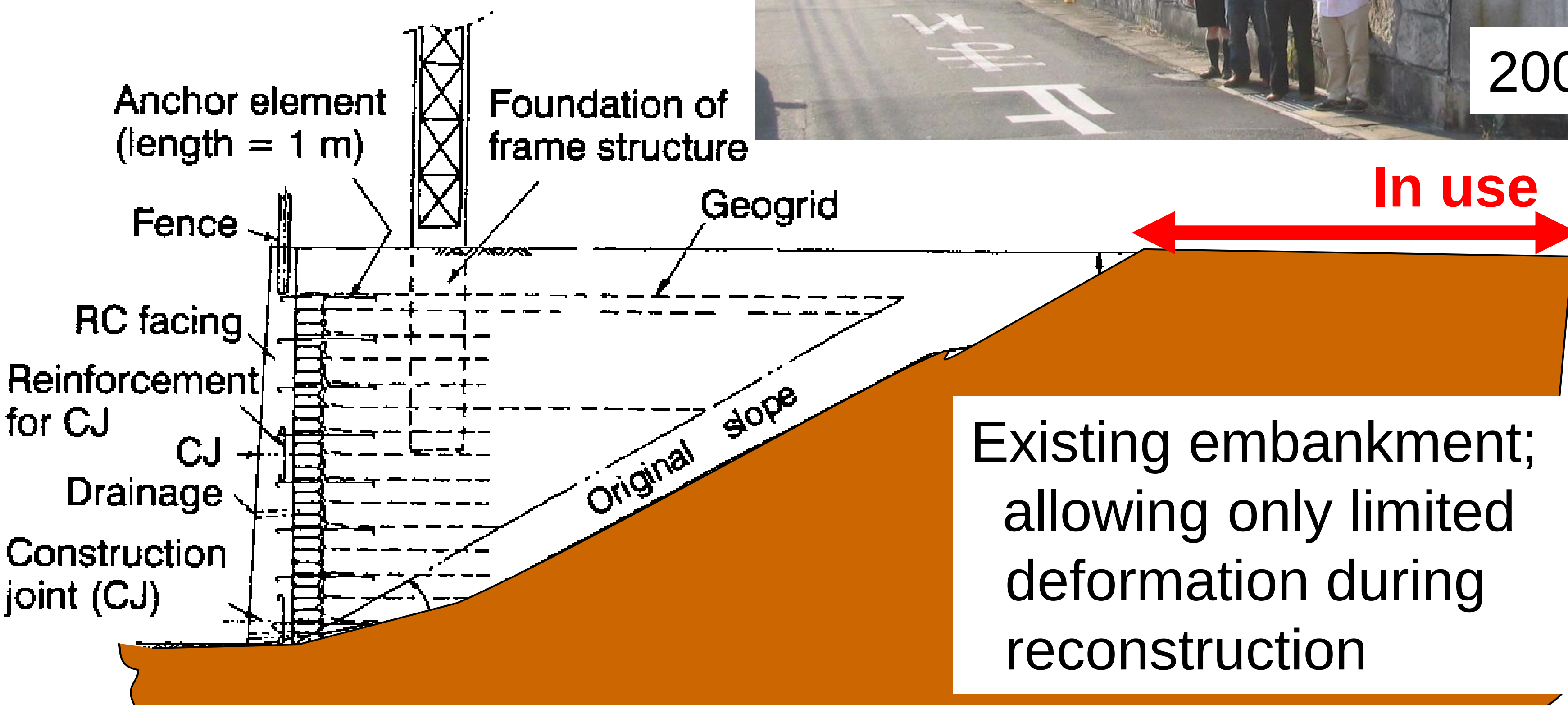


6) FHR facing by casting-
in-place concrete

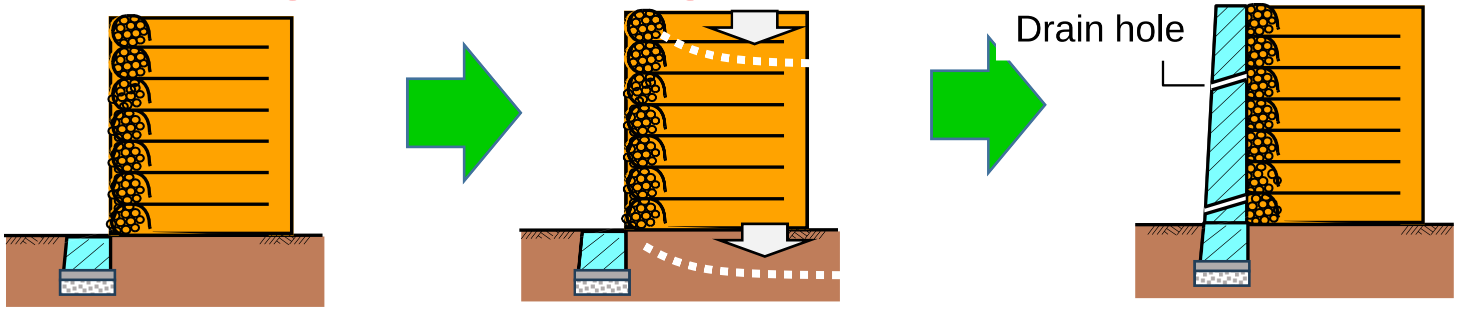
Typical completed GRS RW for a depot of HSR (Shinkansen) at Biwajima, Nagoya



Re-construction of a slope to a vertical wall



Advantages of staged construction- 1/3

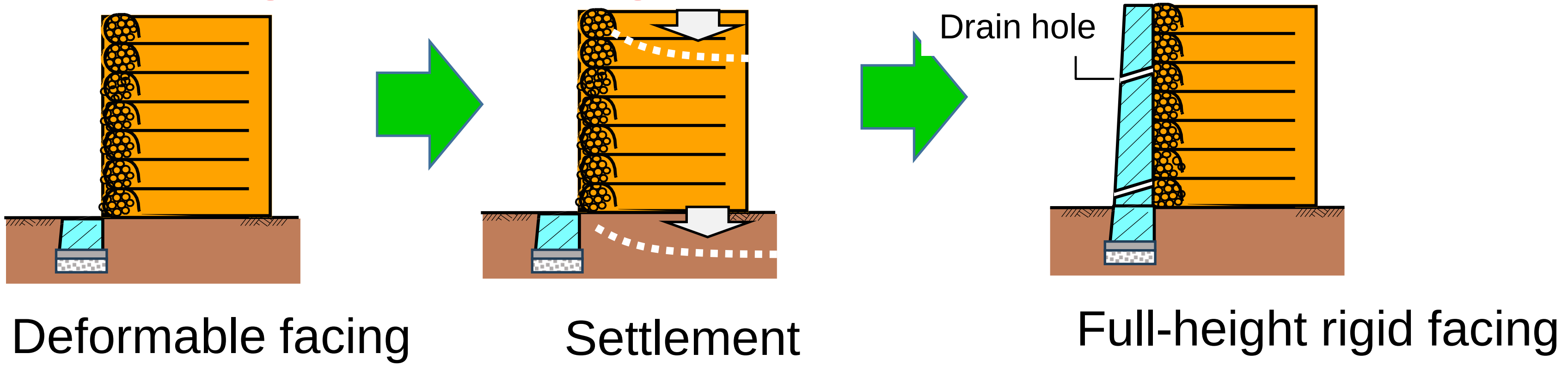


Deformable facing | Settlement | Full-height rigid facing

1) The temporary facing consisting of soil bags (or their alternative) enhances **effective soil compaction** near the wall face. The temporary facing is **strong** enough for sufficient stability of “the temporary wall” while **deformable** enough to accommodate the deformation of backfill & subsoil.

2) During long-term service, the FHR facing is **stiff & strong** enough to keep small the wall deformation, ensuring high wall stability, even when subjected to severe seismic loads.

Advantages of staged construction- 2/3



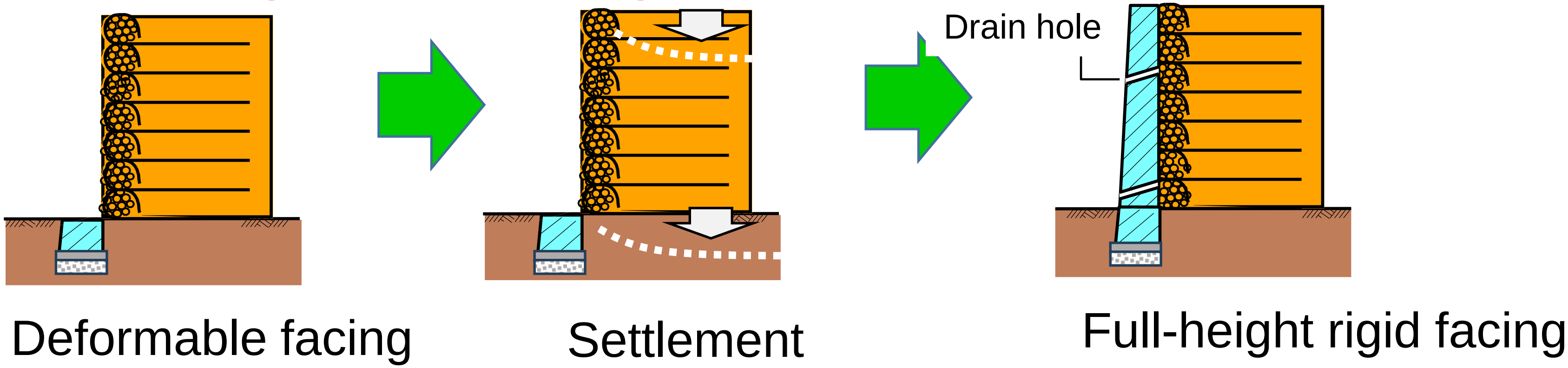
3) Essentially no damage to the facing/geogrid connection during long-term service & against severe seismic loads, because:

a) the post-construction differential settlement between the FHR facing and the backfill is essentially zero; and

b) the gravel bags protect the facing/geogrid connection.

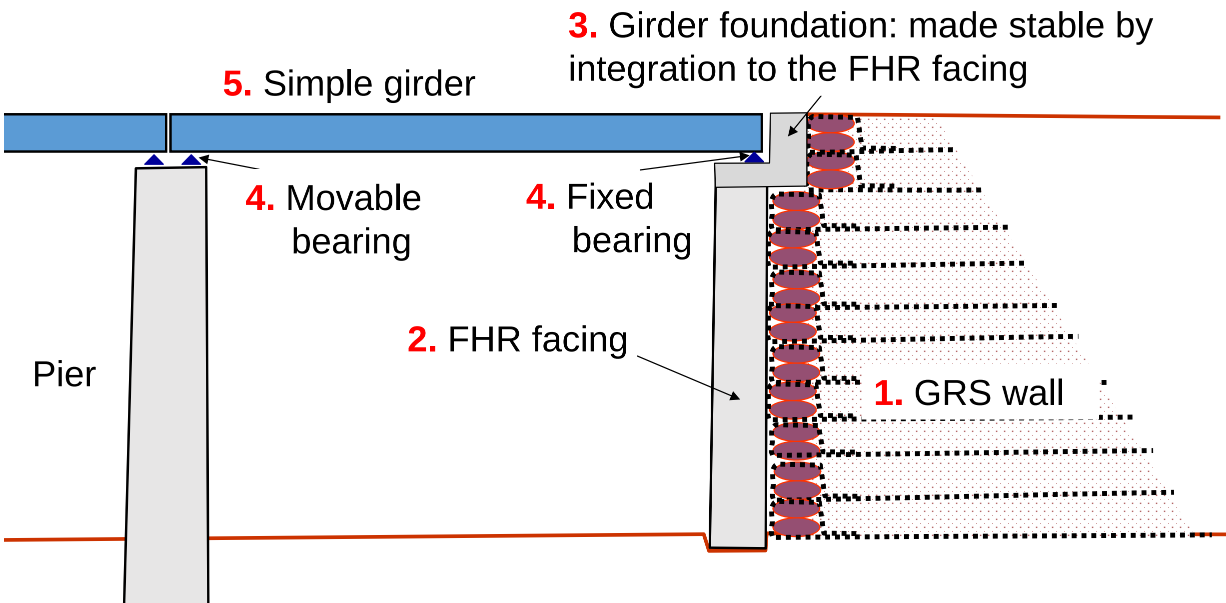
4) The potential deformation of the backfill & subsoil has taken place before the construction of FHR facing. So, the pile foundation to restrain the displacements of the facing becomes unnecessary.

Advantages of staged construction- 3/3

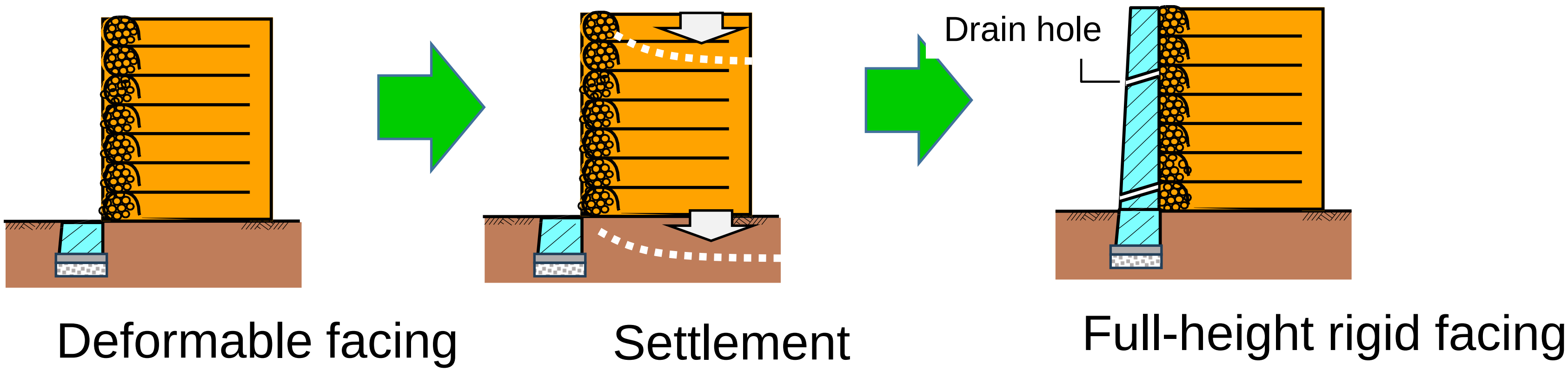


Then, the residual displacement of the bridge girder supported by GRS Bridge Abutment is kept very small despite no use of a pile foundation.

GRS Bridge Abutment



Advantageous features of GRS structure having stage-constructed FHR facing that alleviate many problems



High performance and high cost-effectiveness by:

1) High stability despite no use of a pile foundation.

2) Very small post-construction deformation/settlement.

3) Narrow space occupied during & after construction.

4) Cost-effective construction of stable RW on slope.

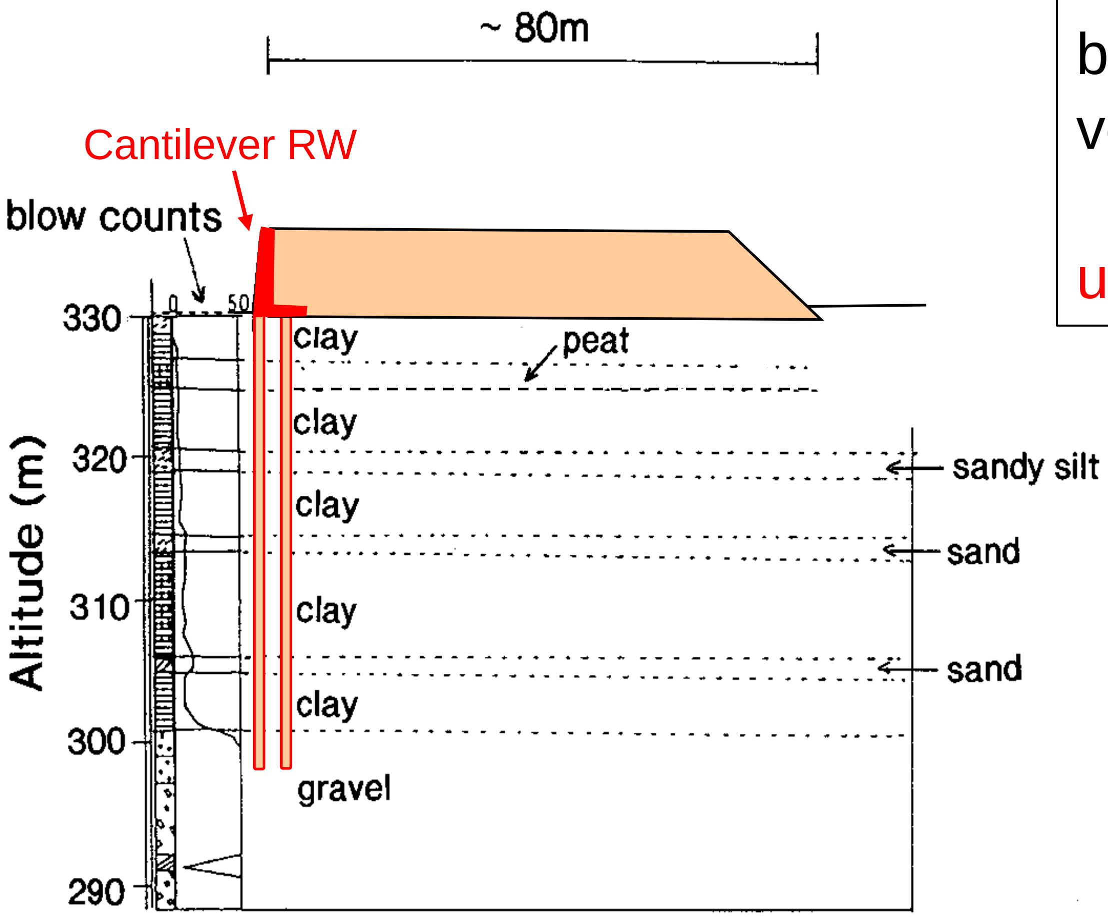
5) FHR facing can directly support other structures (e.g., bridge girder).

6) High stability against severe seismic load, scouring, erosion etc.

7) GRS structures for High Speed Railways

Embankment in Nagano, Japan

- Depot for High Speed Railway (Shinkansen)
- 2.0 m-high & 2 km-long on a very thick clay deposit

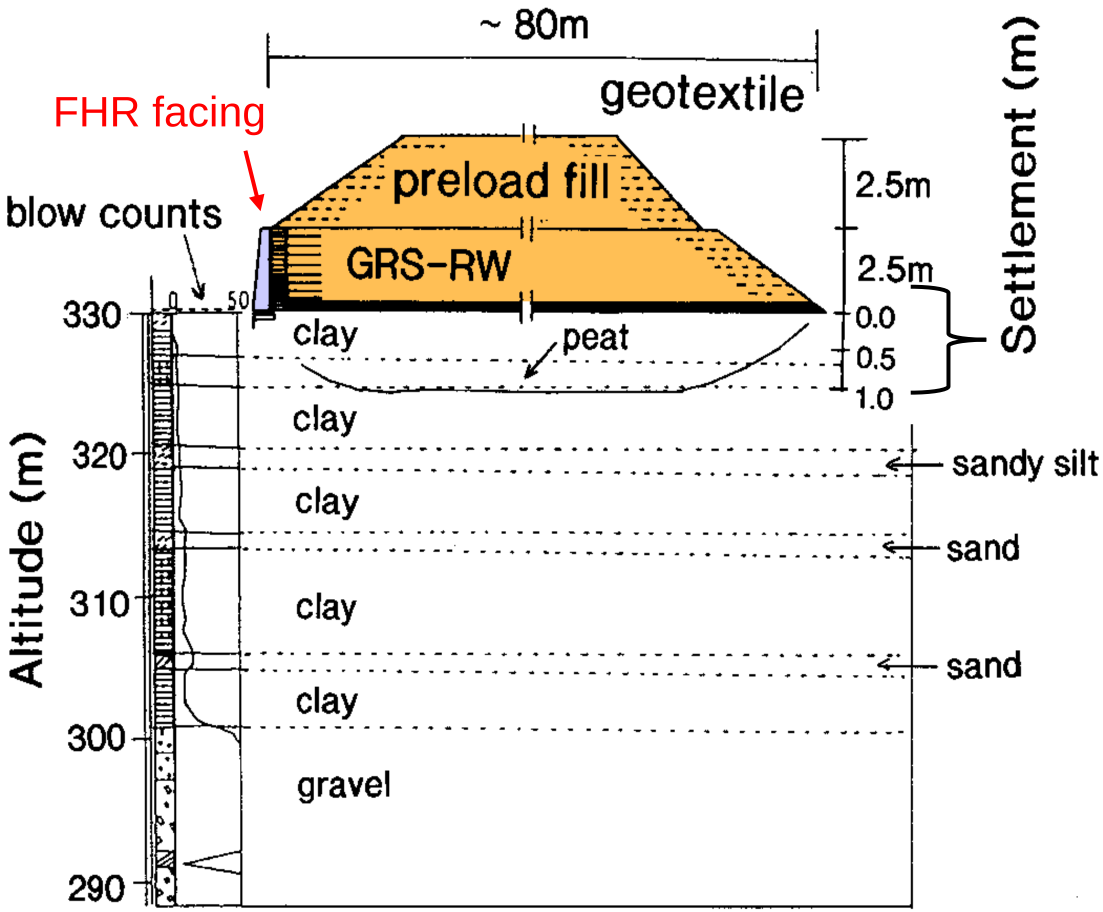


RW is necessary,
but canti-lever RW needs a very long pile:

utterly not cost-effective

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 (1993 – 1994)

wall height

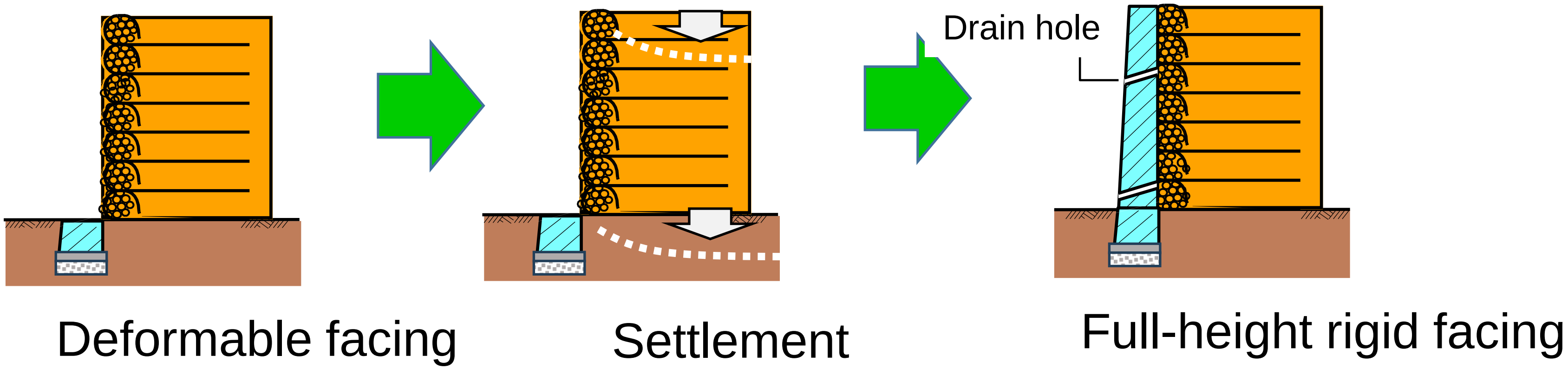
before preloading: 3.0 m

after preloading: 2.0 m

Construction of FHR facing after removing the preload fill, so FHR facing is free from large backfill settlement (≈ 1m) & irregular wall face deformation.

20 years after construction, 6th July 2014

Advantageous features of GRS structure having stage-constructed FHR facing that alleviate many problems



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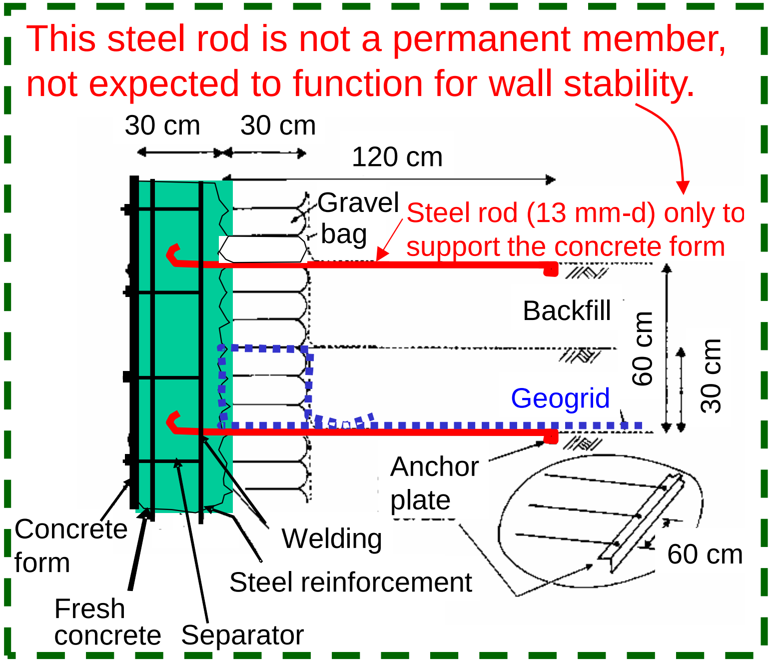
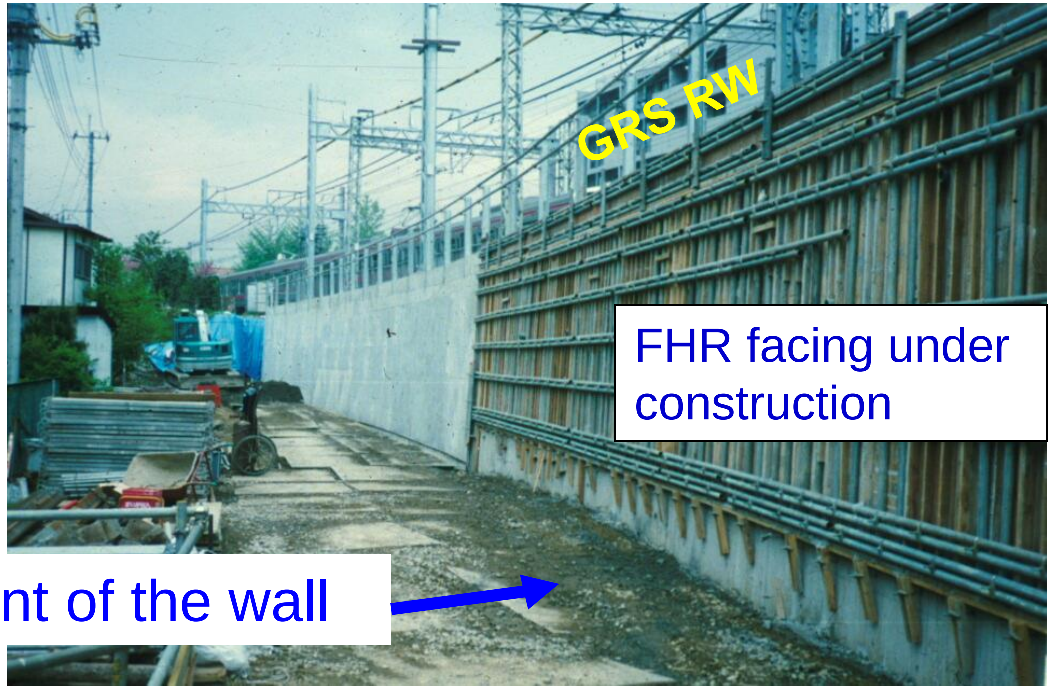
7) GRS structures for High Speed Railways

Keio Line, Hirayama Joshi

RW for a railway

A wide space occupied in front of the wall for a propping supporting external concrete form

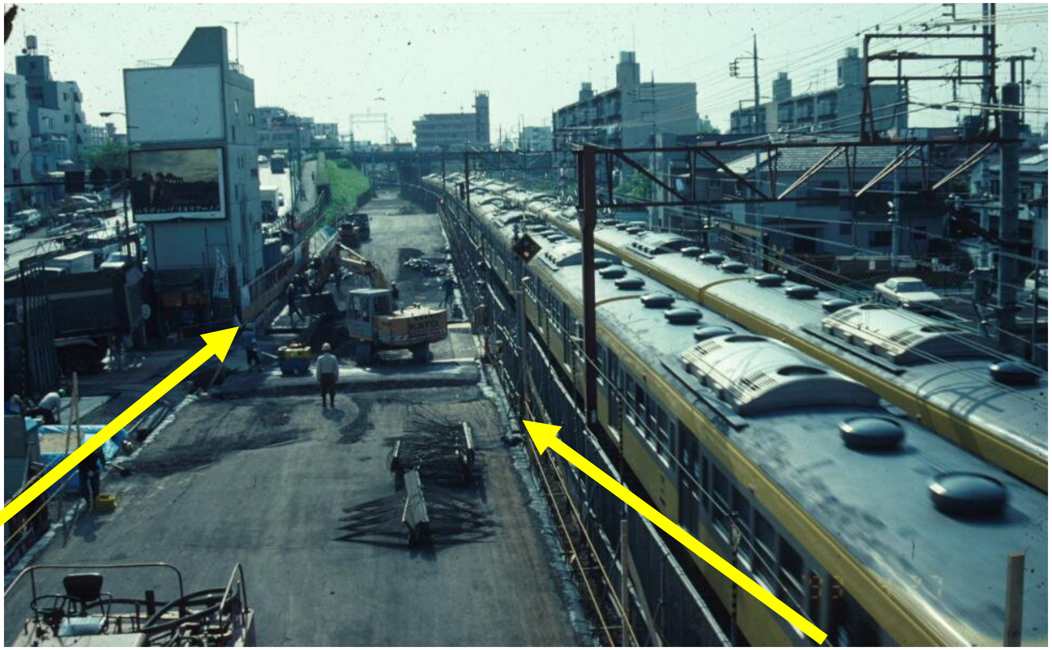




No space occupied in front of the wall

Seibu Ikebukuro Line, Tokyo, 1993

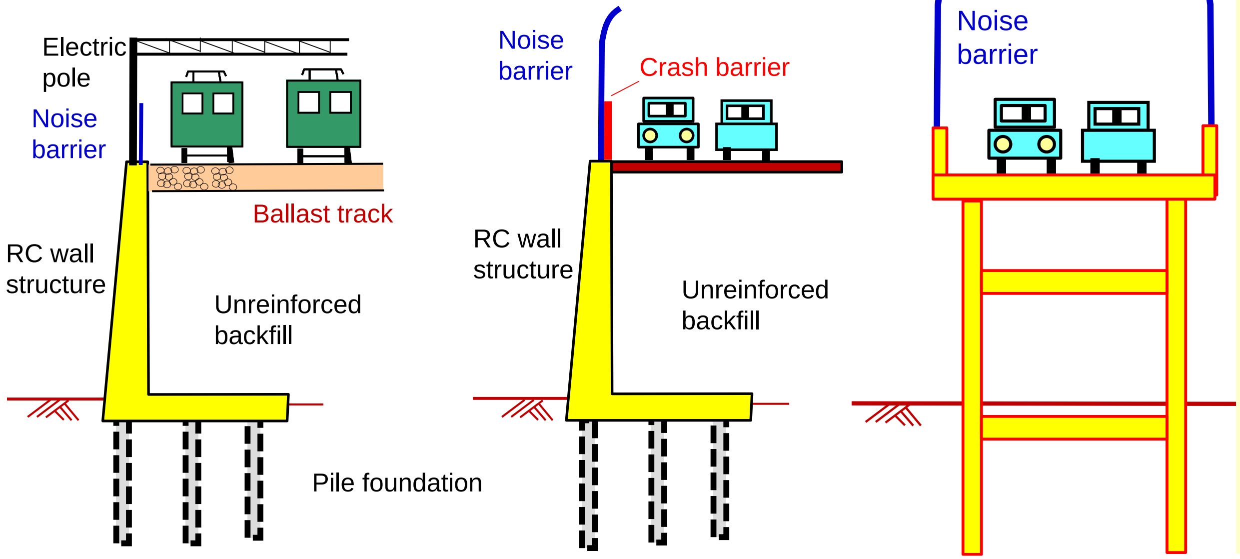
Construction of FHR facing at both sides of GRS approach fill in very narrow space in front of the wall face



No FHR facing during the compaction

Completed FHR facing

Conventional RWs & RC viaduct



<u>Advantages</u>

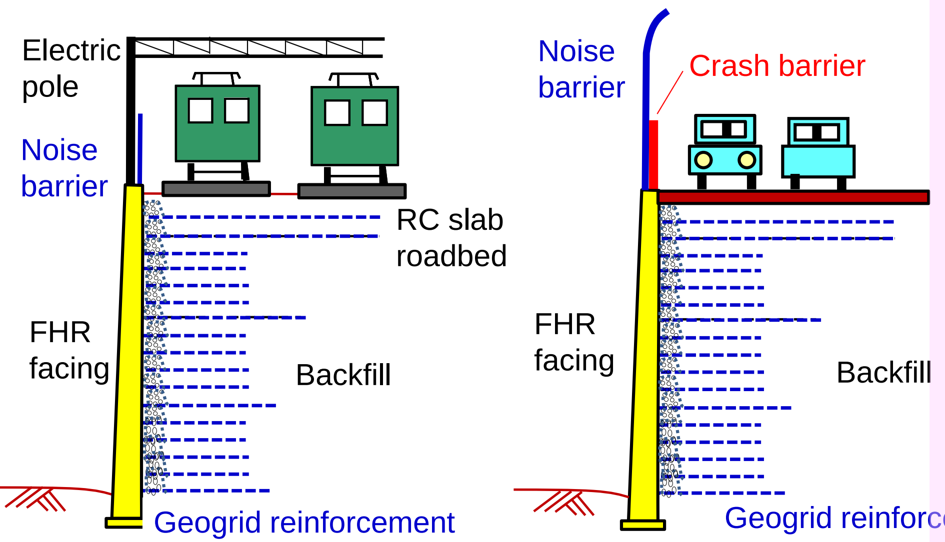
① Limited occupied space

② Ability to support other structures

<u>Disadvantages</u>

Not cost-effective

GRS RWs with FHR facing



Cost-effective; <u>largely by keeping two advantageous features ① & ② of conventional RWs & RC viaduct,</u>

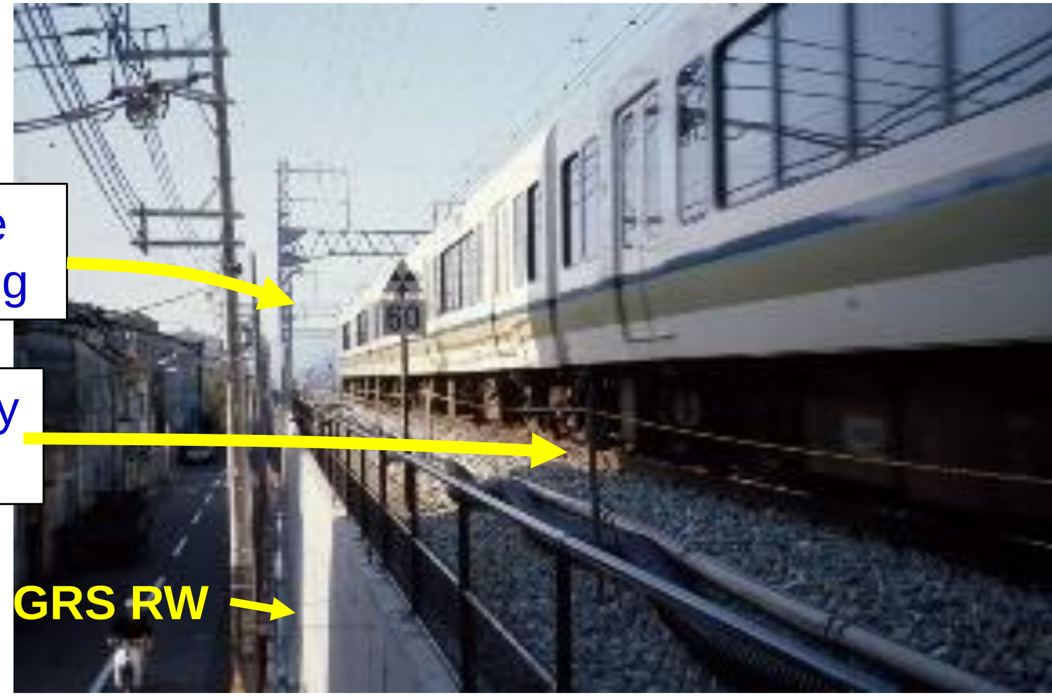
① railway & road can be arranged very close to the wall face, so the occupied space is narrow; and

② FHR facing can effectively support other structures, despite no pile foundation.

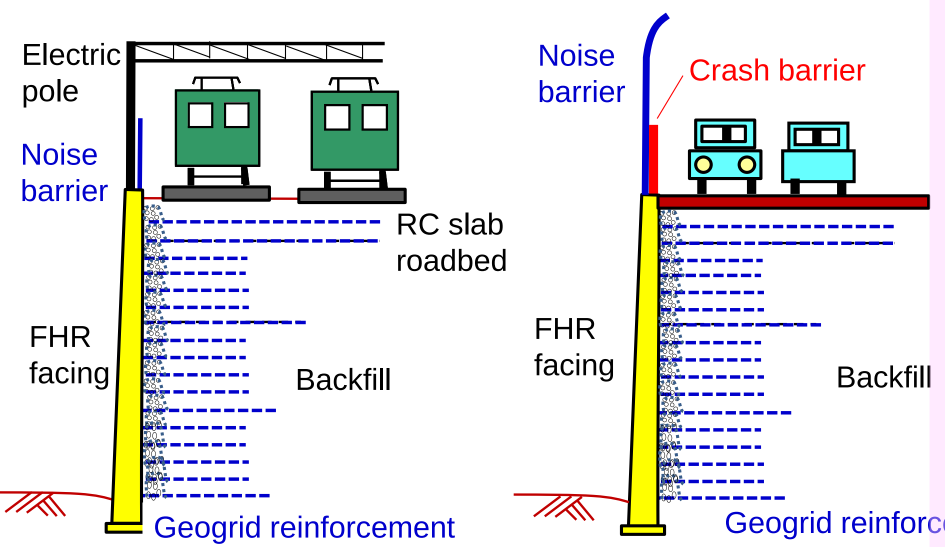
JR Kobe line, Amagasaki

Electric supply structure supported by FHR facing

Track located very close to wall face



GRS RWs with FHR facing



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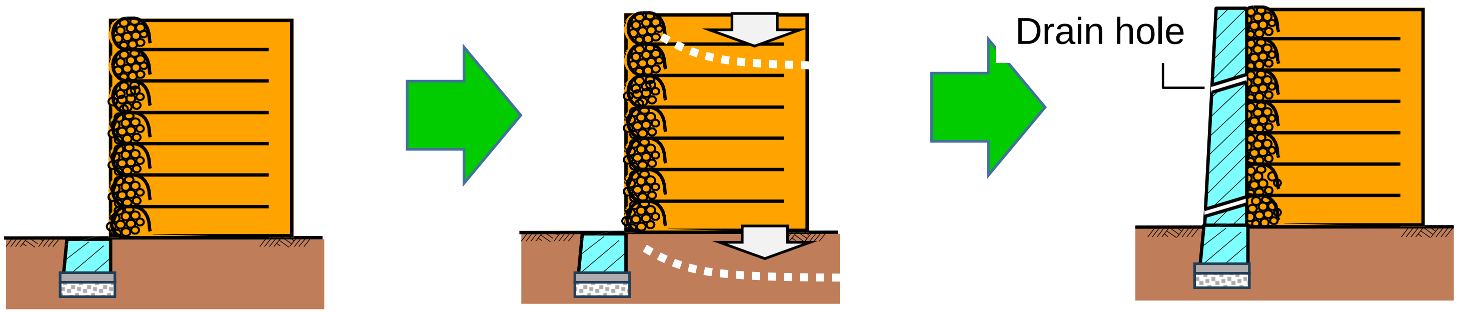
Advantageous features of GRS structure having stage-constructed FHR facing that alleviate many problems



Deformable facing Settlement Full-height rigid facing

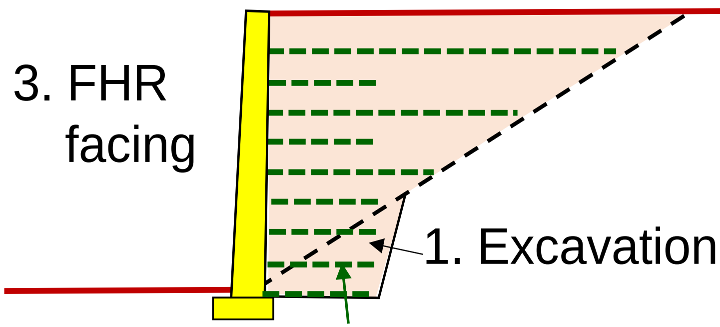
High performance and high cost-effectiveness by:

1) High stability despite no use of a pile foundation.
2) Very small post-construction deformation/settlement.

3) Narrow space occupied during & after construction.
4) Cost-effective construction of stable RW on slope.
5) FHR facing can directly support other structures (e.g., bridge girder).
6) High stability against severe seismic load, scouring, erosion etc.
7) GRS structures for High Speed Railways

GRS RW with FHR facing

2. Wall construction w/o FHR facing

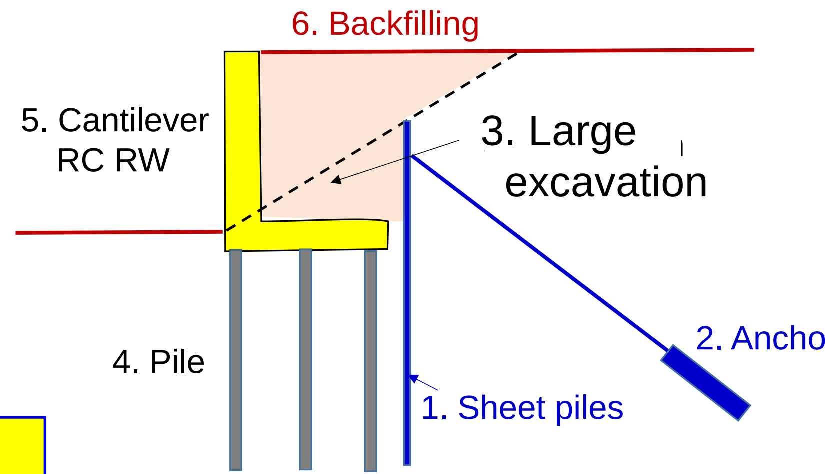


Short basic geogrid layers to reduce slope excavation & not use anchored sheet piles

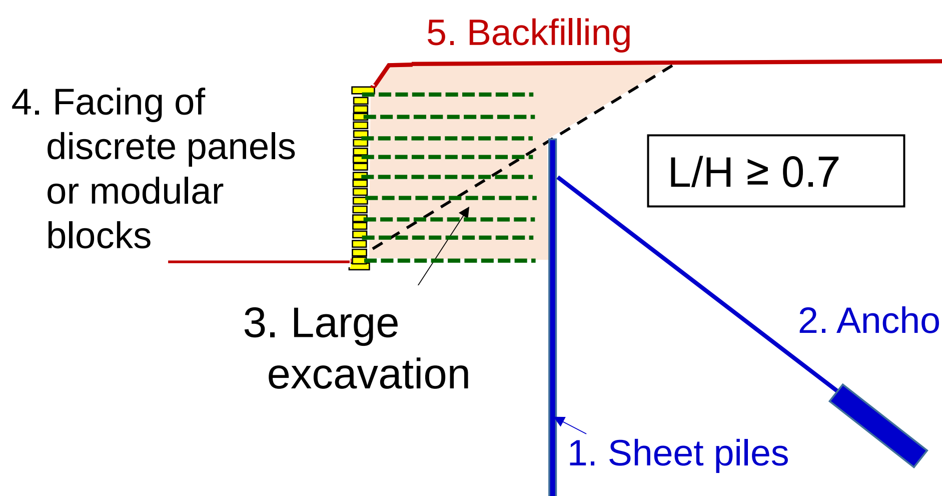
A reduction in the wall stability by the use of short basic geogrid layers is covered by:

1. closely spaced planar geogrid layers having a high pull-out strength;
2. several long geogrid layers; &
3. FHR facing.

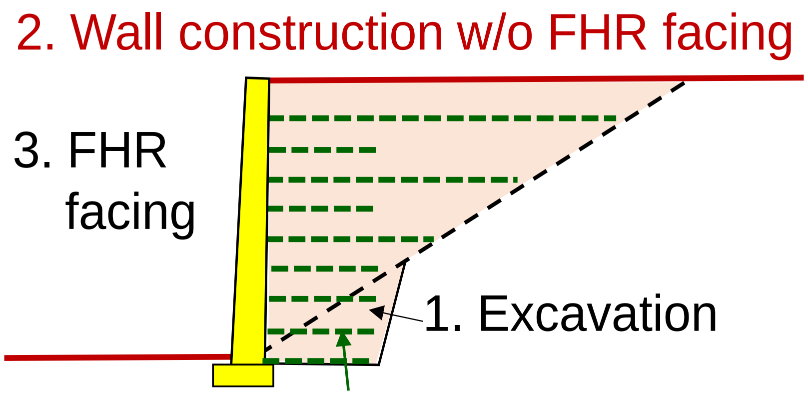
Conventional cantilever RW



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



GRS RW with FHR facing

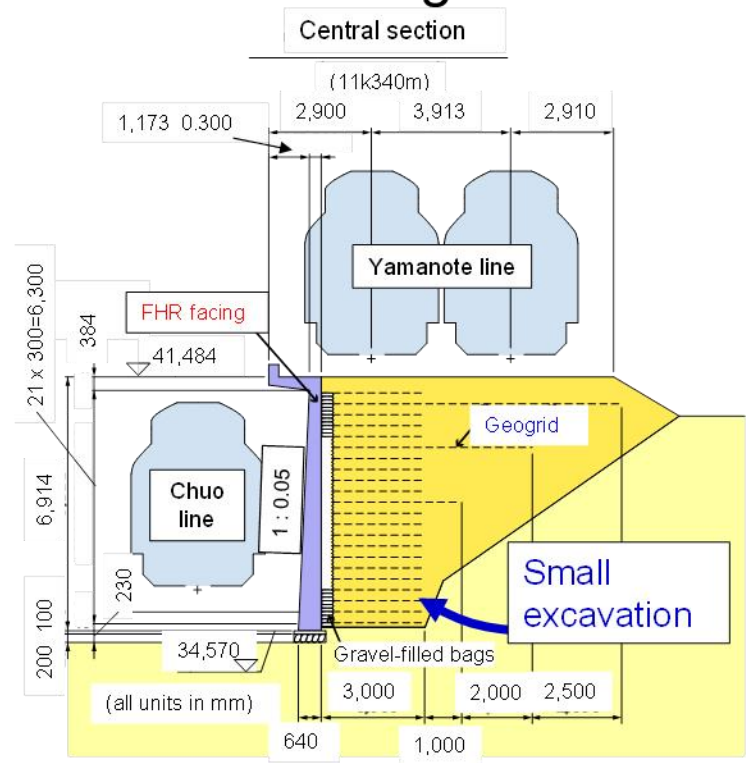


Short basic geogrid layers to reduce slope excavation & not use anchored sheet piles

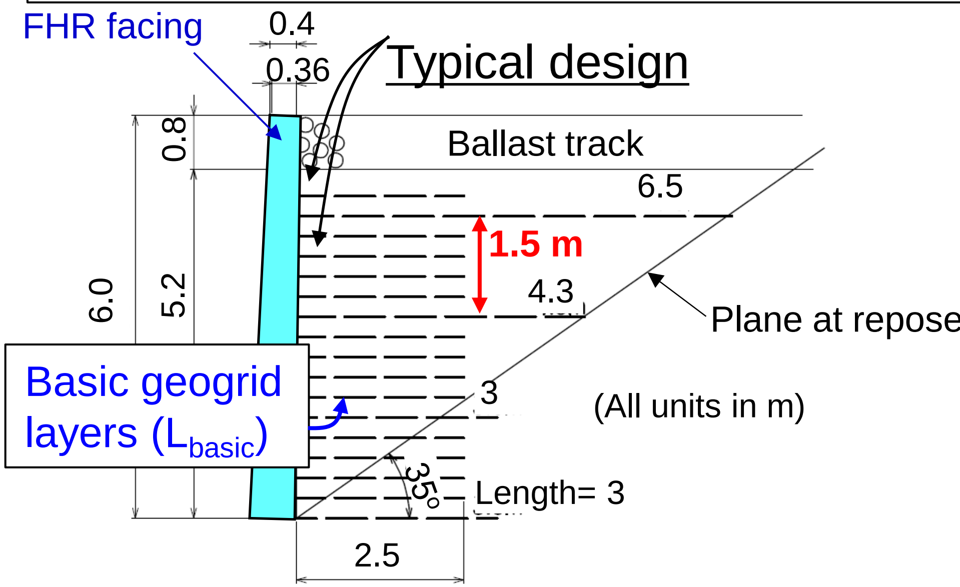
A reduction in the wall stability by the use of short basic geogrid layers is covered by:

1. closely spaced planar geogrid layers having a high pull-out strength;
2. several long geogrid layers; &
3. FHR facing.

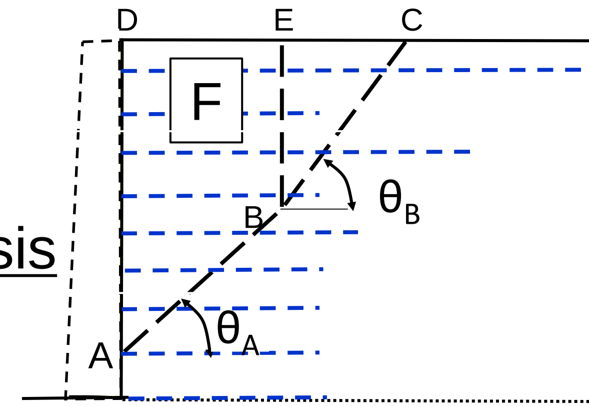
Near Shinjuku Station, Tokyo, constructed during 1995 – 2000



Geogrid arrangement by the current design



Two-wedge stability analysis



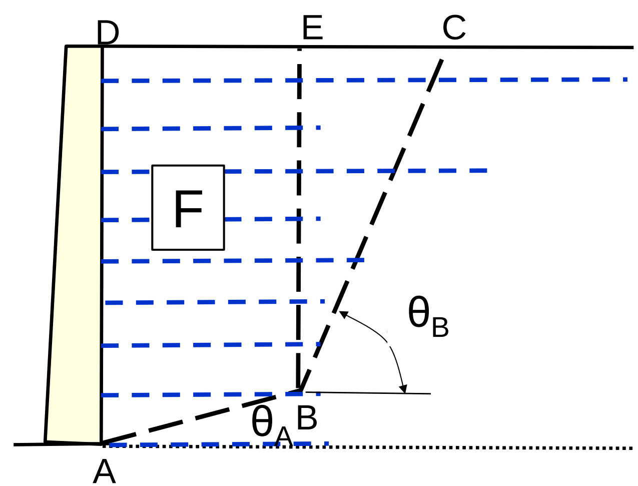
The minimum stability of "facing & front wedge F together" is sought for all possible locations of points A & B and all possible angles θ_A & θ_B of trial slip plane.

The length L_{basic} is the largest value among:
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).

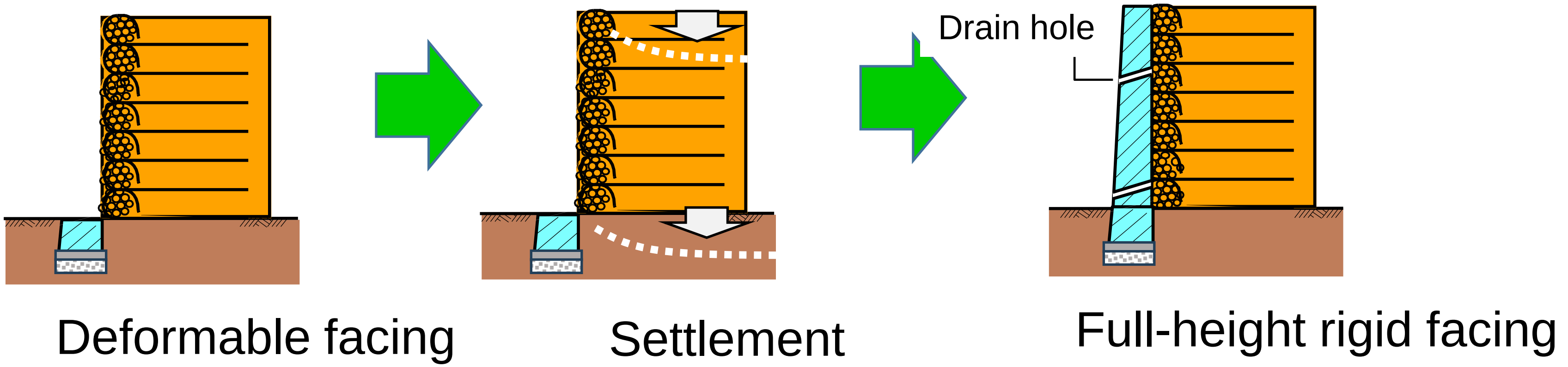
* the values by over-turning & lateral sliding evaluated by "*the Newmark method based on the TW stability analysis*" plus the value by shear deformation of "equivalent reinforced zone with a width equal to the average length of geogrid".

<u>When using FHR facing, …</u>



⇒ Point A is always at the heel of the facing base, which largely increases the wall stability.

Advantageous features of GRS structure having stage-constructed FHR facing that alleviate many problems



High performance and high cost-effectiveness by:

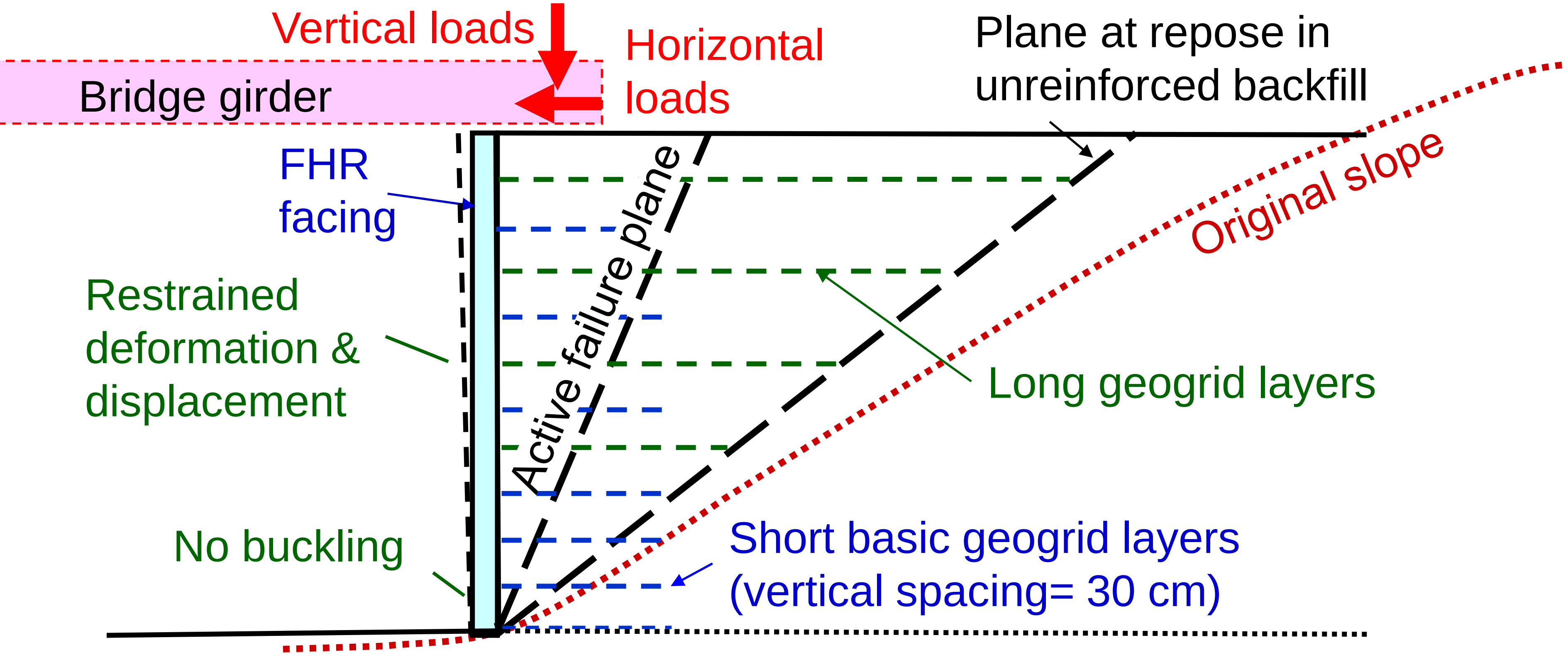
1) High stability despite no use of a pile foundation.
2) Very small post-construction deformation/settlement.
3) Narrow space occupied during & after construction.
4) Cost-effective construction of stable RW on slope.
5) FHR facing can directly support other structures (e.g., bridge girder).
6) High stability against severe seismic load, scouring, erosion etc.
7) GRS structures for High Speed Railways

FHR facing and closely-spaced short basic geogrid layers together with several long geogrid layers behave monolithically as a composite, not developing internal local failure:

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

a) static and seismic earth pressures from the backfill; and

b) external loads at and/or near the FHR facing !



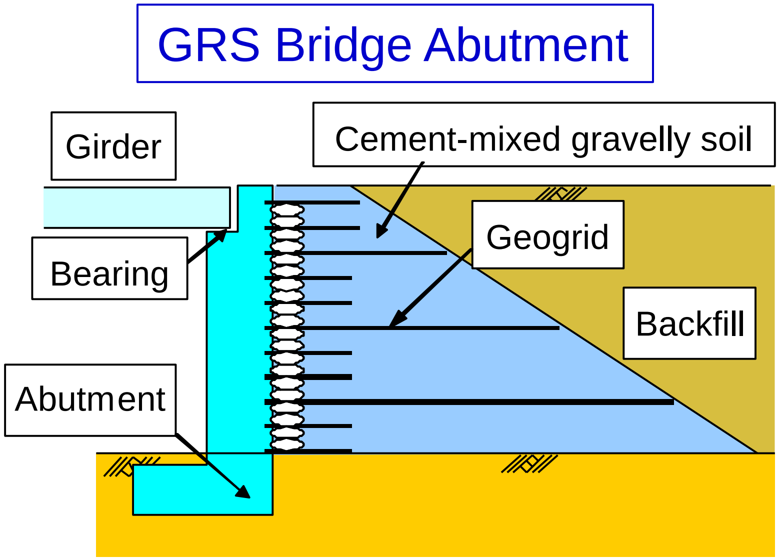
FHR facing and closely-spaced short basic geogrid layers together with several long geogrid layers behave monolithically as a composite, not developing internal local failure:

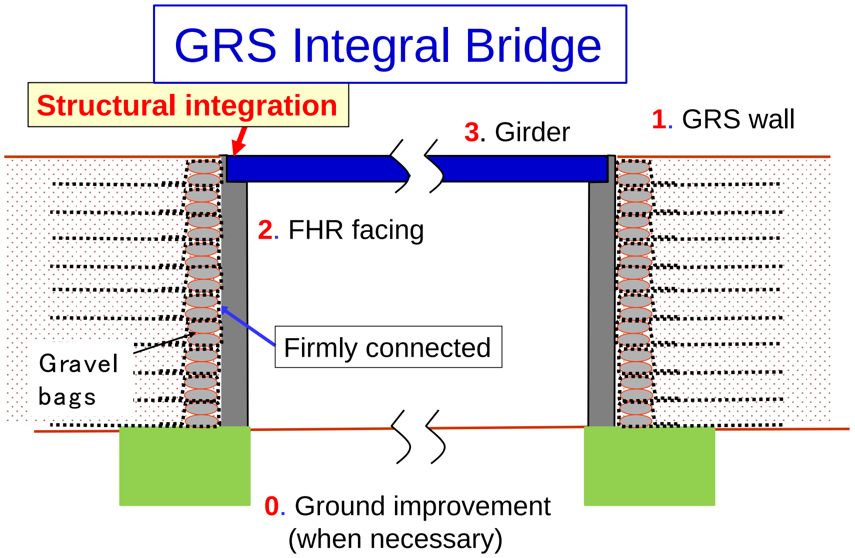
⇒ High wall stability against over-turning & lateral sliding and small shear deformation when subjected to:

a) static and seismic earth pressures from the backfill; and

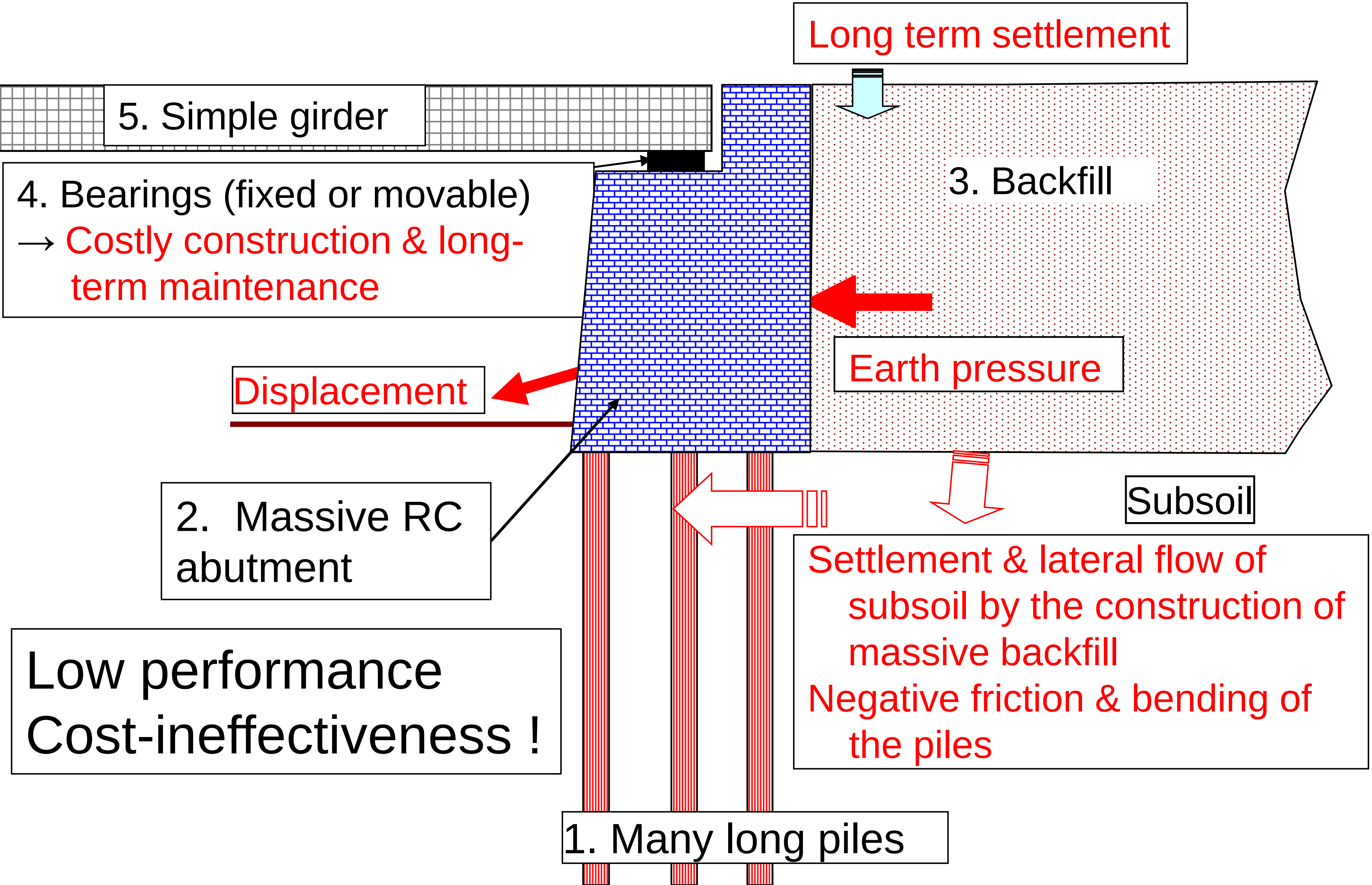
b) external loads at and/or near the FHR facing !

⇒ Developments of GRS bridge structures:



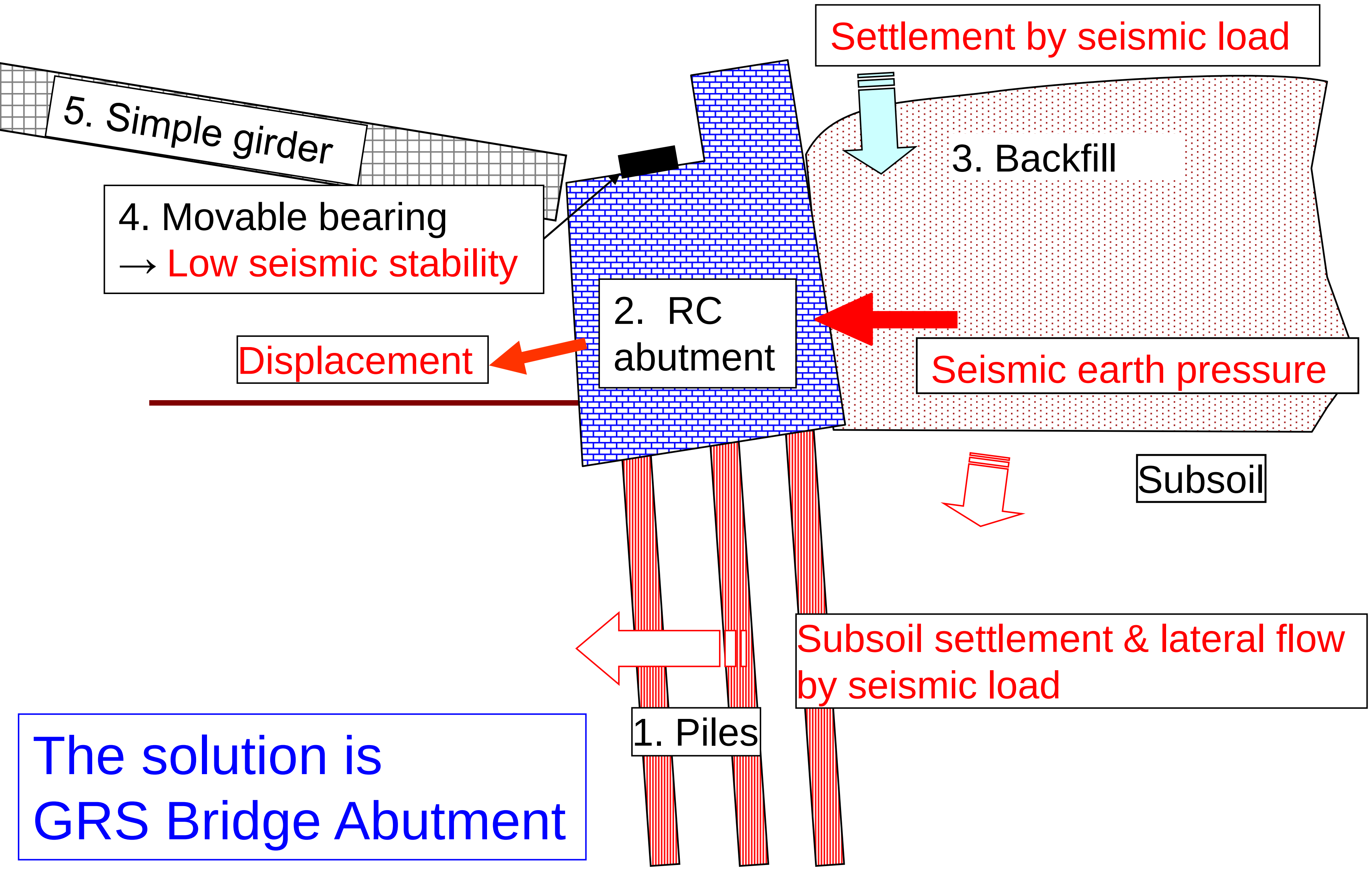


A number of serious problems with conventional type bridge abutment



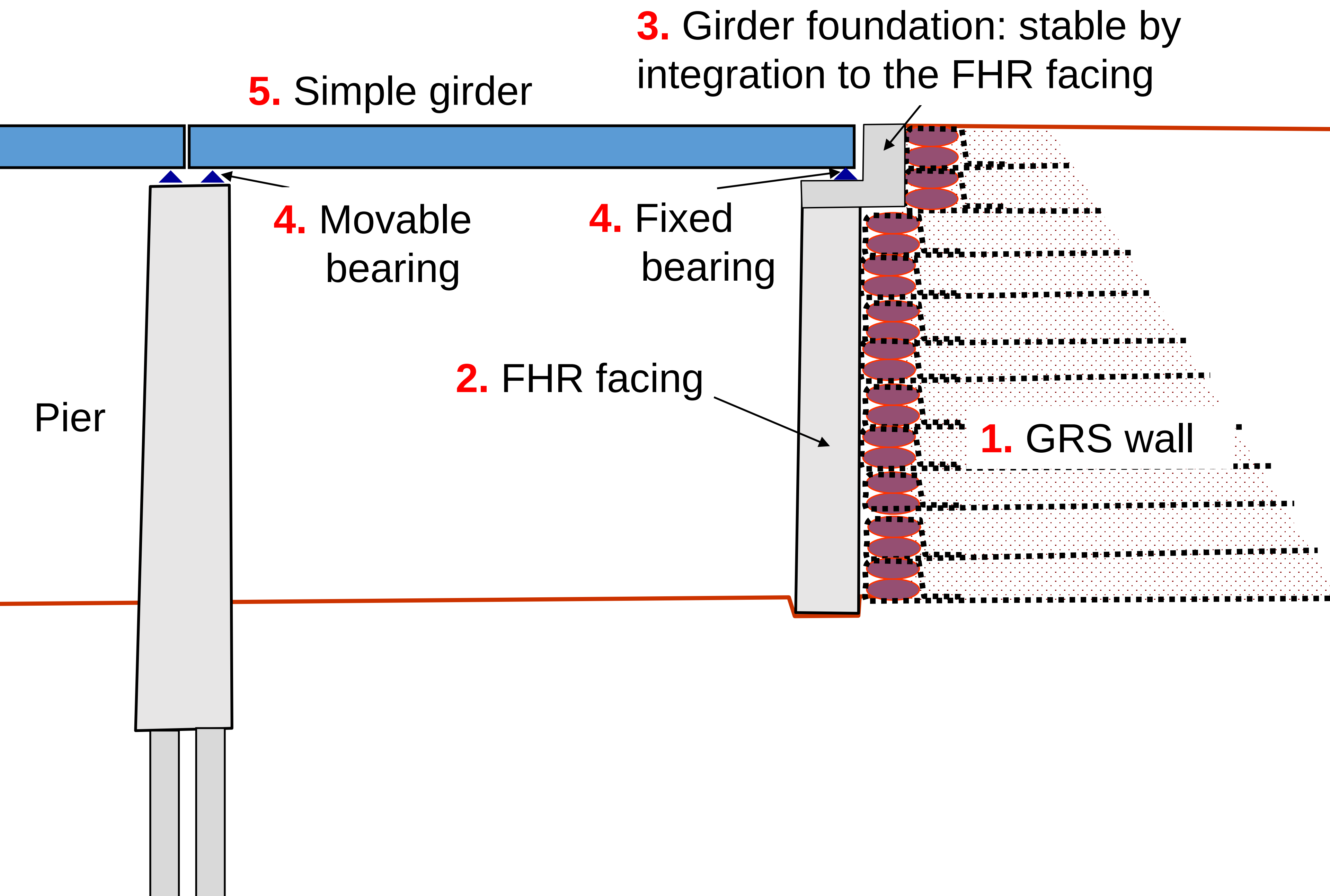
Low performance
Cost-ineffectiveness !

… and problems by seismic loads

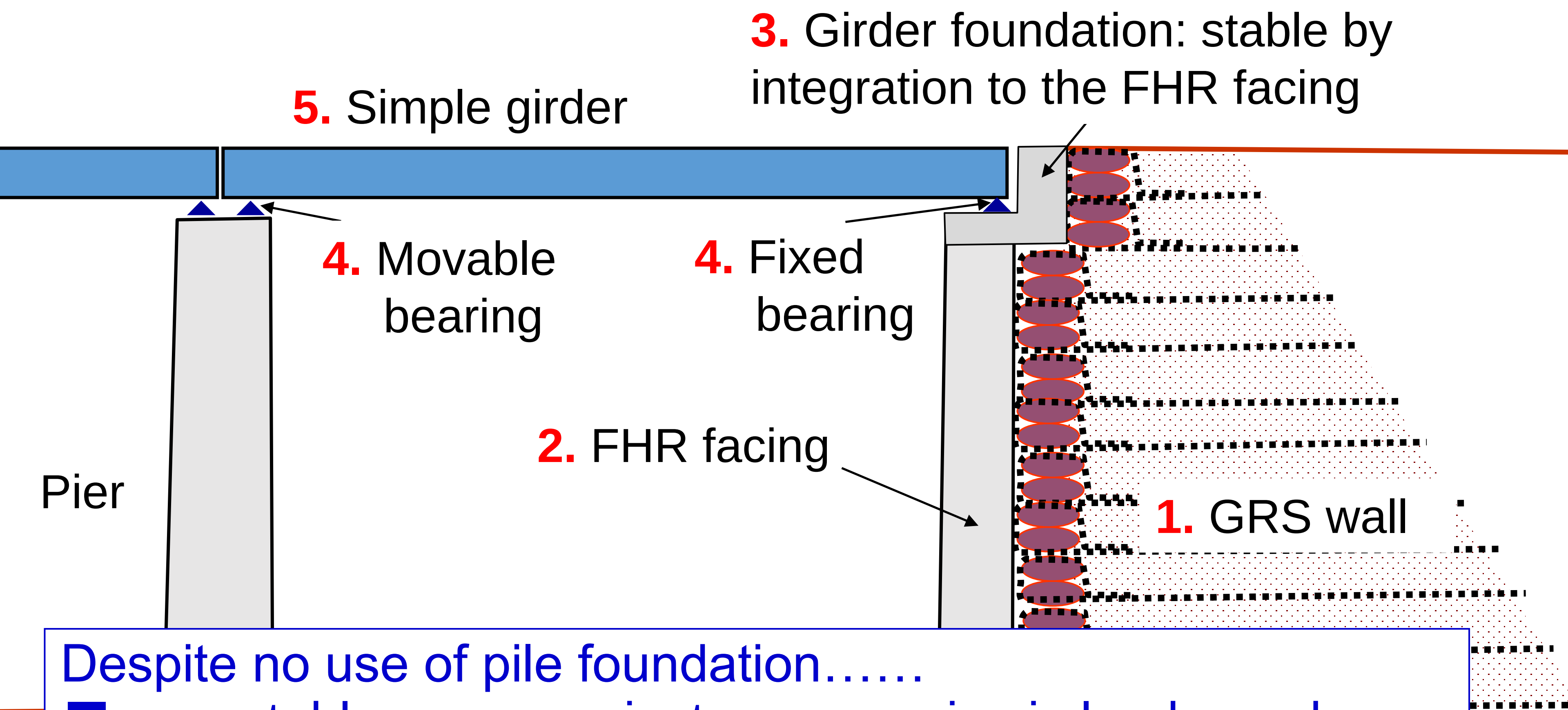


The solution is
GRS Bridge Abutment

GRS Bridge Abutment – a good solution



GRS Bridge Abutment – a good solution



Despite no use of pile foundation……

■ very stable, even against severe seismic loads; and

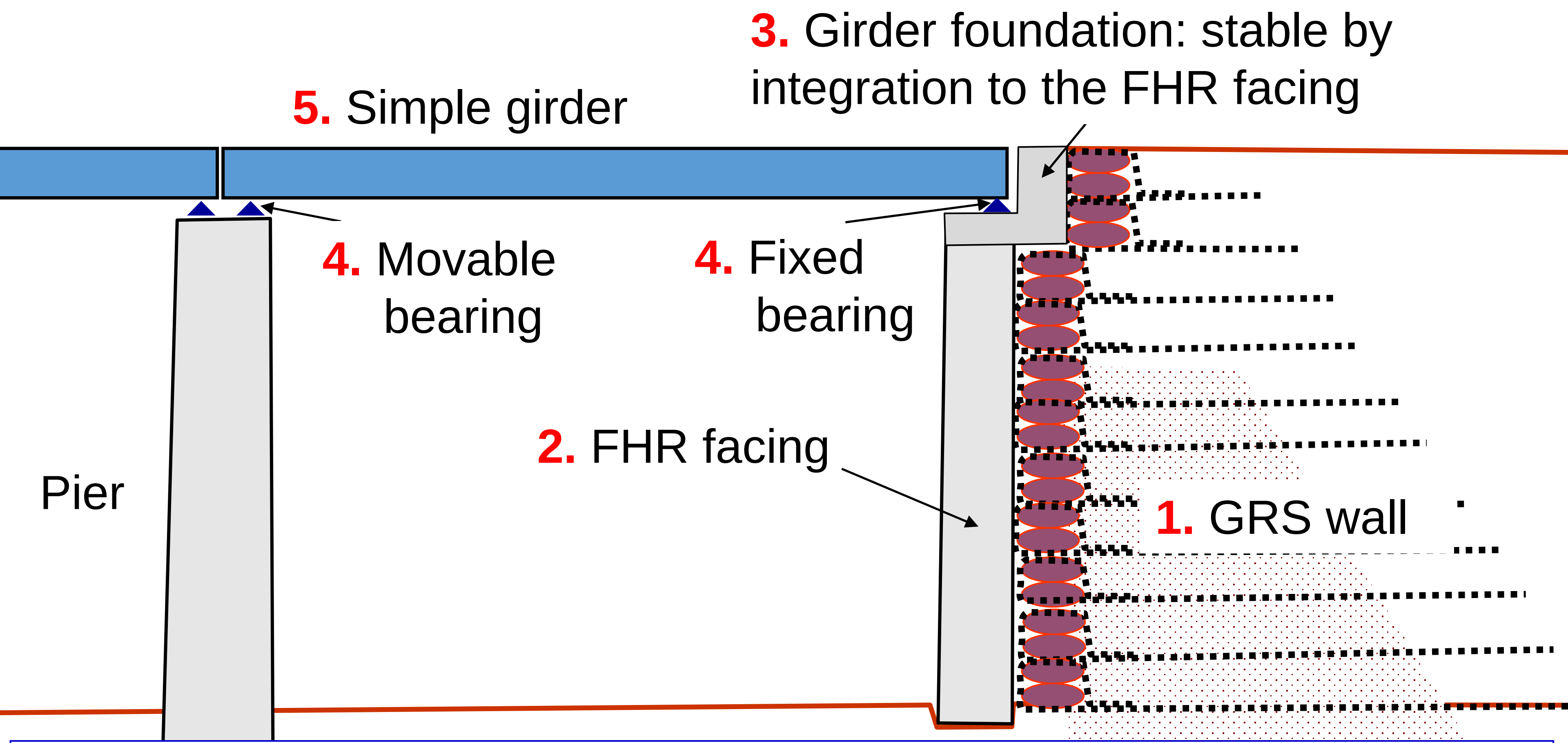
■ no bump by the settlement of backfill, because of:

① the construction of FHR facing after the potential deformation of backfill and subsoil has taken place;

② enhancement of good compaction of the backfill; and

③ firm connection of the facing to all of the geogrid layers.

GRS Bridge Abutment – a good solution



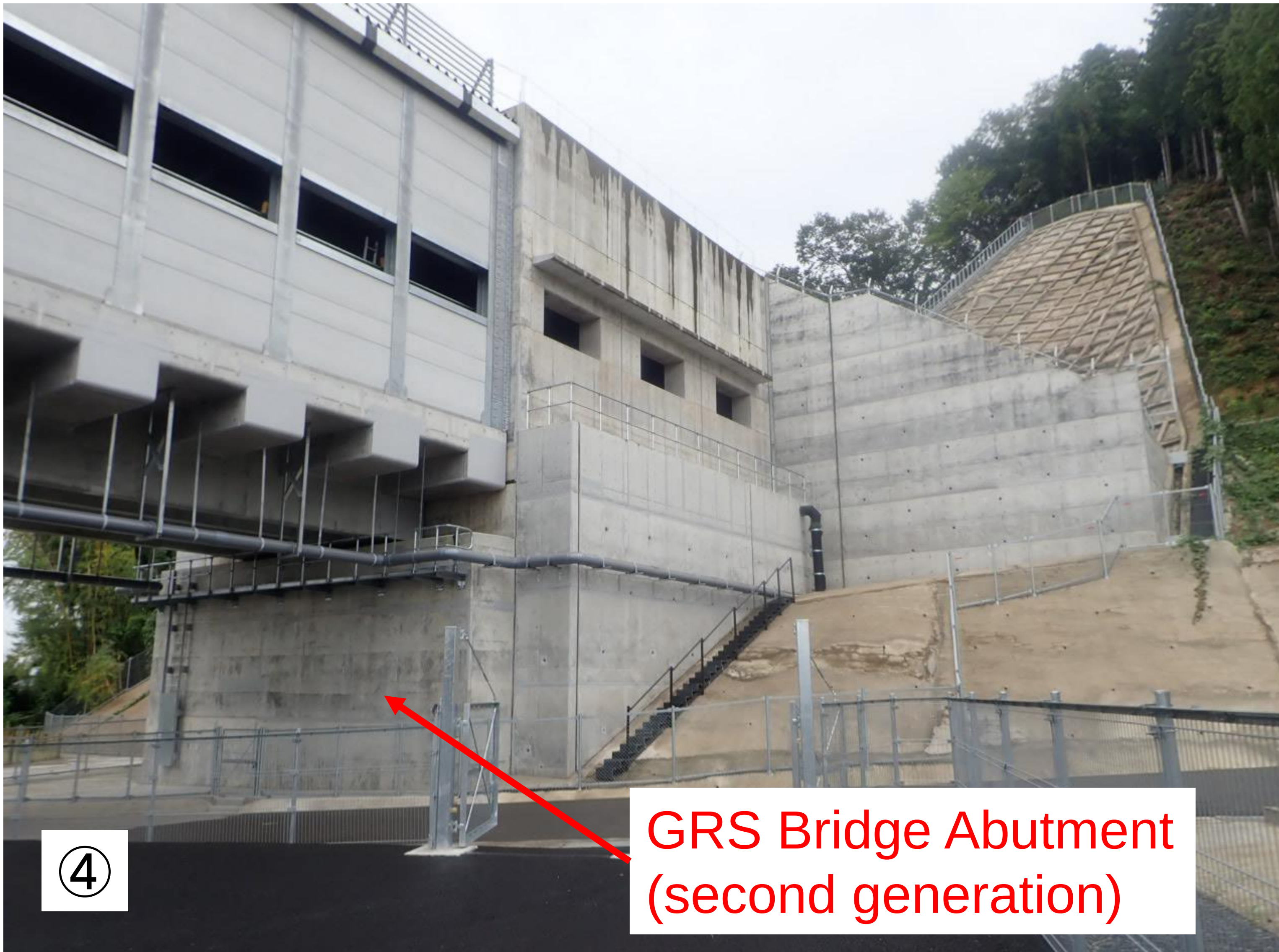
Statically determinate due to the use of movable & fixed bearings.
So, the internal forces in the girder & FHR facing are not sensitive to the thermal deformation of the girder and the post-construction deformation of backfill and subsoil.
⇒ The design of the girder & FHR facing is not sophisticated.

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

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

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

By the courtesy of JRTT



Summary of GRS Bridge Abutment

First GRS Bridge Abutment,
at Takada for Kyushu Shinkansen

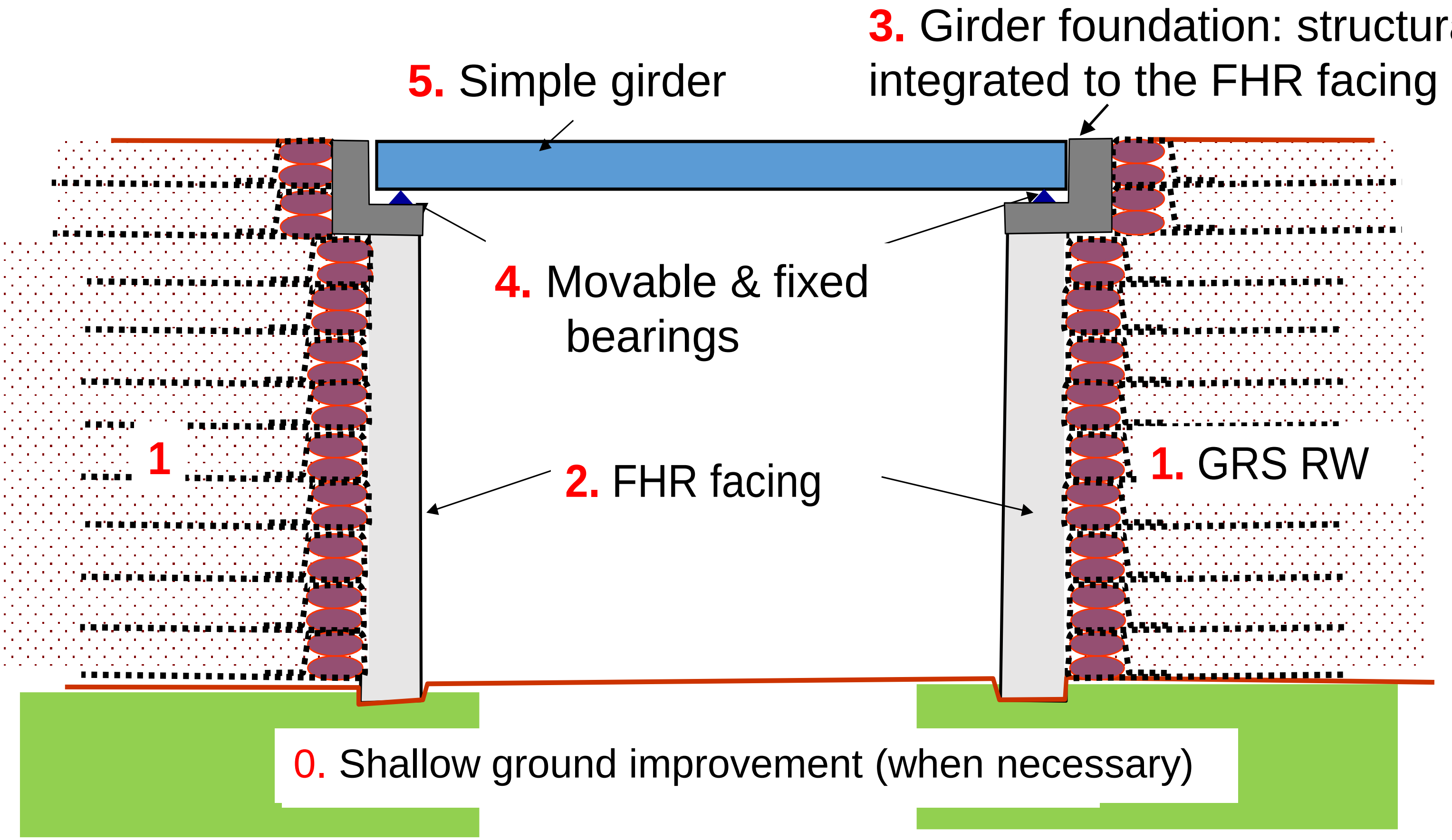
Tallest GRS Bridge Abutment at
Mantaro for Hokkaido Shinkansen

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 supporting a simple girder via movable & fixed bearings:

Much better performance & much higher cost-effectiveness than the conventional simple girder bridge
⇒ constructed at many places



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

GRS Bridge Abutment

GRS Bridge Abutment

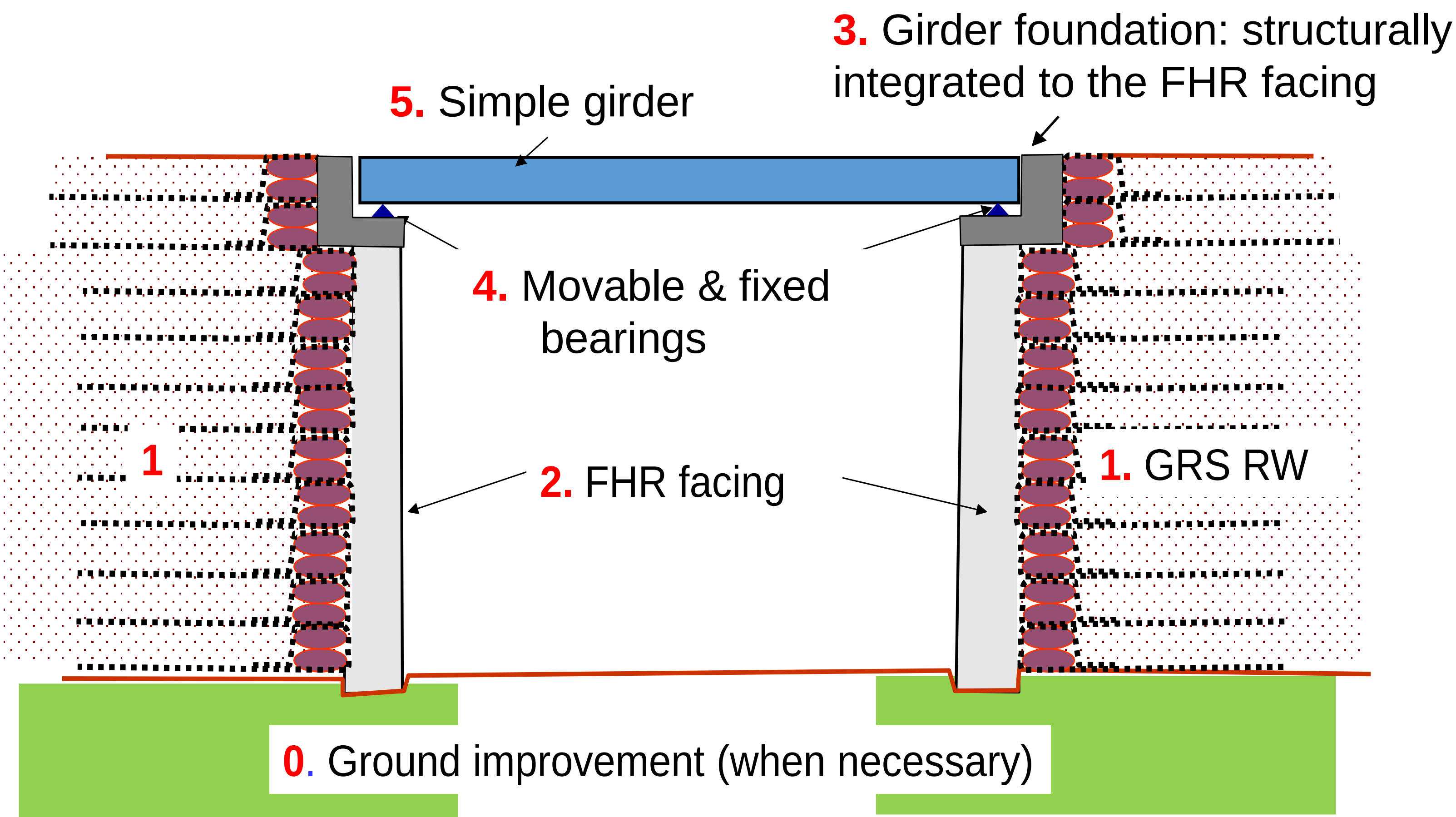
A pair of GRS Bridge Abutments supporting a simple girder via a pair of bearings: - very good performance.

However, two remaining problems:

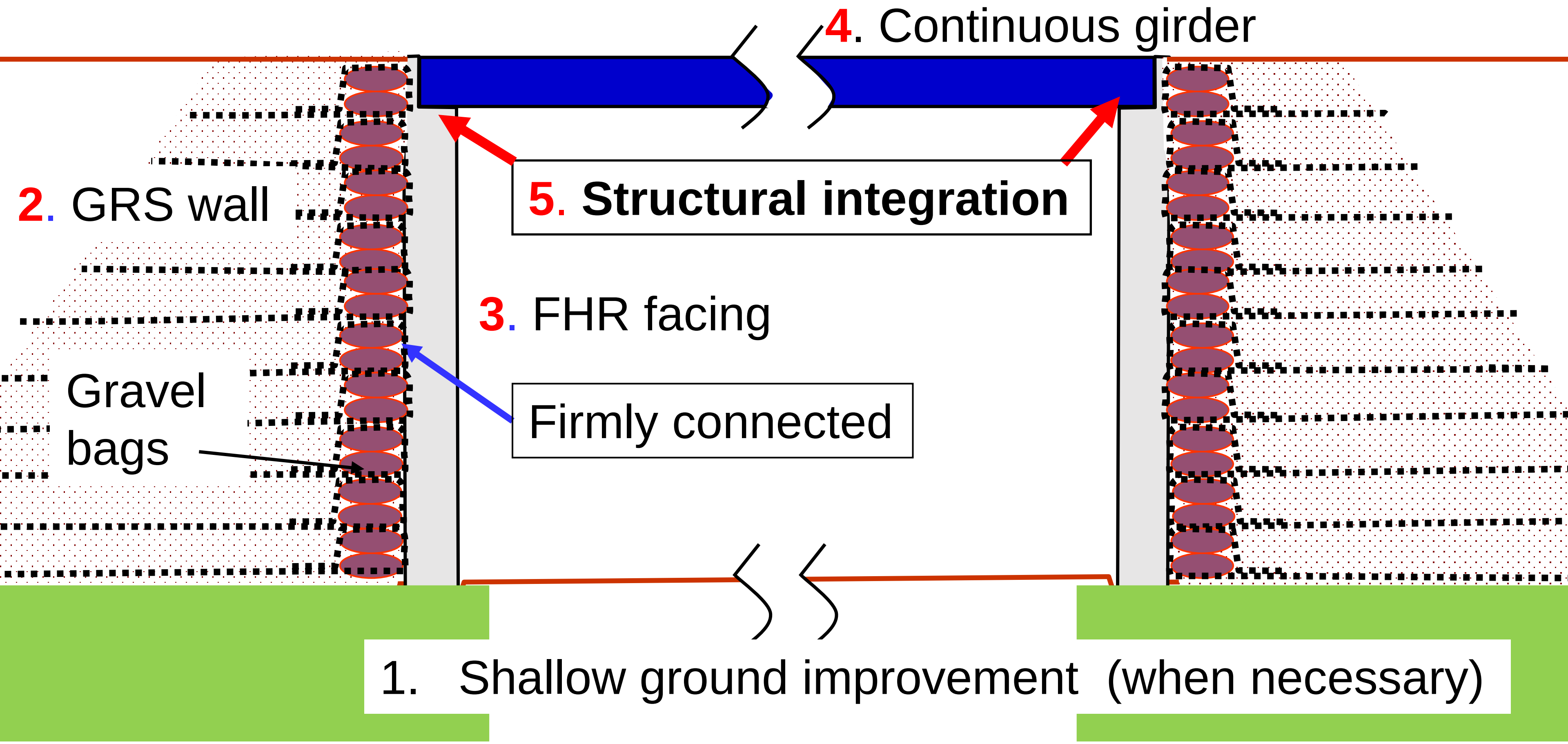
1) costly construction & maintenance of the bearings; and

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

⇒ The solution is GRS Integral Bridge

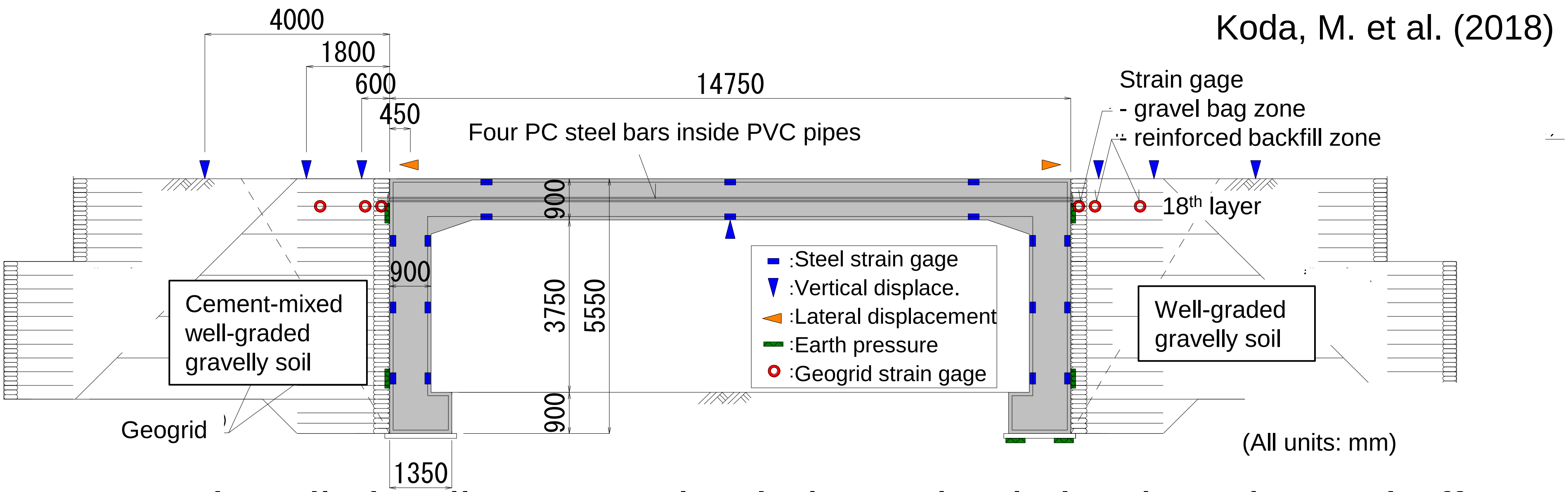


GRS Integral Bridge



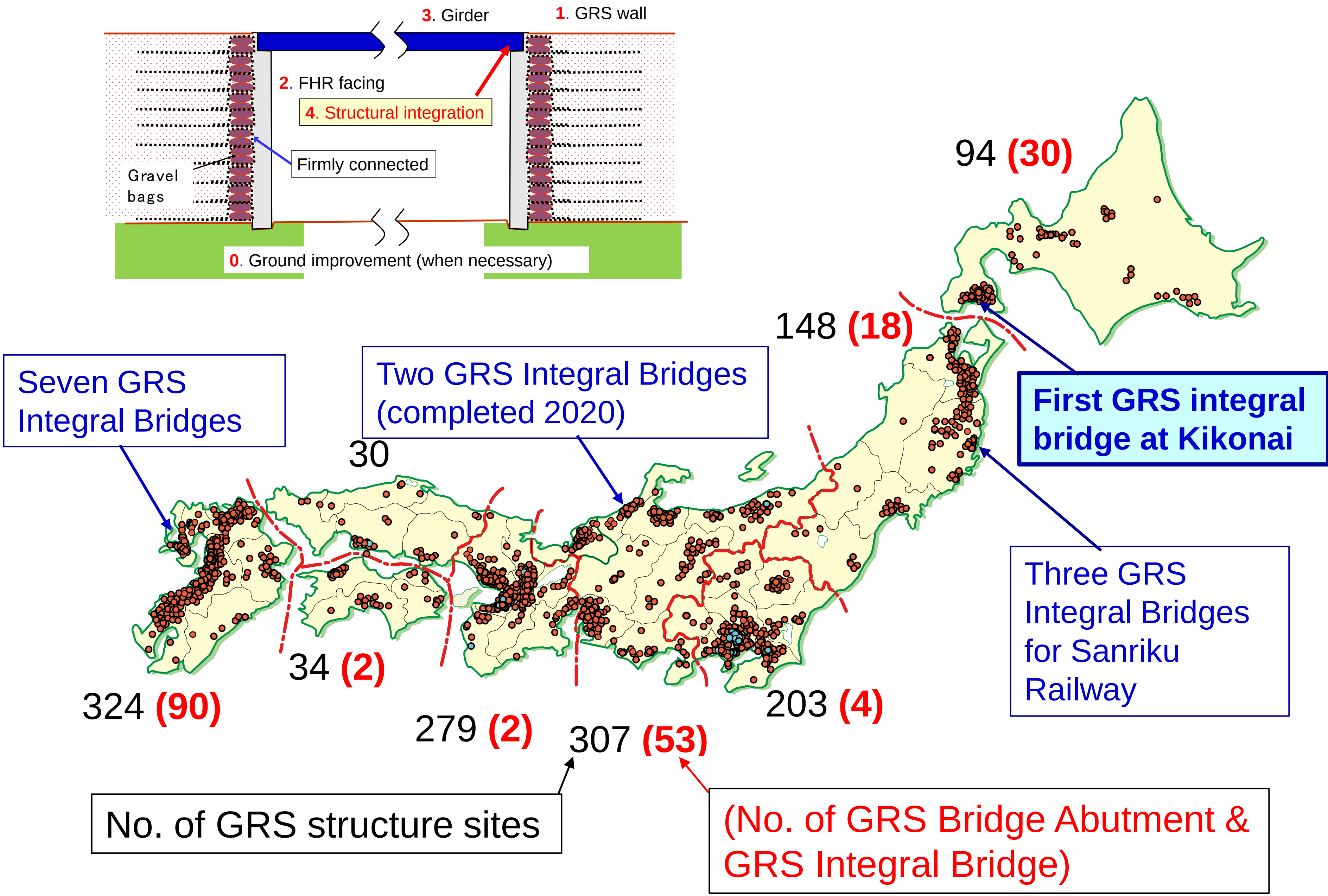
⇒ To evaluate the performance:
static & dynamic model tests in the laboratory; and
a full-scale model and cyclic loading tests

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

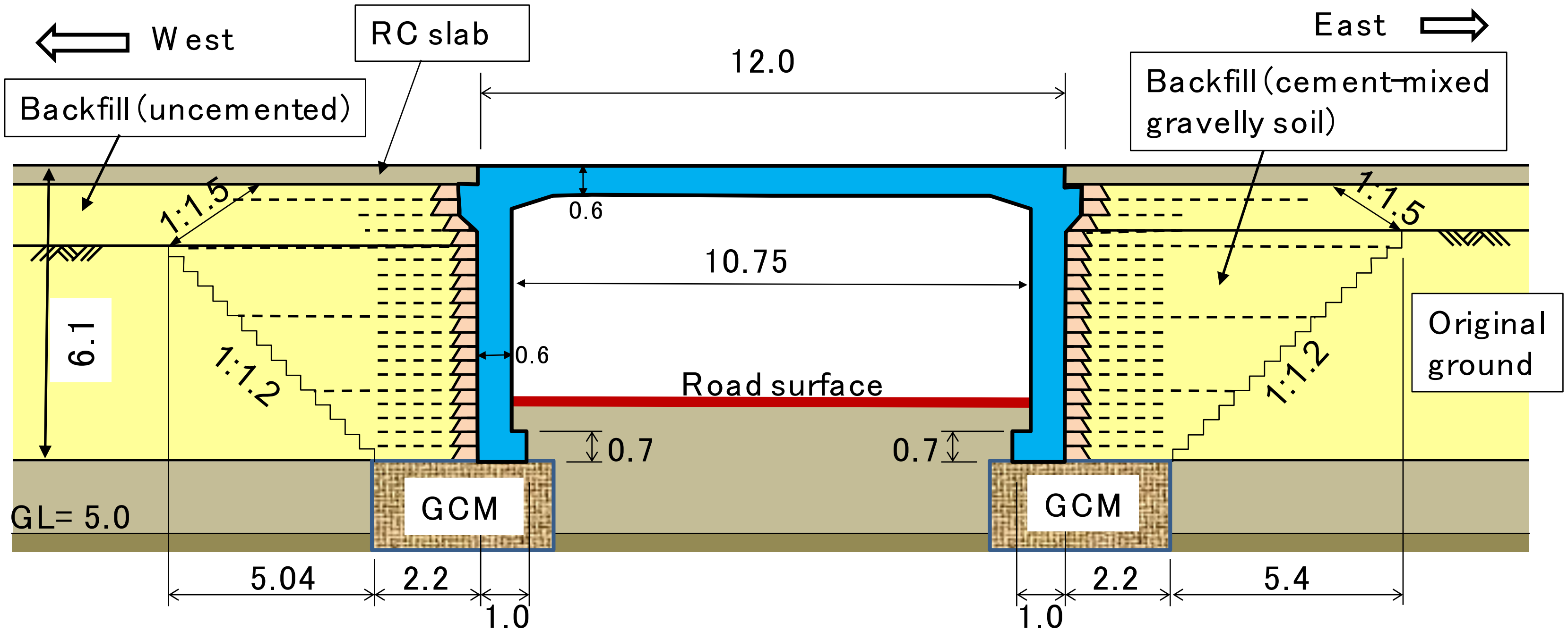


Lateral cyclic loading tests simulating seismic loads & thermal effects

GRS Integral Bridges for railways



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



[All units in m]

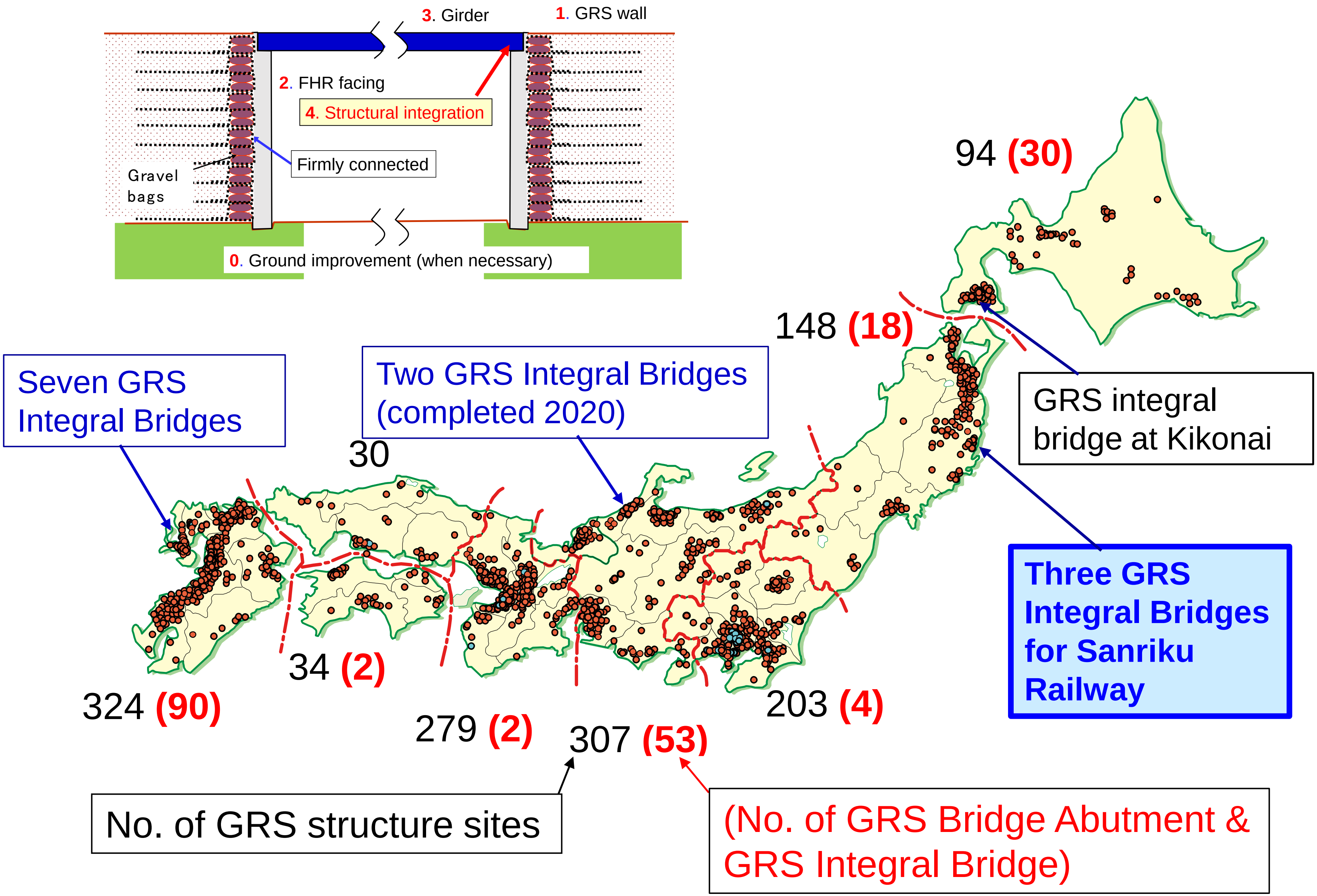
GCM: Ground improvement by cement-mixing

- Slender girder & FHR facing, by 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



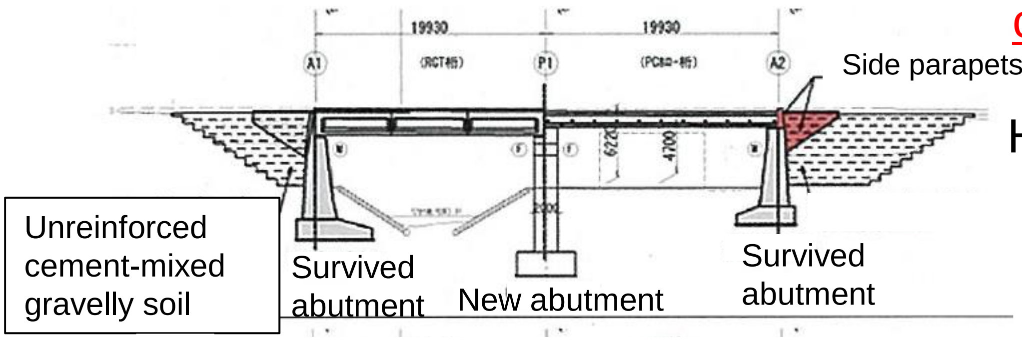
20 days after the 2011 Great East Japan E.Q. (11 March 2011), Koikoreobe, Sanriku Railway

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

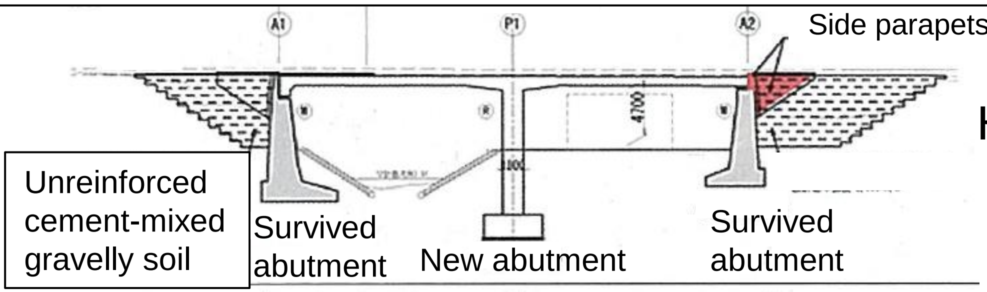
Three candidates for restoration

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

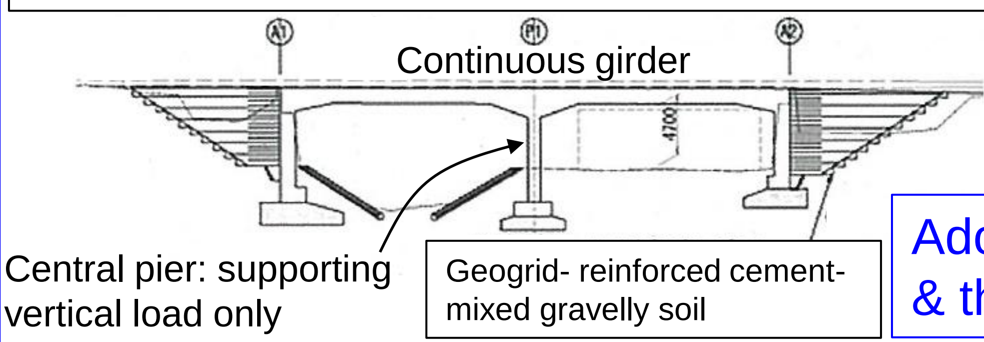
Two-span simple girders supported by two pairs of bearing (the same as the collapsed bridge)



Single continuous girder supported by a pair of bearing

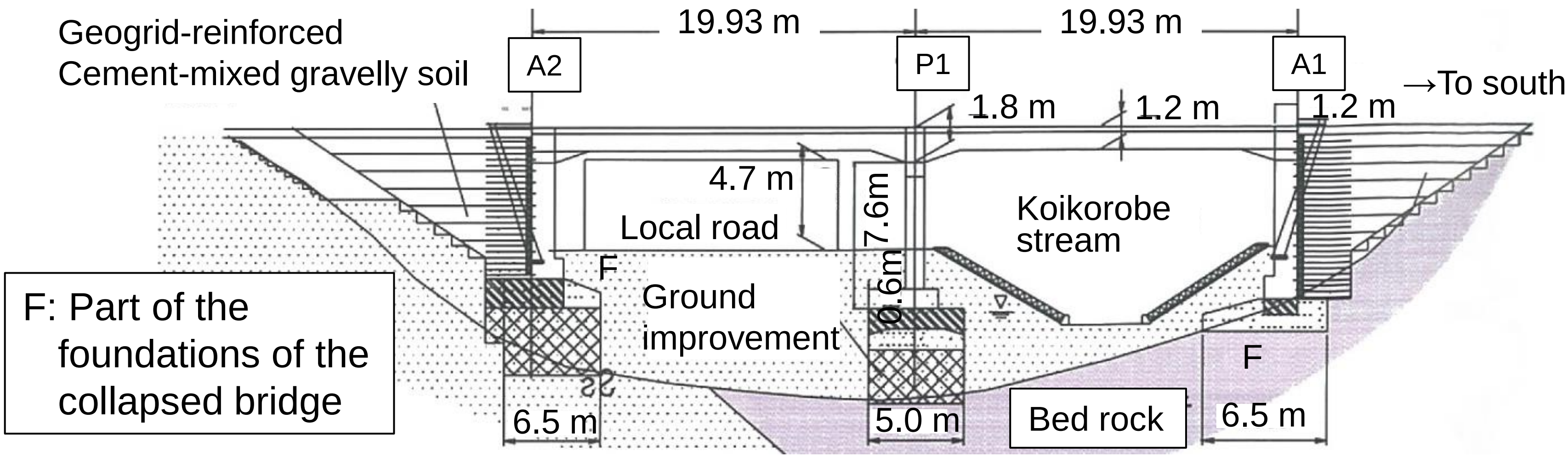


GRS Integral Bridge without using bearings

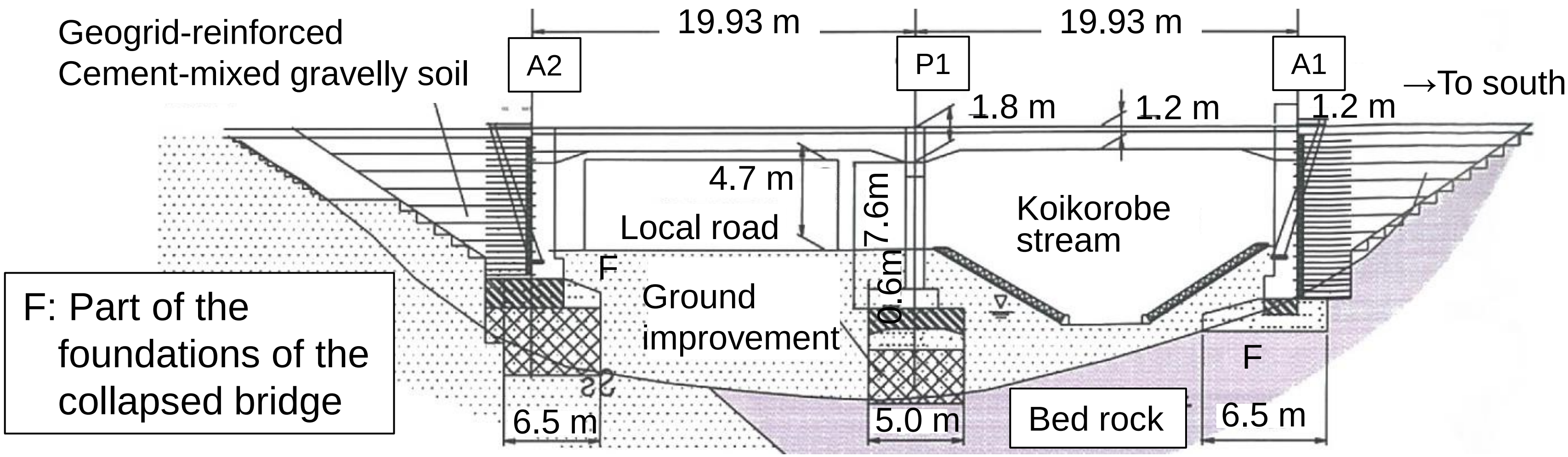


Adopted, because of the best performance & the best cost-effectiveness

GRS Integral Bridge at Koikorobe, Sanriku Railway

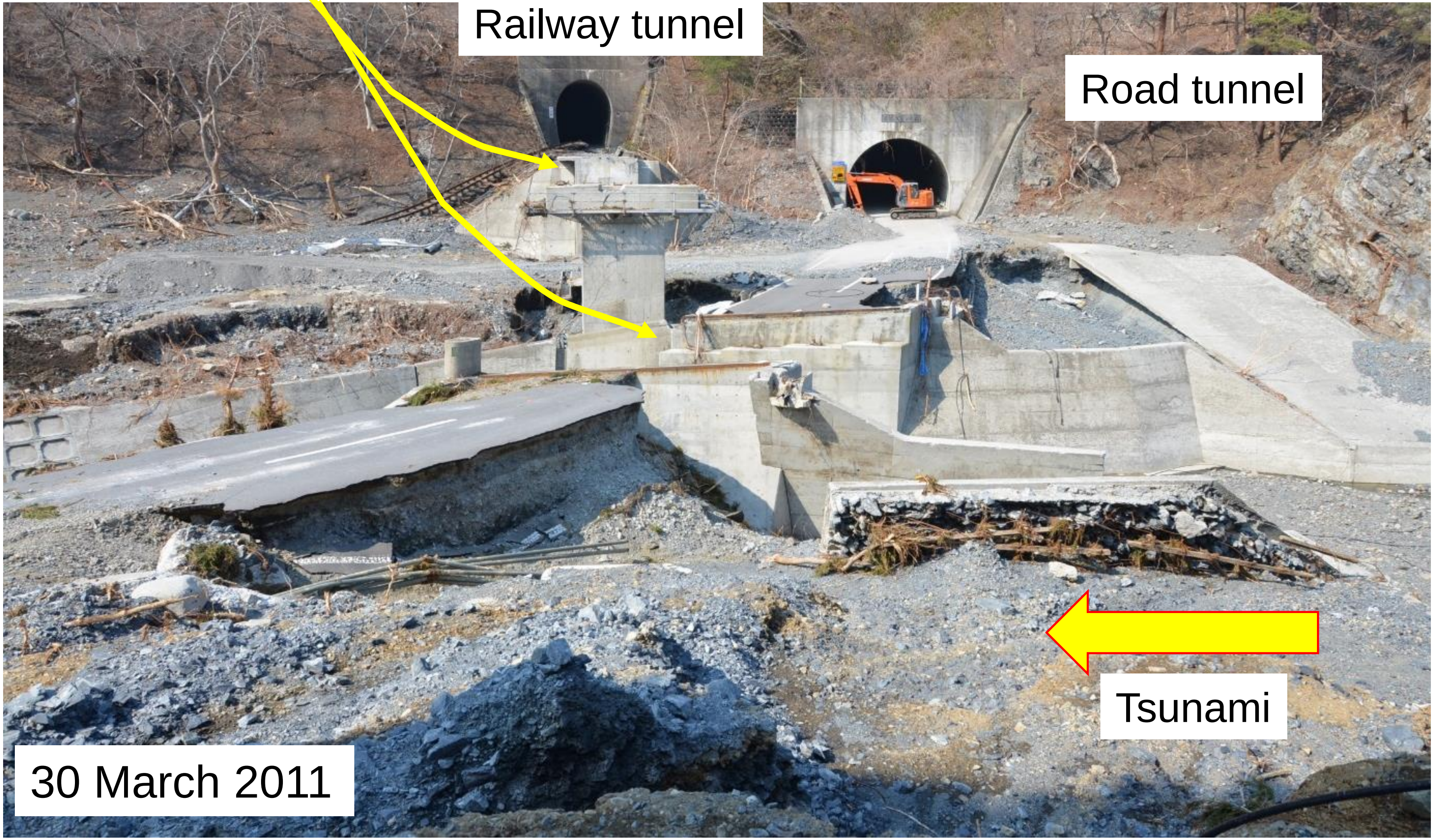


GRS Integral Bridge at Koikorobe, Sanriku Railway

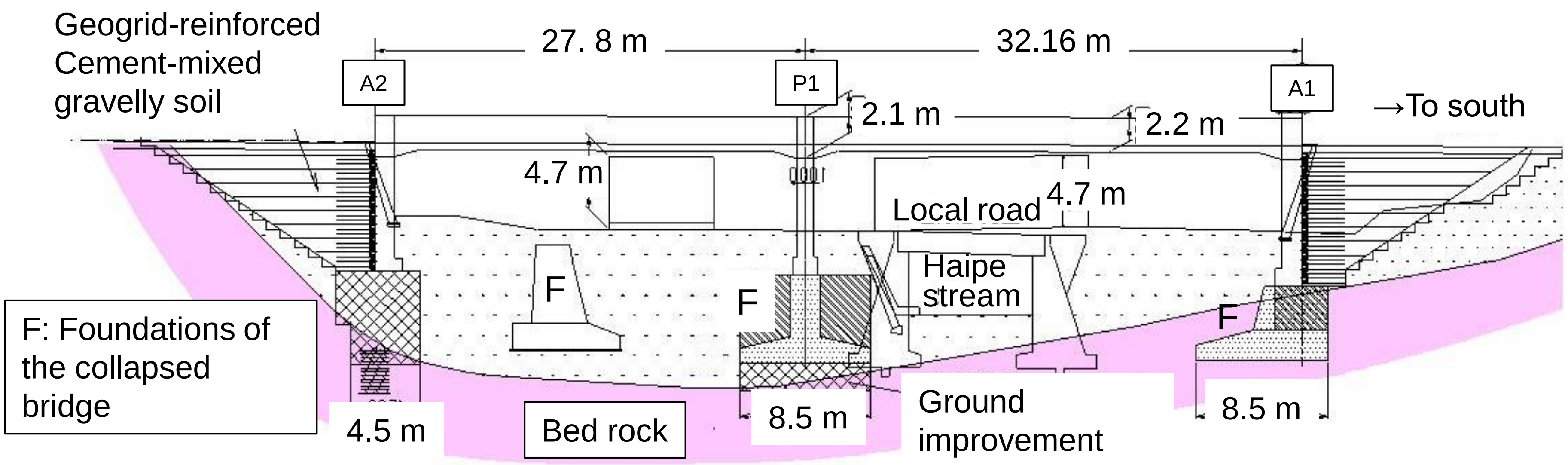


20 days after the E.Q. at Haipe, Sanriku Railway

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



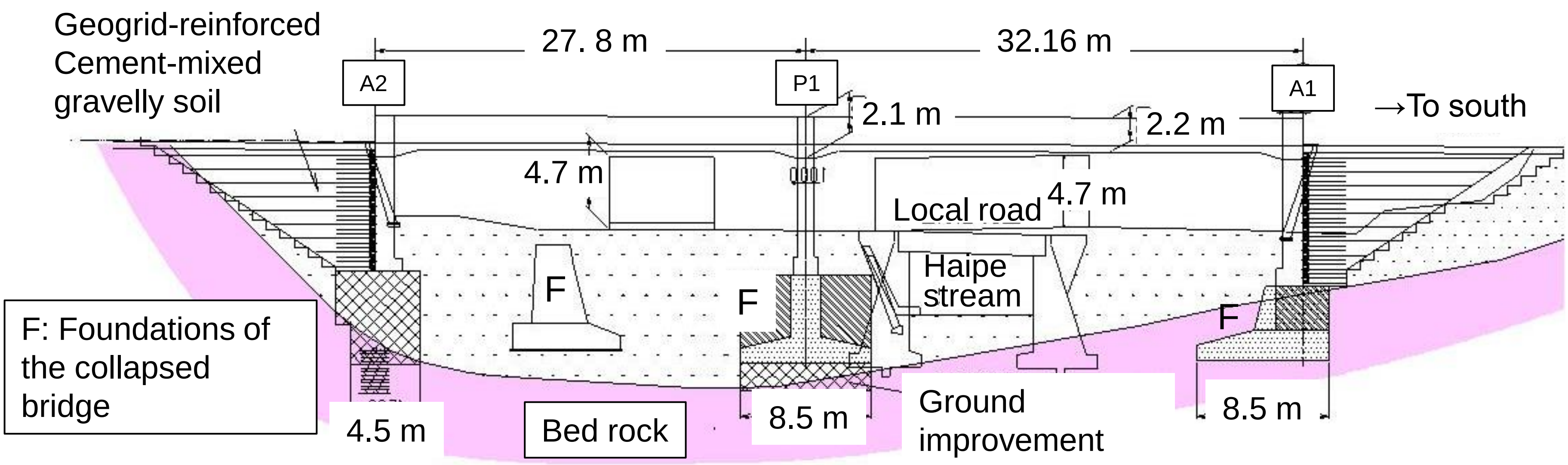
GRS Integral Bridge at Haipe, Sanriku Railway



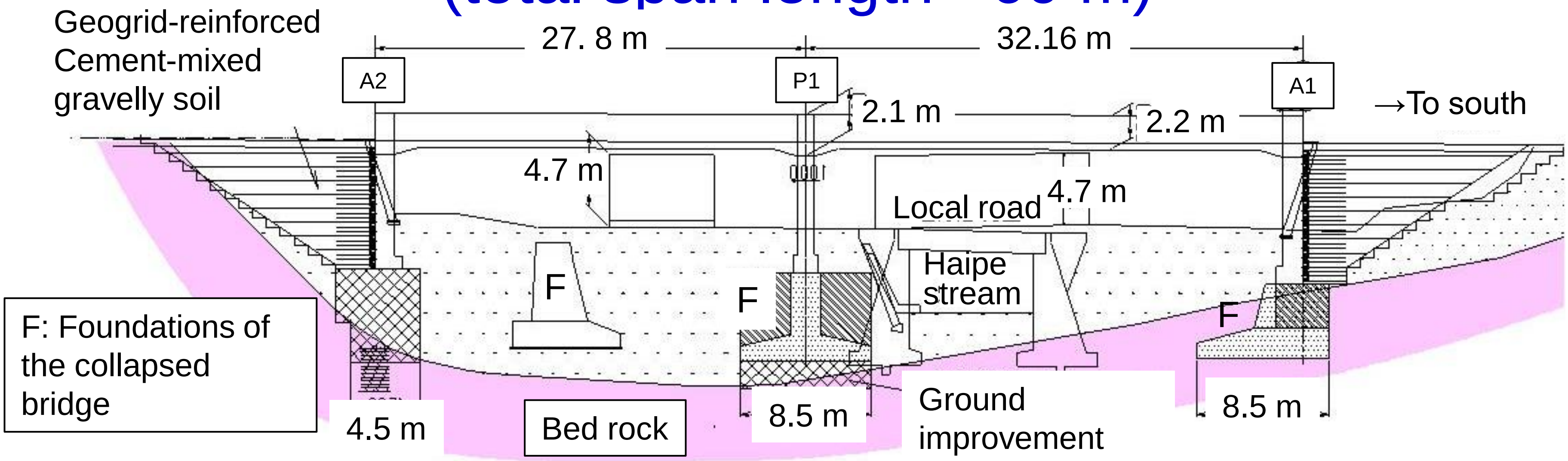
GRS Abutment (before the construction of FHR facing)

22 May 2013

GRS Integral Bridge at Haipe, Sanriku Railway



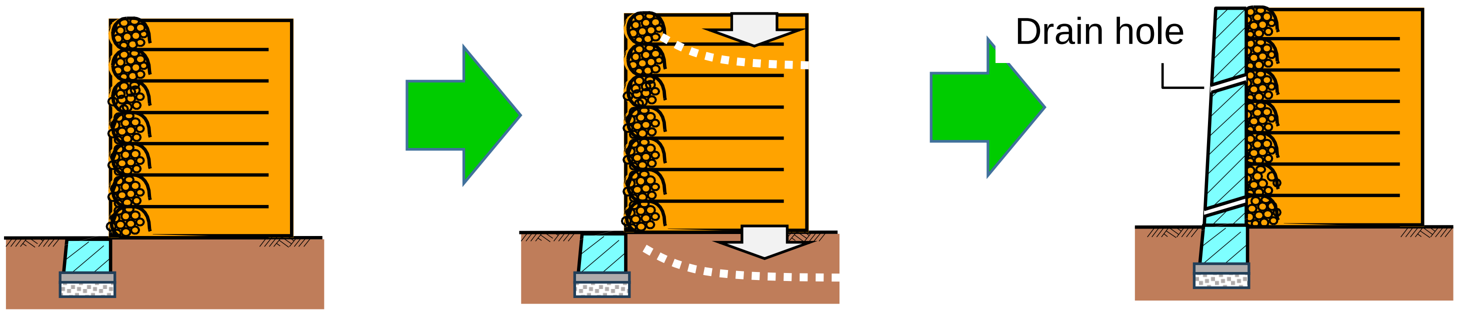
GRS Integral Bridge at Haipe, Sanriku Railway (total span length= 60 m)



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

⇒ A large cost reduction in construction & maintenance

Advantageous features of GRS structure having stage-constructed FHR facing that alleviate many problems



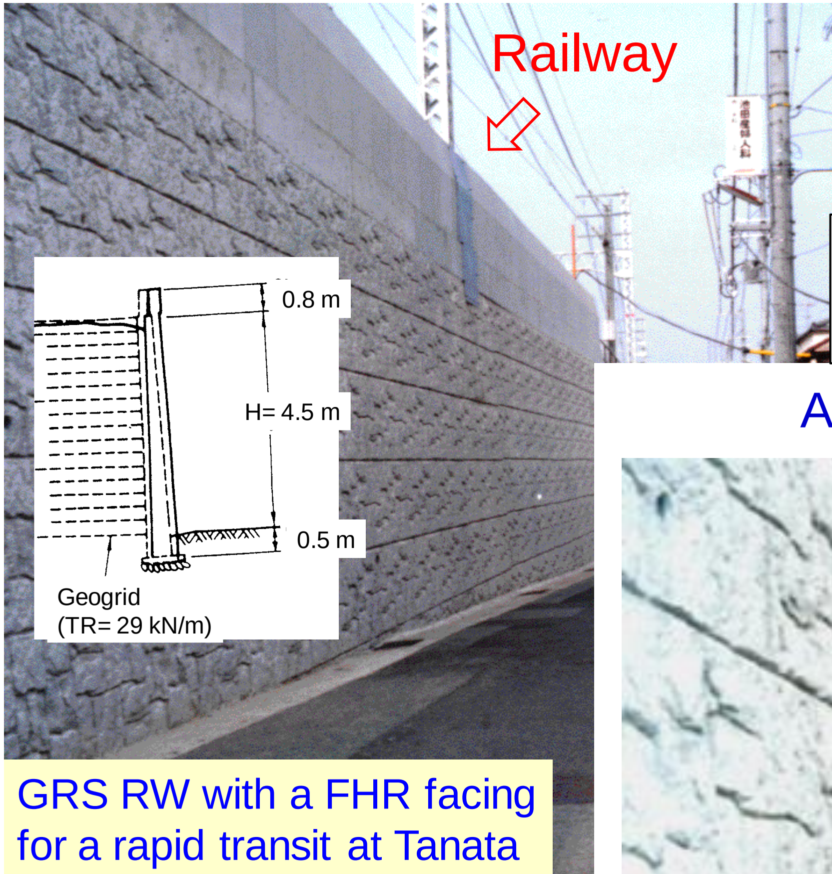
Deformable facing Settlement Full-height rigid facing

High performance and high cost-effectiveness by:

1) High stability despite no use of a pile foundation.
2) Very small post-construction deformation/settlement.
3) Narrow space occupied during & after construction.
4) Cost-effective construction of stable RW on slope.
5) FHR facing can directly support other structures (e.g., bridge girder).
6) **High stability against severe seismic load, scouring, erosion and tsunami.**
7) GRS structures for High Speed Railways

Immediately after completion, 1992

GRS RW with FHR facing at Tanata



GRS RW with a FHR facing for a rapid transit at Tanata

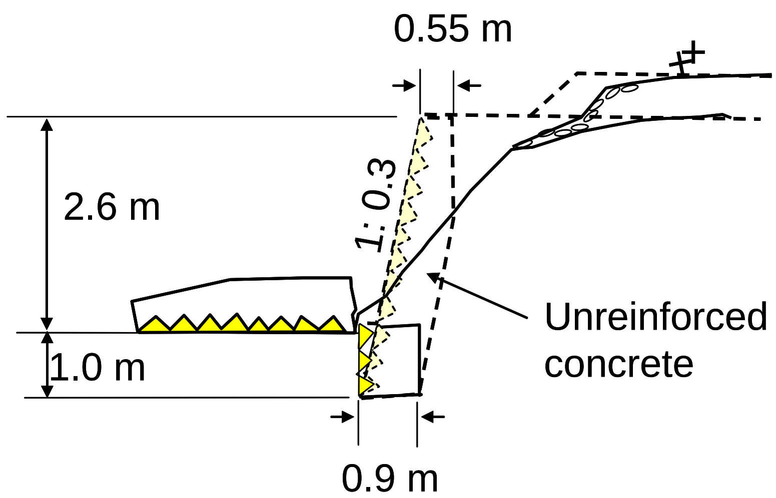
Very high performance against very high seismic load

A week after the 1995 Kobe Earthquake

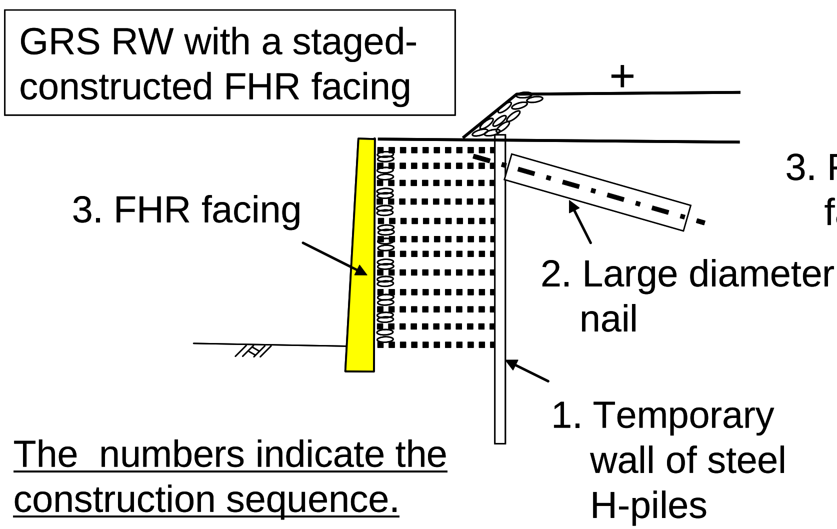
The wall survived!

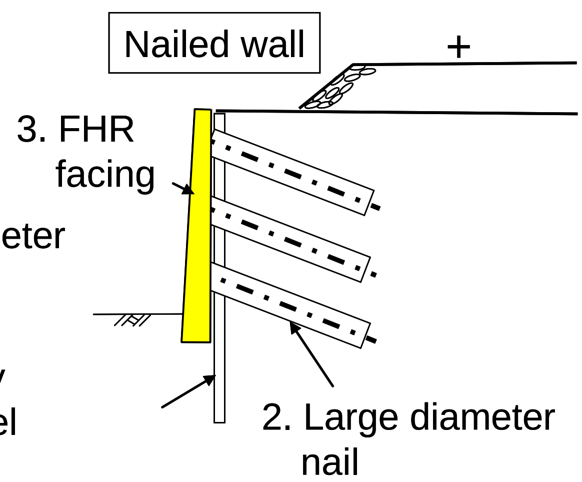
A week after the 1995 Kobe E.Q.

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



Restoration





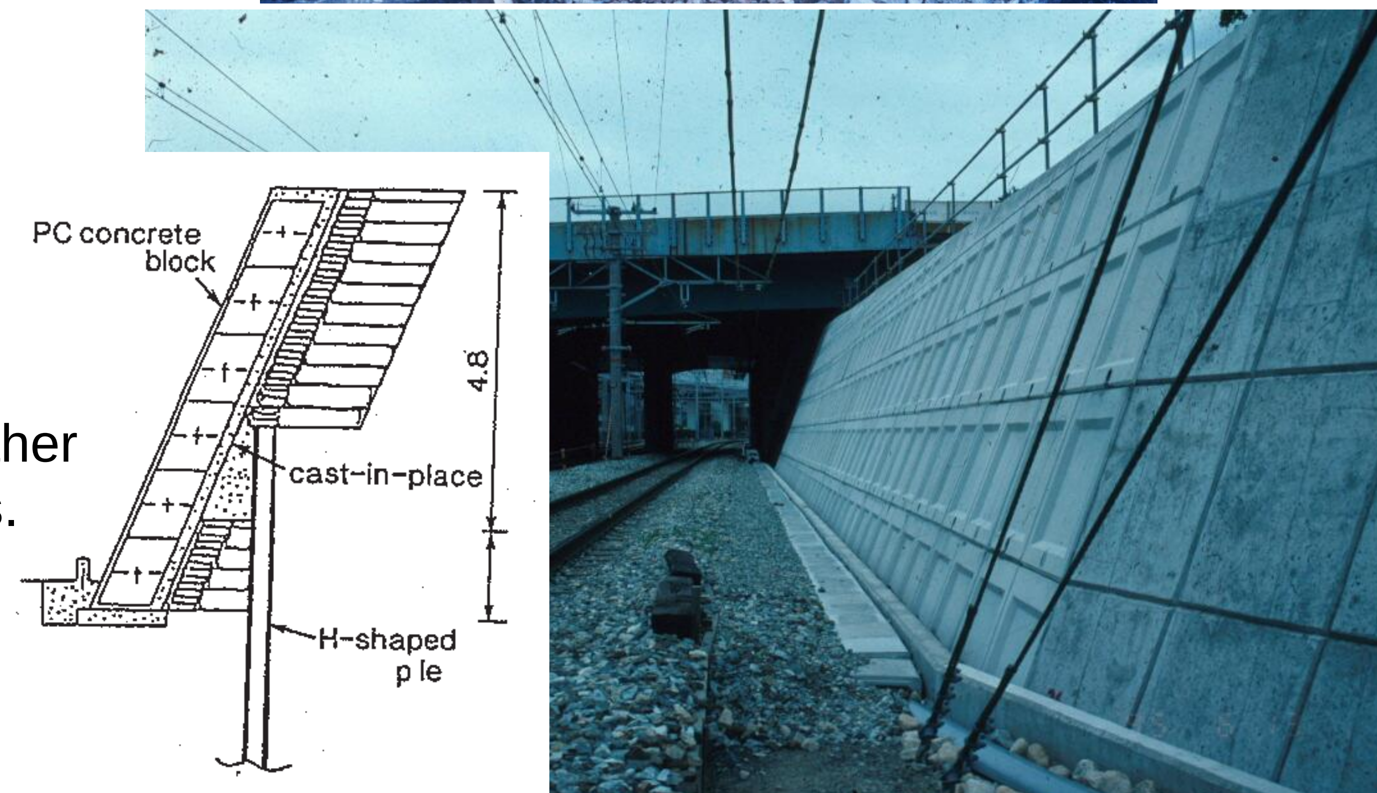
<u>The numbers indicate the construction sequence.</u>

Collapse of masonry RW by the 1995 Kobe EQ and reconstruction to GRS RW

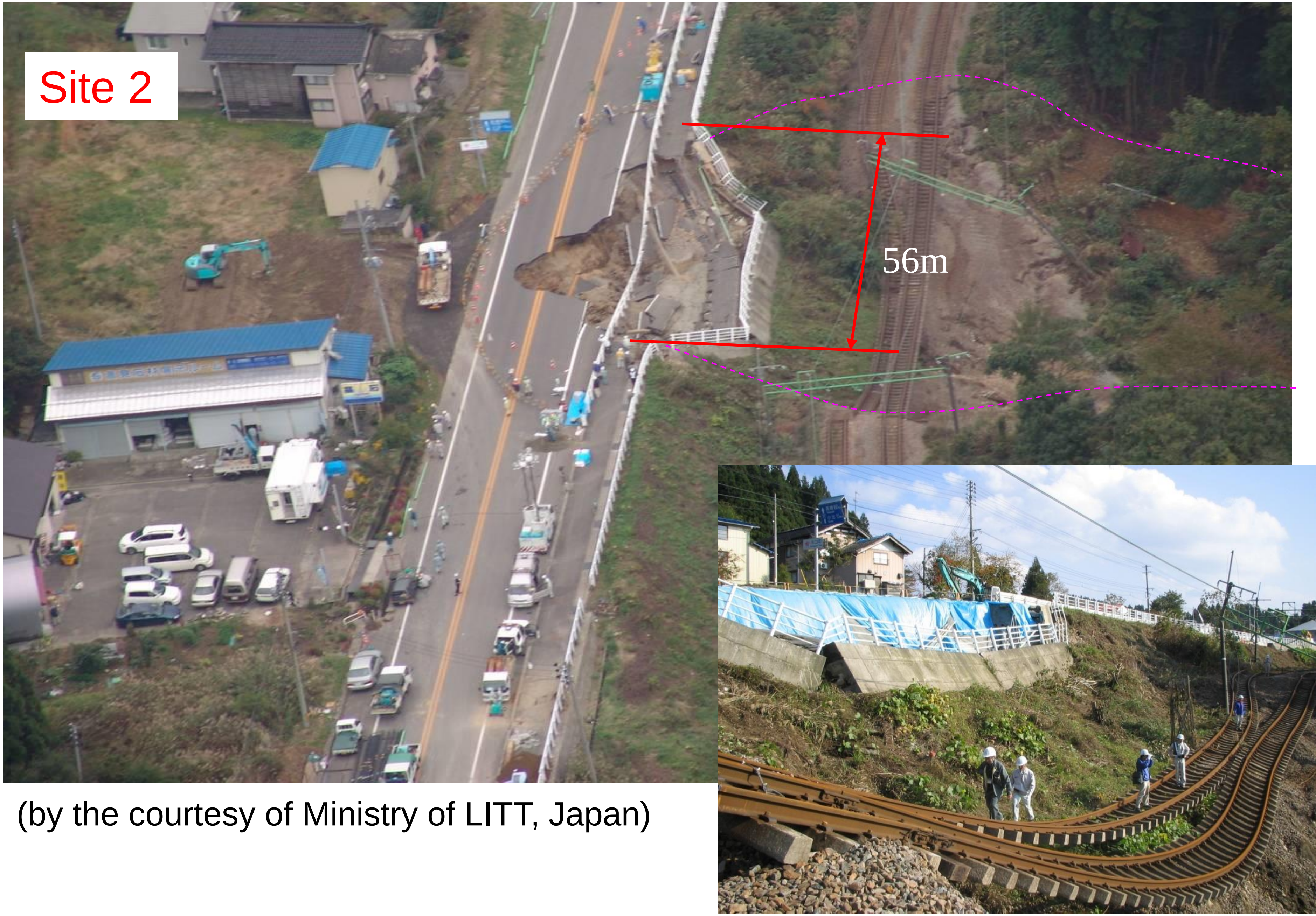
JR Kobe line
Mountain-side
Between Setsu-Motoyama and Sumiyoshi Stations

Restoration

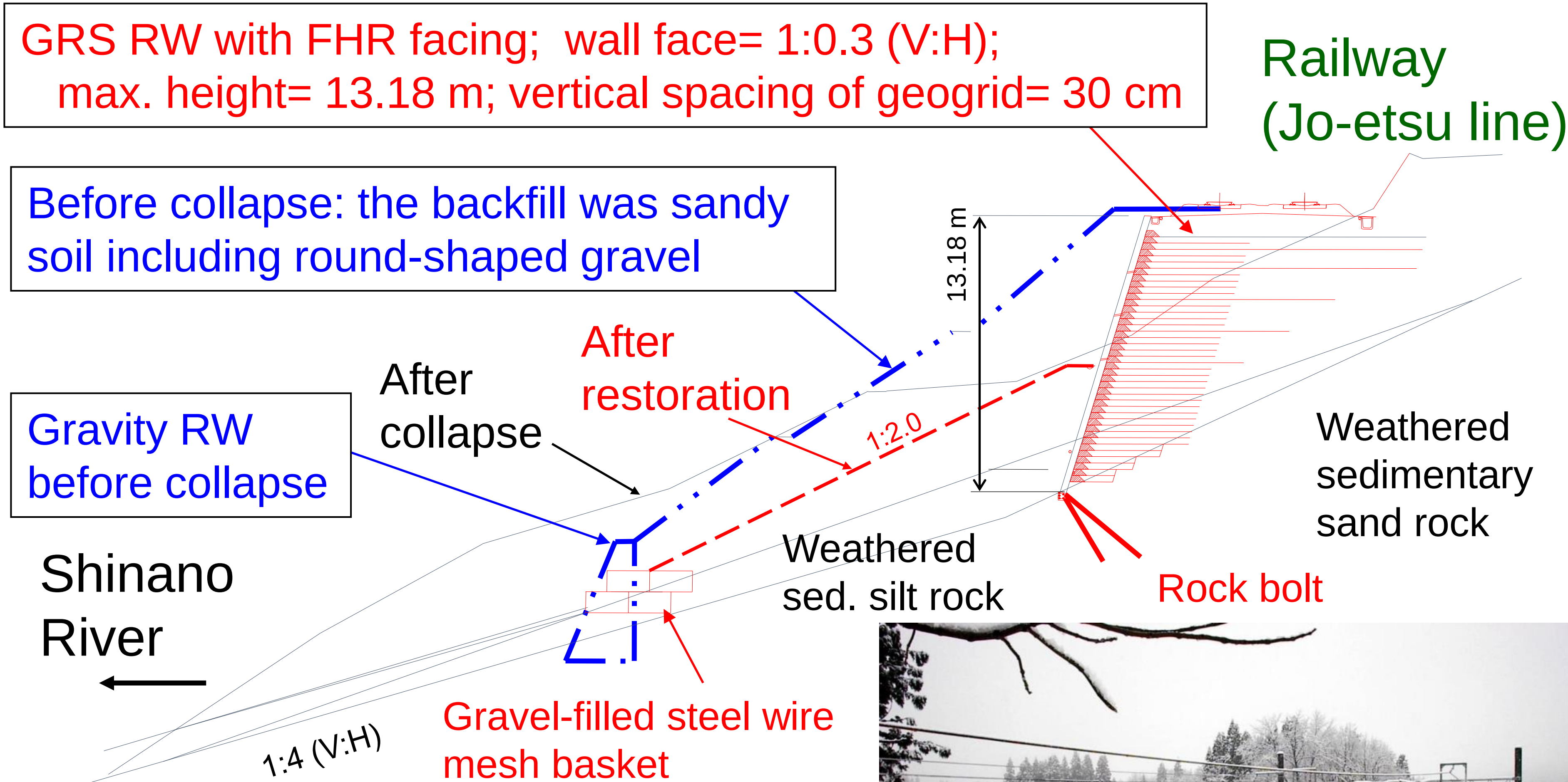
FHR facing of PC concrete blocks connected to each other and to the grid layers.



2004 Niigata-ken Chuetsu EQ, October 2004



(by the courtesy of Ministry of LITT, Japan)



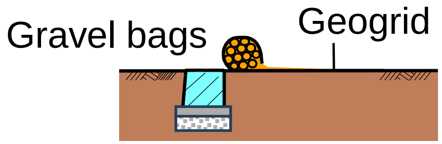
Site 2

First train

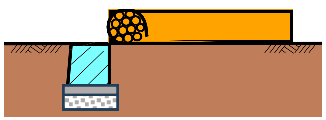
Max. wall height = 13.18 m

Staged construction of FHR facing

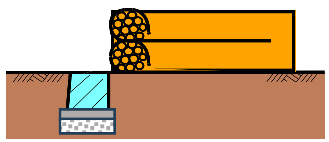
1) Levelling pad & buried part of facing



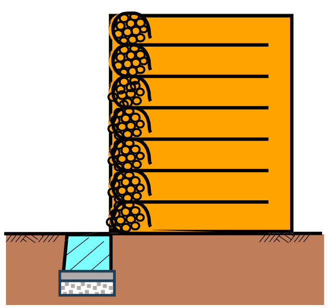
2) Placing gravel bags wrapped-around with geogrid



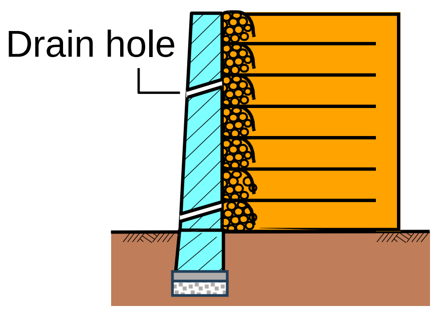
3) Backfilling & compaction



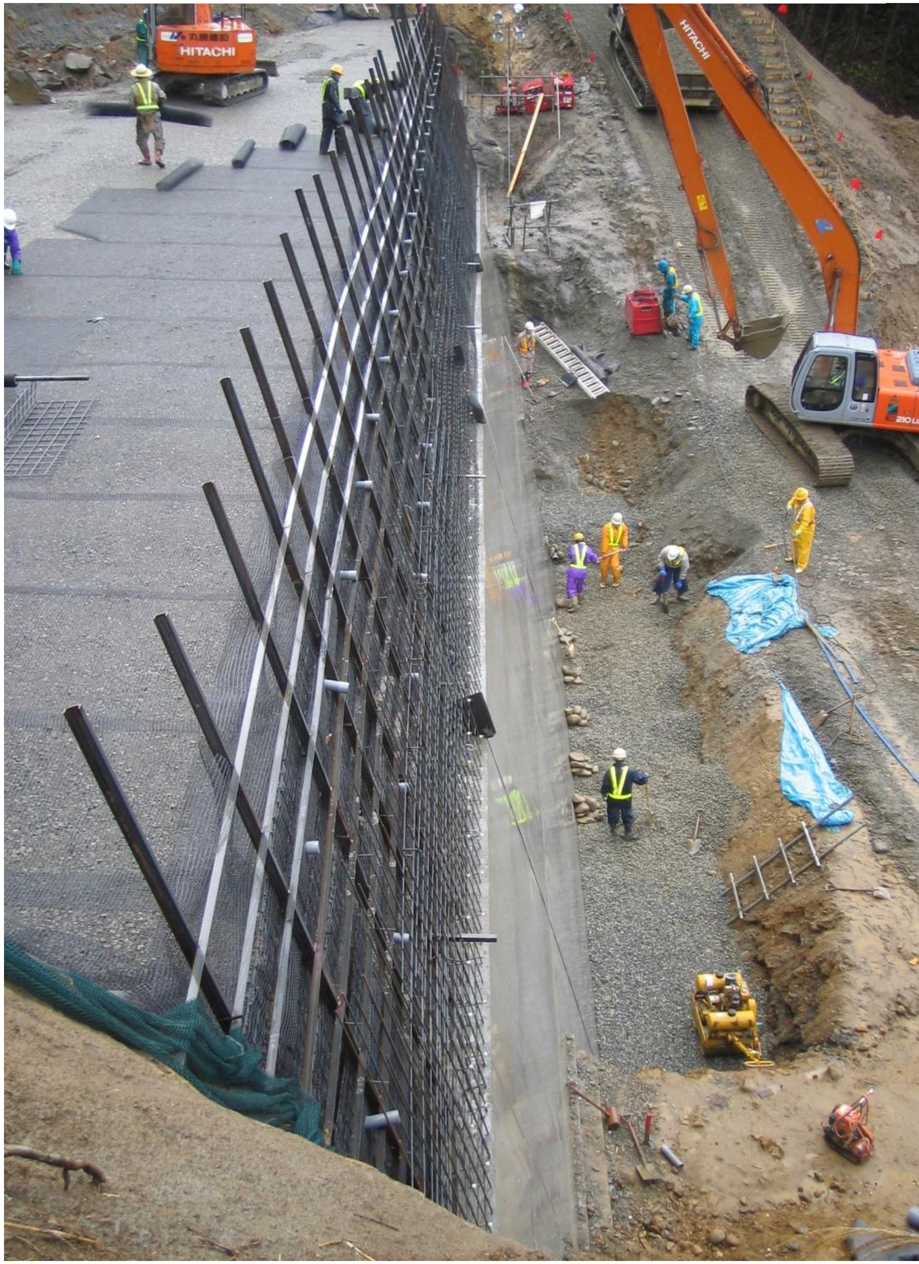
4) Second layer

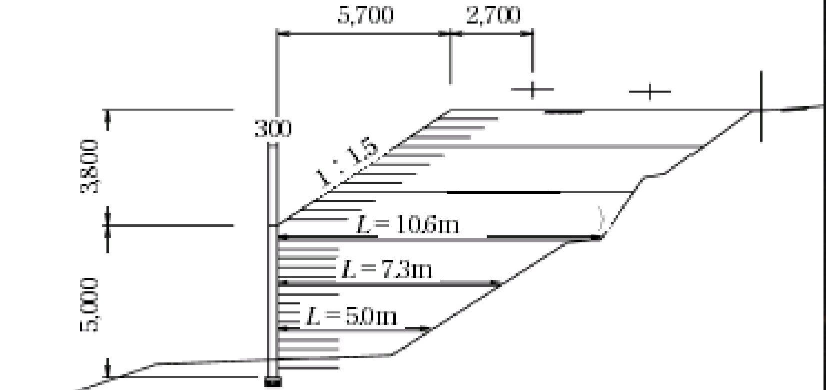


5) Completing GRS wall (w/o FHR facing)



6) FHR facing by casting-in-place concrete




5,700
2,700
300
3800
5,000
1 : 1.5
L = 10.6m
L = 7.3m
L = 5.0m
(Unit in mm)


2004/12/14

Site 3

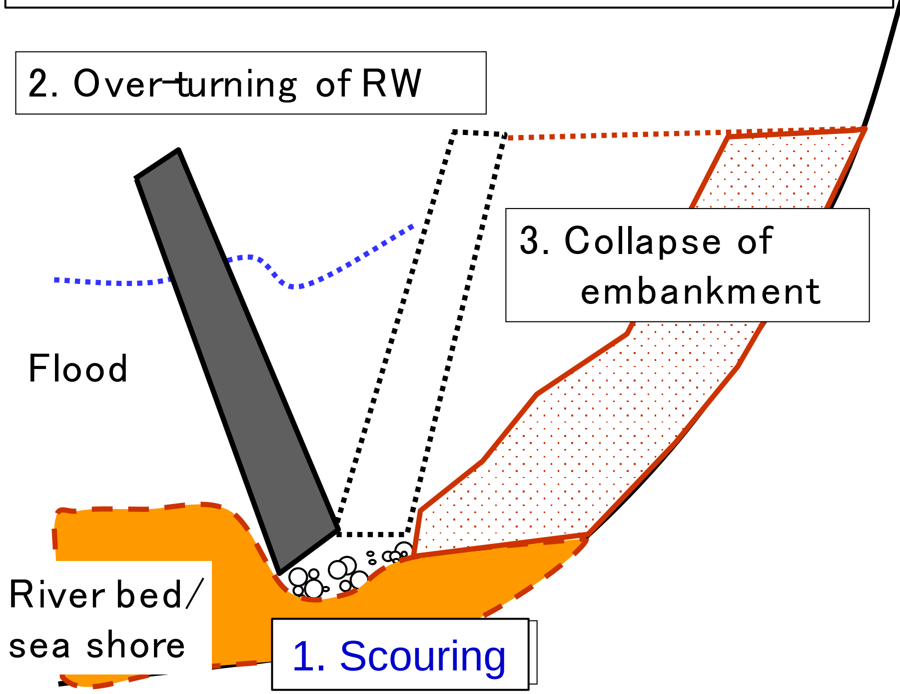
Conventional type cantilever RW

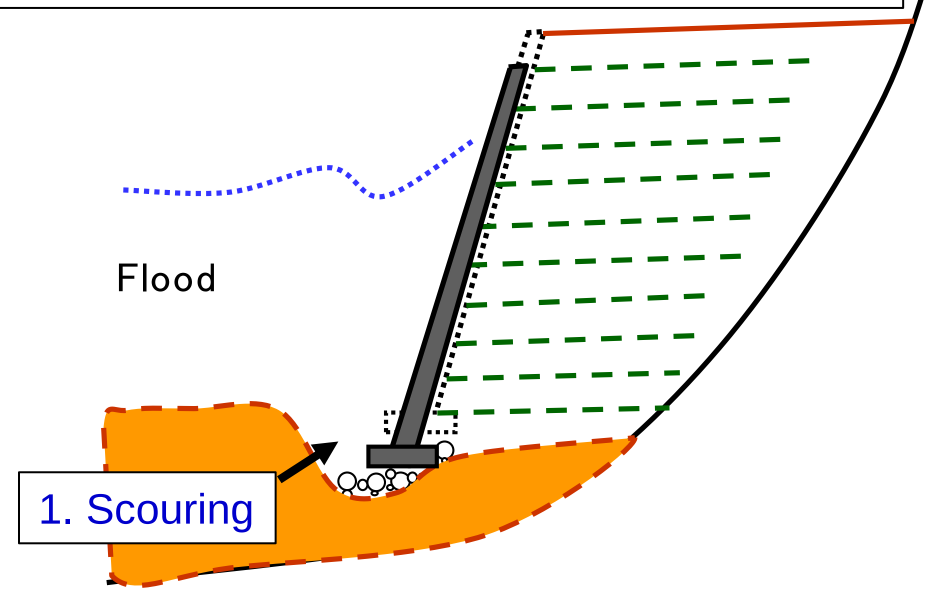
GRS-RW with FHR facing

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

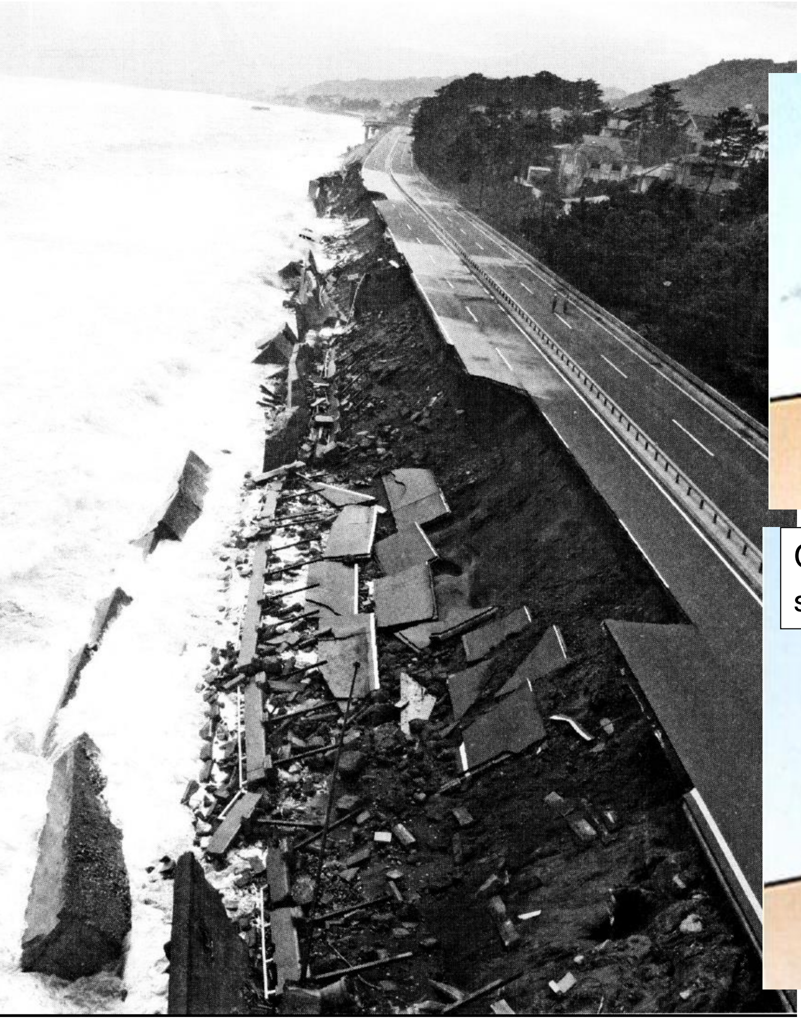
Much better performance: i.e.,

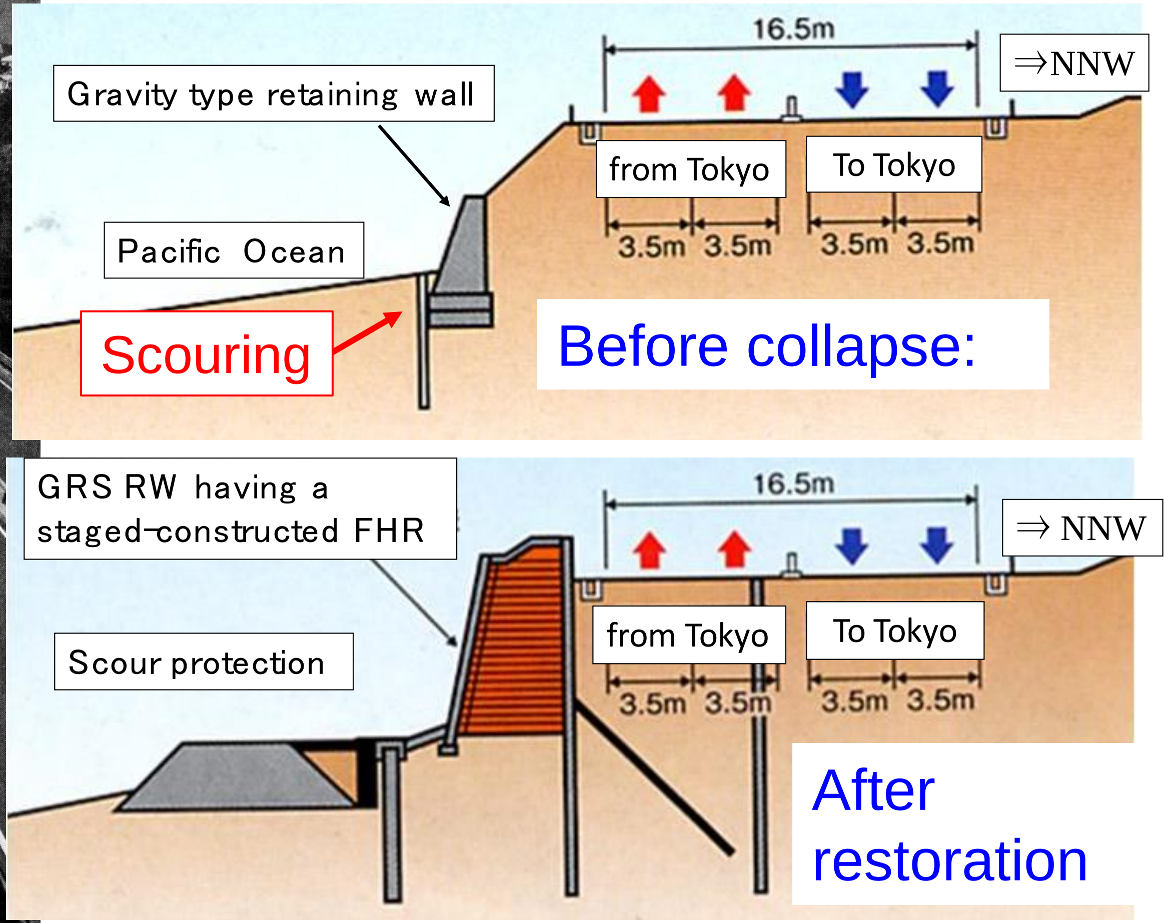
1) over-turning failure of FHR facing by scouring is difficult to take place;
2) so, the embankment can survive allowing emergency use of road & railway.





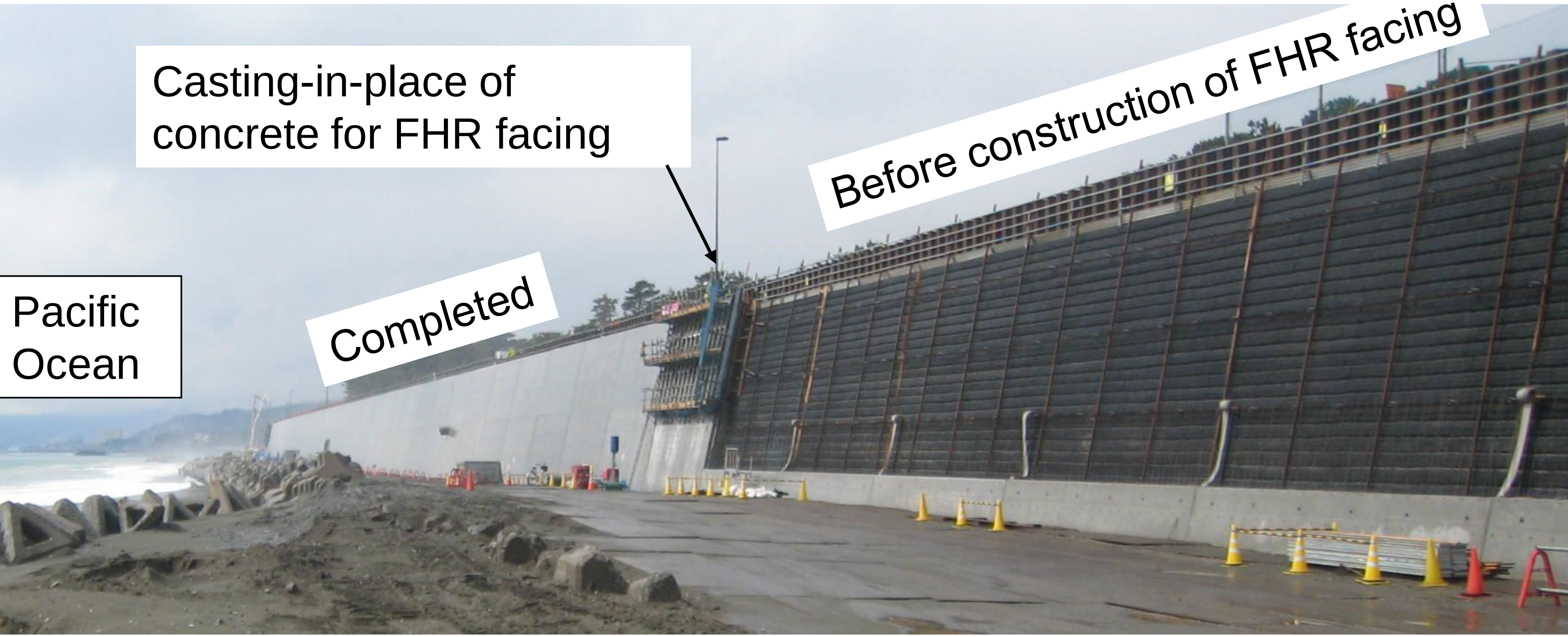
Collapse of gravity-type seawall for a length of 1.5 km by ocean waves during a storm (Typhoon No. 9), 8 Sept. 2007, National Road No. 1, southwest of Tokyo





(by the courtesy of Ministry of LITT, Japan)

Restoration to GRS RW with FHR facing



10 March 2010

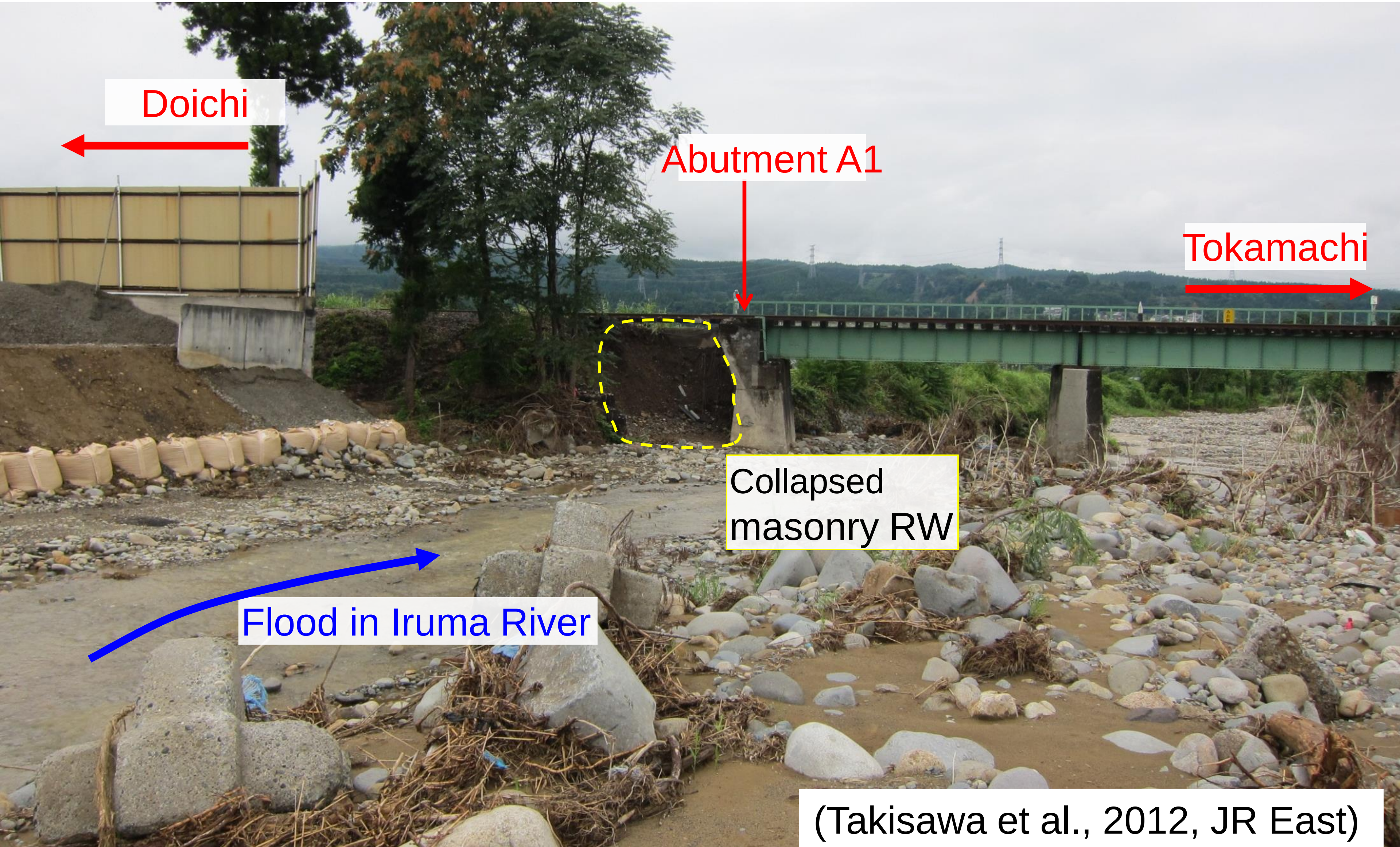
- have survived frequent attacks of storm ocean wave,
  on average twice a year ……..

13 years after restoration to GRS RW with FHR facing

26 Oct. 2023

- have survived frequent attacks of storm ocean wave, on average twice a year ……..

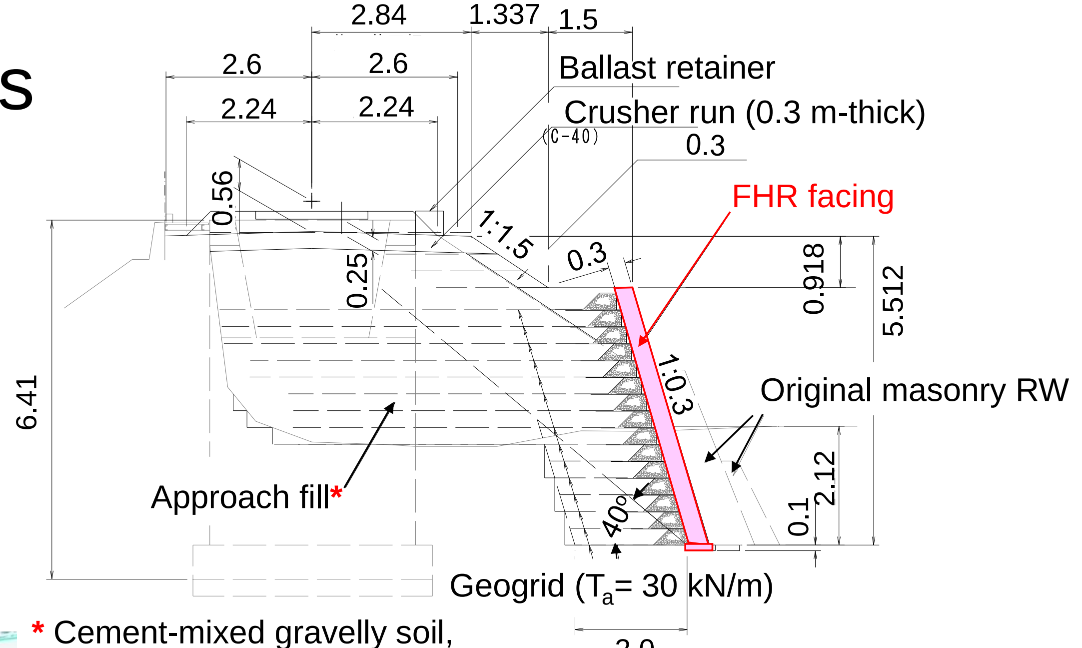
Collapse of a masonry wing RW for a RC bridge abutment by scouring in the subsoil and erosion of the backfill by river flood, Iiyama Line (JR East), July 2011



(Takisawa et al., 2012, JR East)

Restoration to GRS RWs

Only 10 days until the re-open of service: much shorter than the period 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)

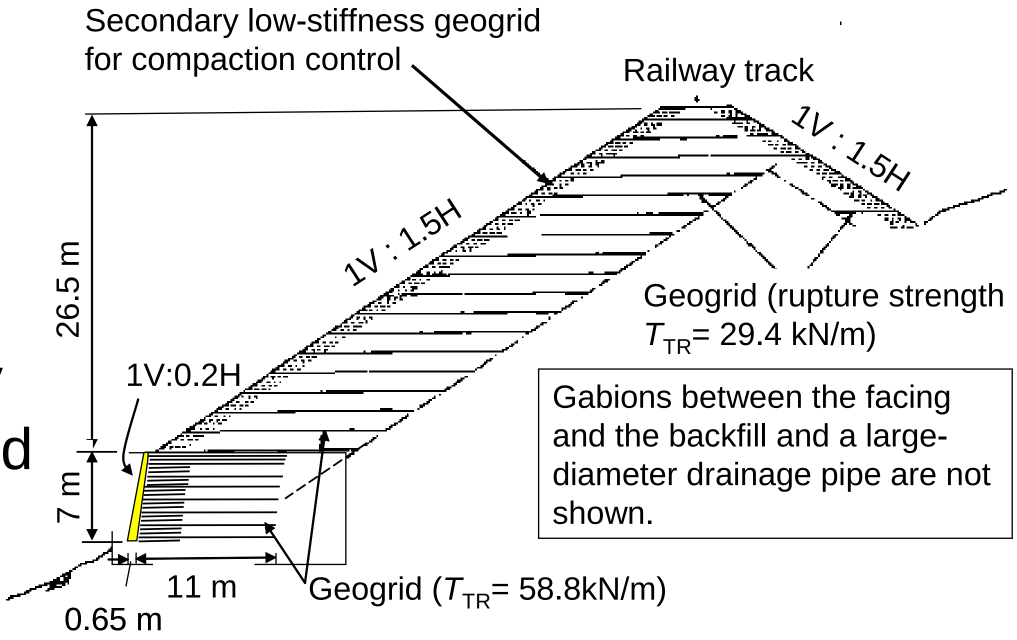
Construction of FHR facing after re-open of service

Site 2

A small drain pipe crossing the embankment was clogged by flowing timbers and a natural reservoir was formed. The embankment was fully eroded by over-topping flood.

GR RWs were constructed, because of:

a) fast construction;
b) only small construction machines necessary;
c) a high stability against heavy rainfalls and earthquakes; and
d) low cost for construction and maintenance



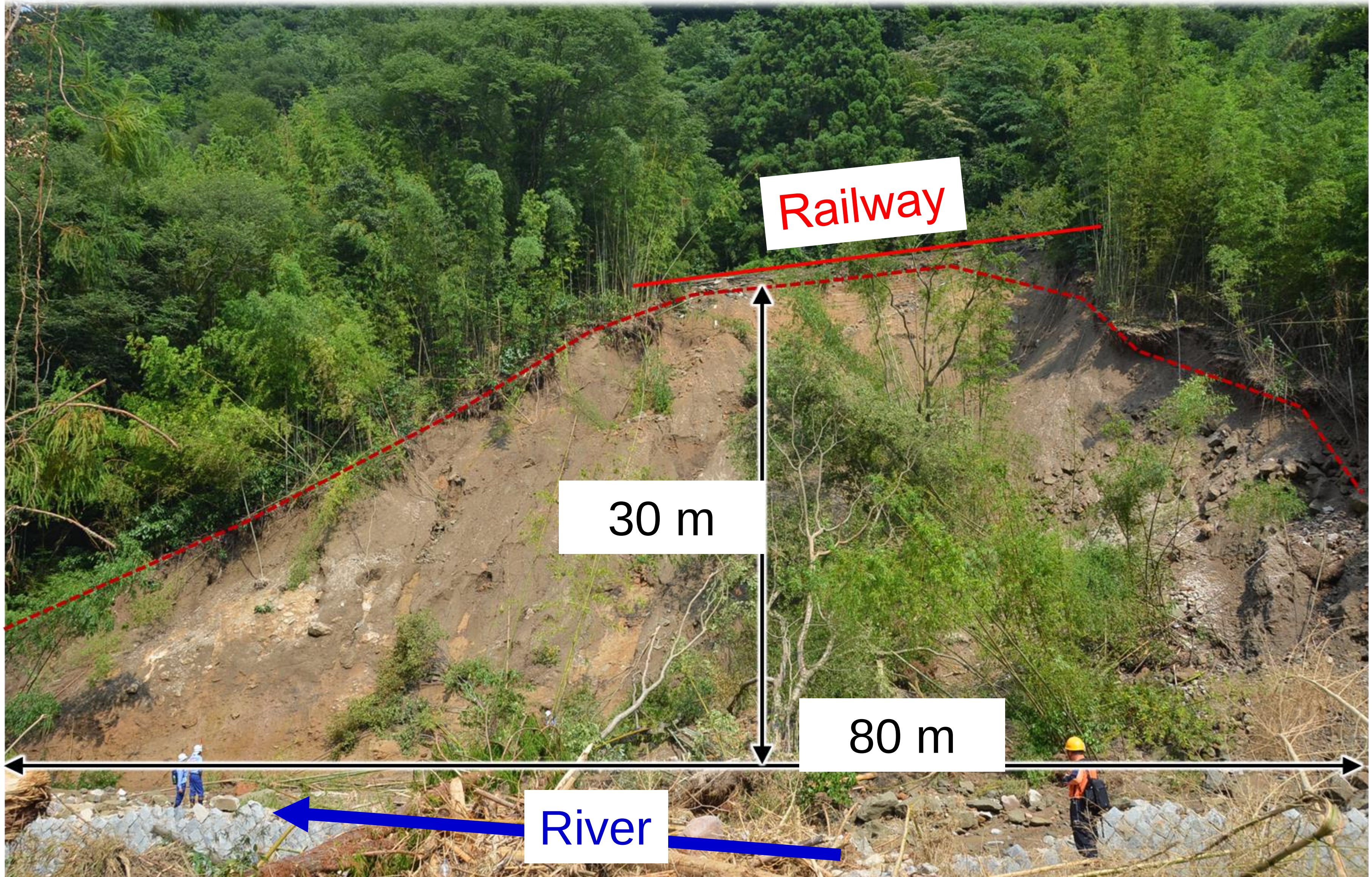
Reconstruction to GR slope and GRS-RW in 1991

1994

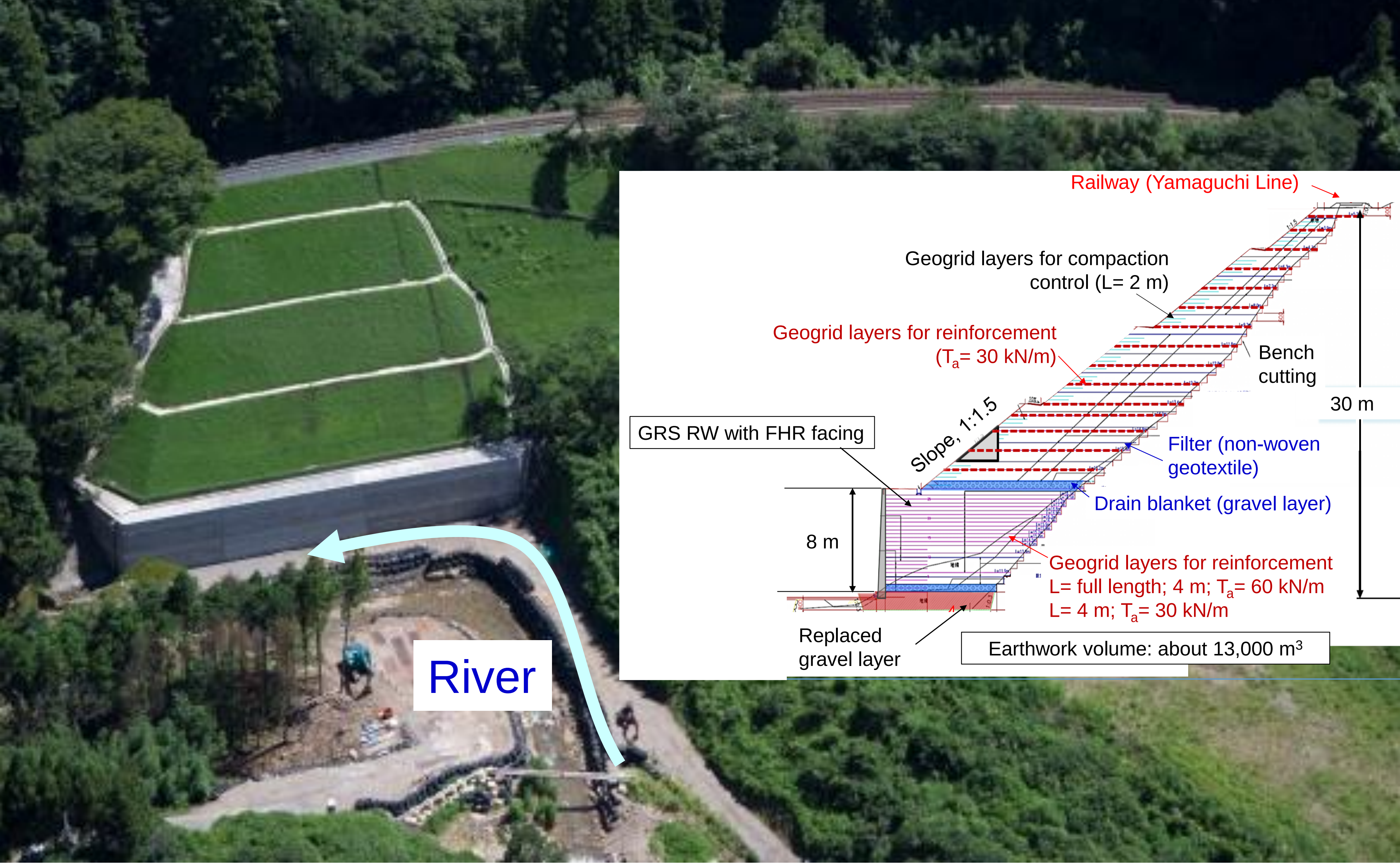
Site 2

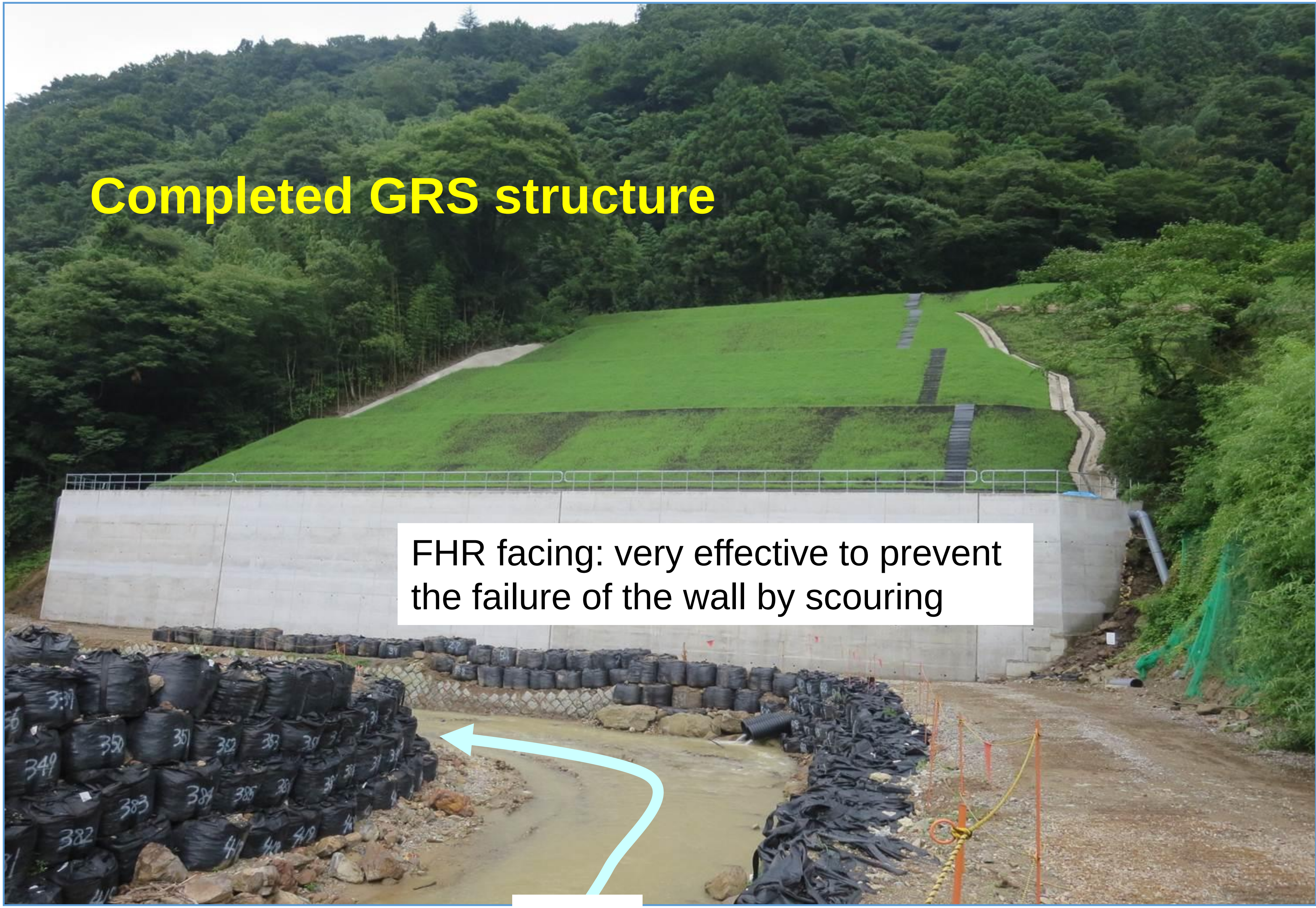
Collapse of railway embankment by scouring at the toe of embankment by river flood (28 July 2013)

JR West



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

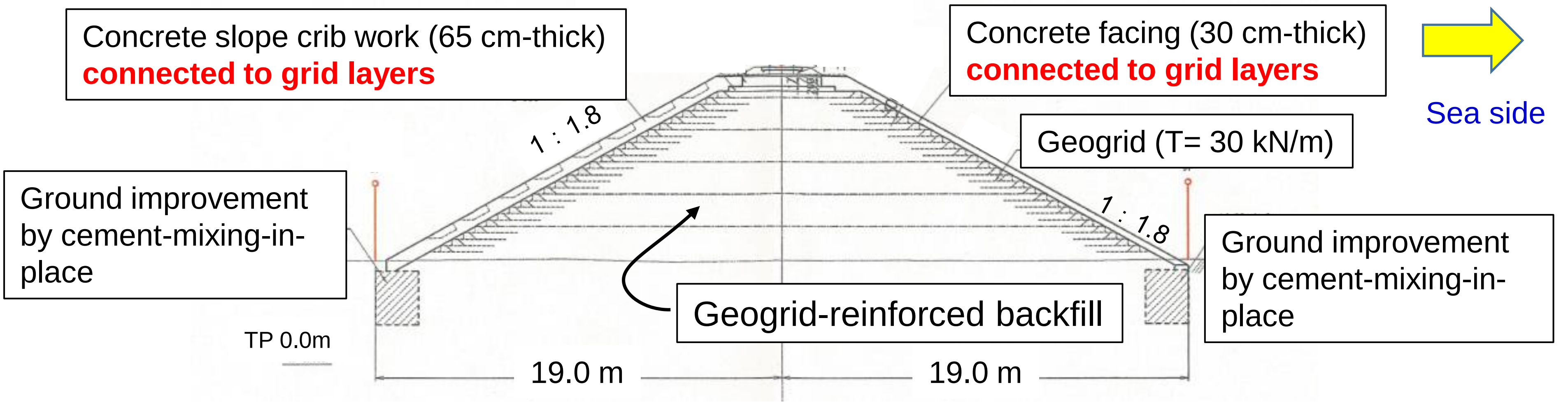



Completed GRS structure
FHR facing: very effective to prevent the failure of the wall by scouring
River

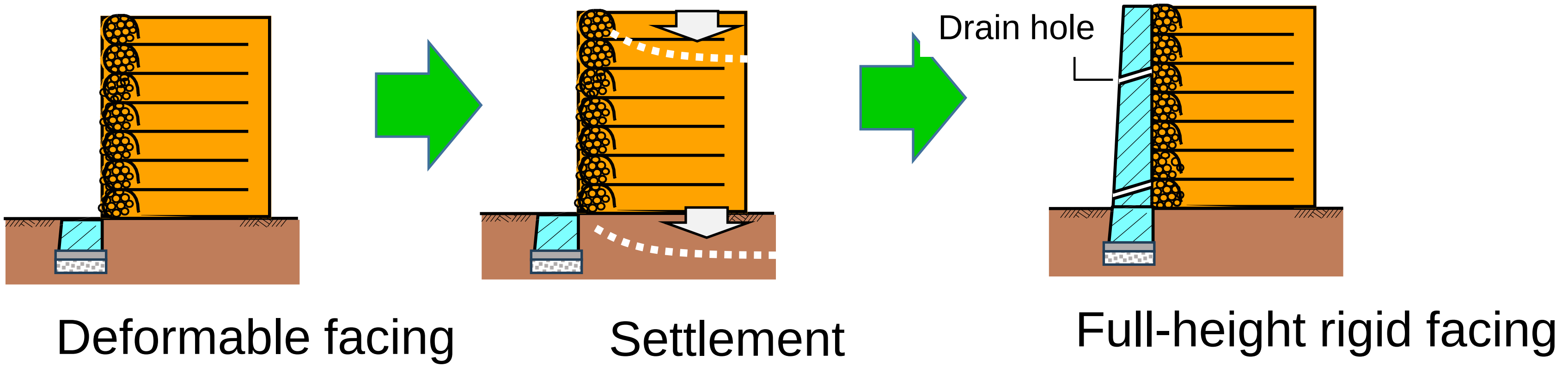
Shima-no-koshi

Immediately after 2011
Great East Japan E. Q.

Railway embankment, also as a tsunami-barrier



Advantageous features of GRS structure having stage-constructed FHR facing that alleviate many problems



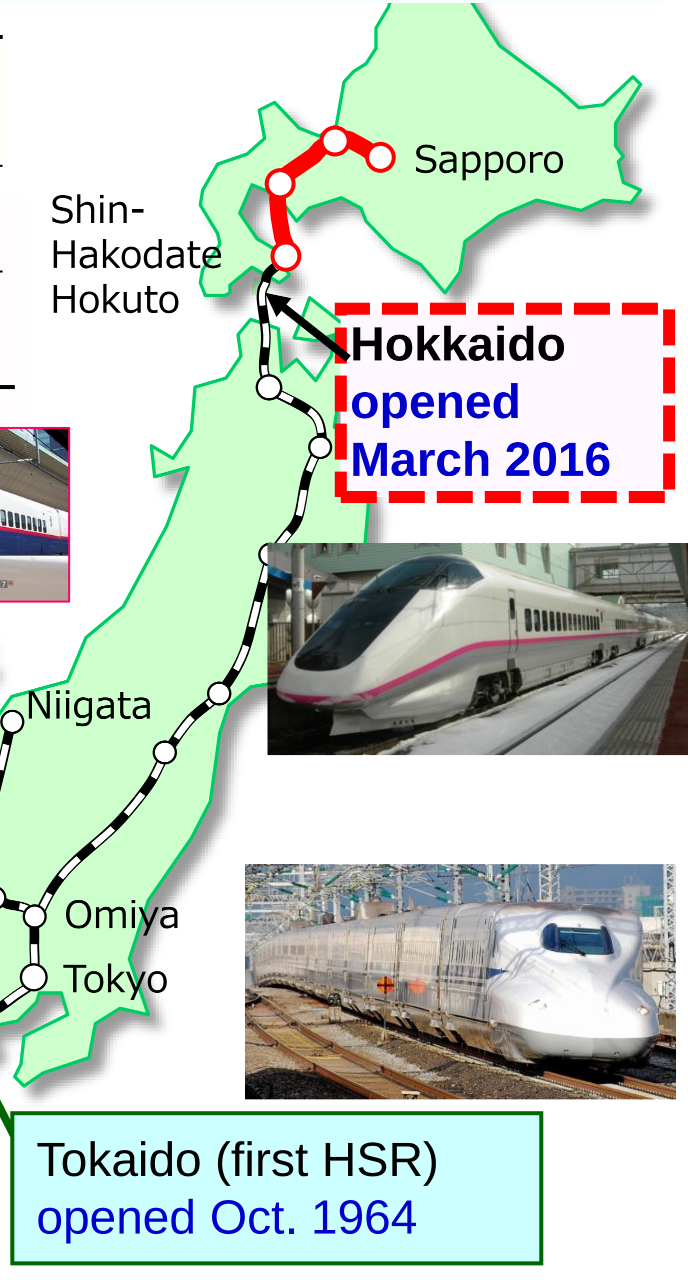
High performance and high cost-effectiveness by:

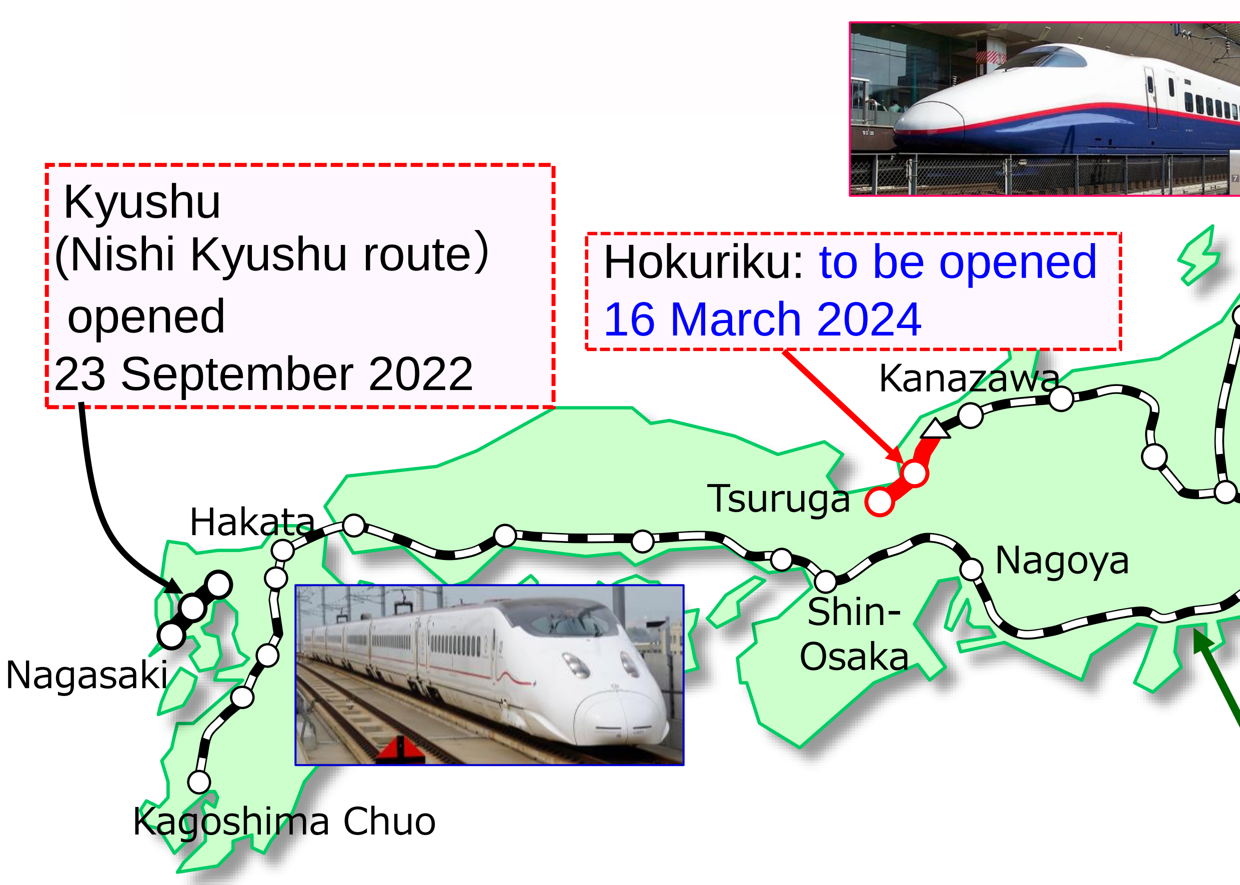
1) High stability despite no use of a pile foundation.
2) Very small post-construction deformation/settlement.

3) Narrow space occupied during & after construction.
4) Cost-effective construction of stable RW on slope.
5) FHR facing can directly support other structures (e.g., bridge girder).
6) High stability against severe seismic load, scouring, erosion etc.
7) GRS structures for High Speed Railways

High-Speed Railways (Shinkansen), 2023

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

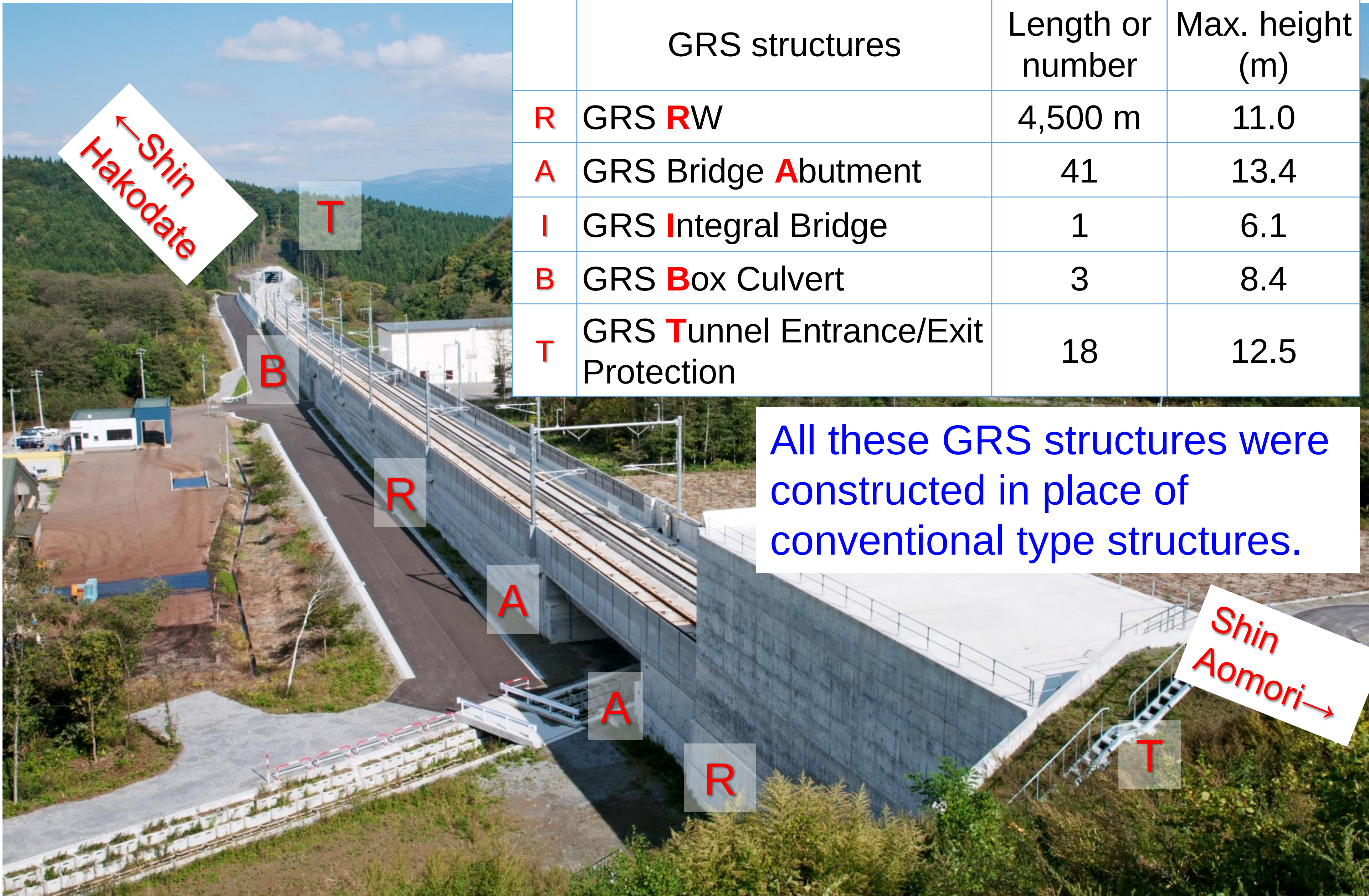




Mantaro site

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

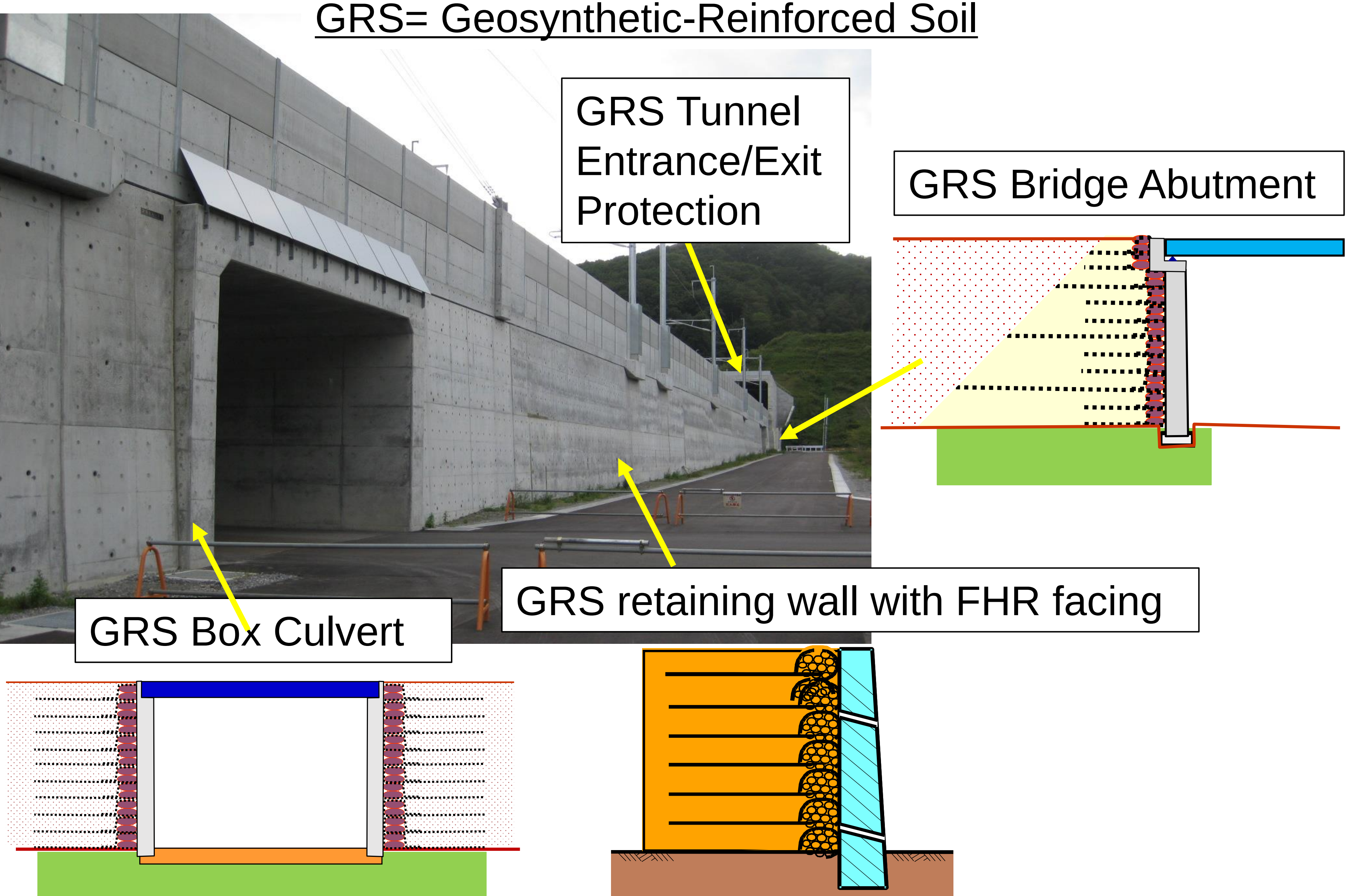


All these GRS structures were constructed in place of conventional type structures.

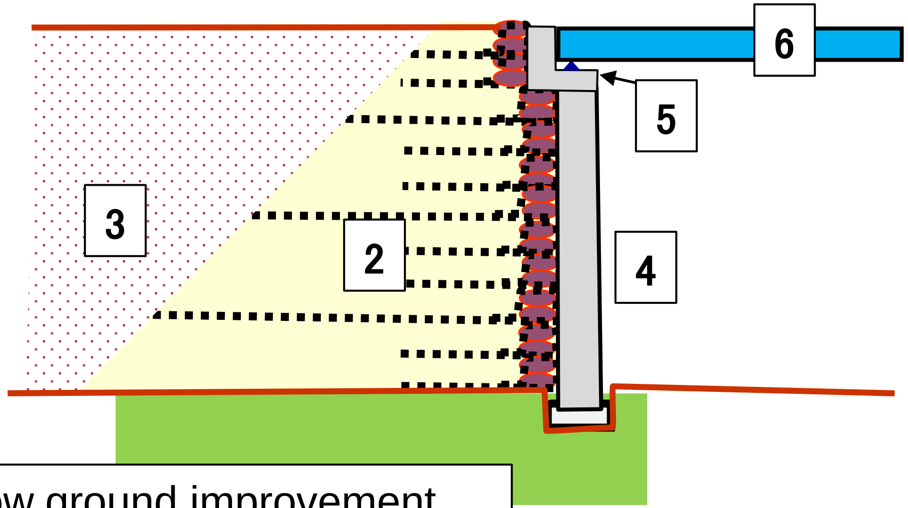
Yonezawa et al. (2014): JRTT

Mantaro site, Hokkaido Shinkansen

GRS= Geosynthetic-Reinforced Soil



GRS Bridge Abutment



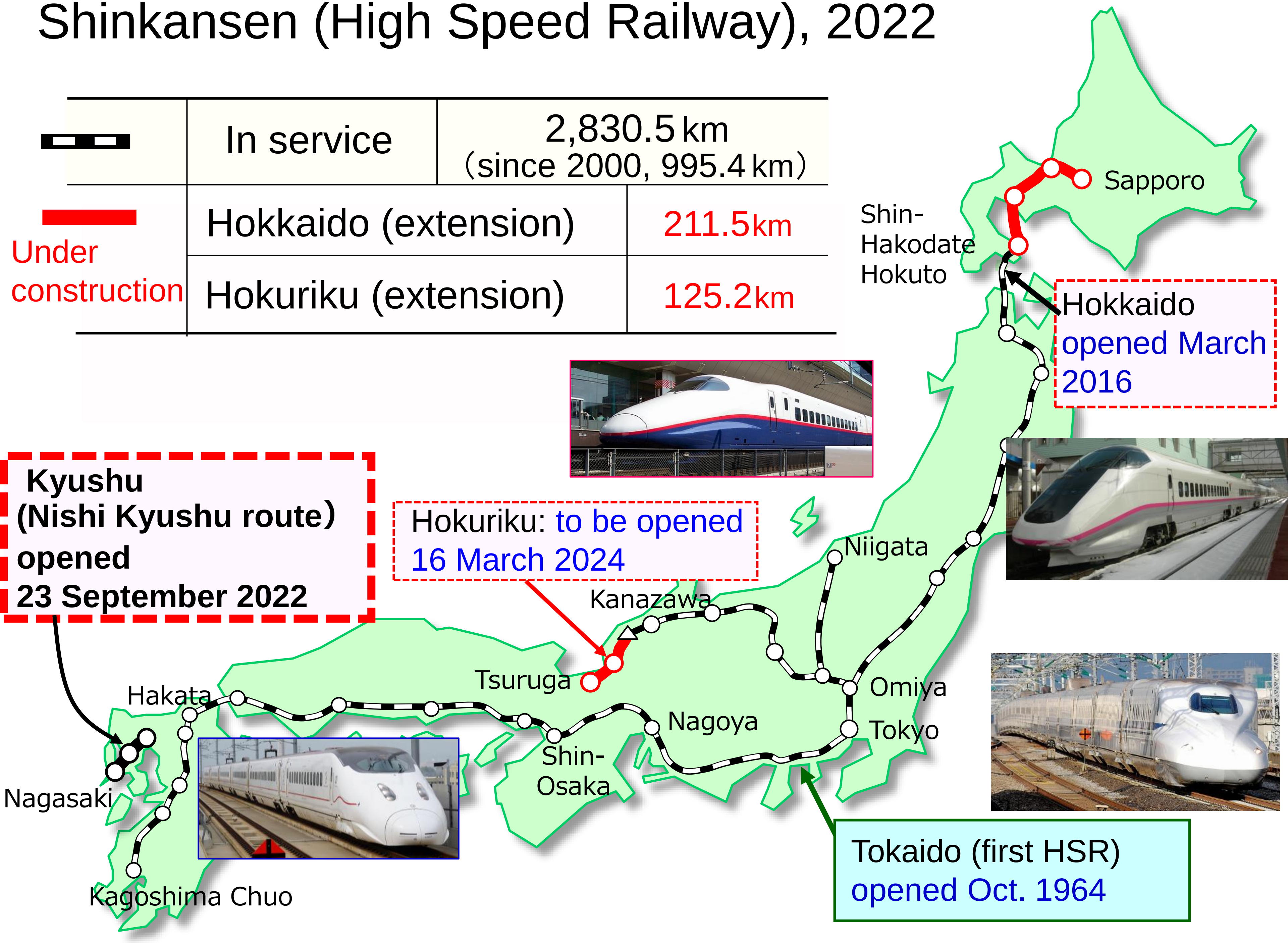
13.4 m-high, Mantaro site

Under construction
Oct. 2011

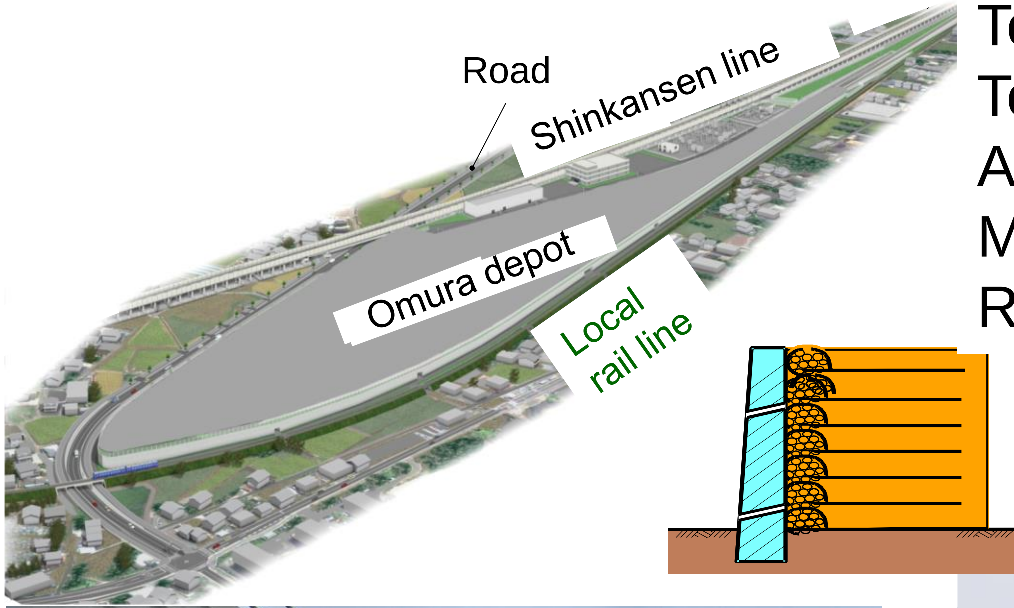
Completed
Aug. 2012

Shinkansen (High Speed Railway), 2022

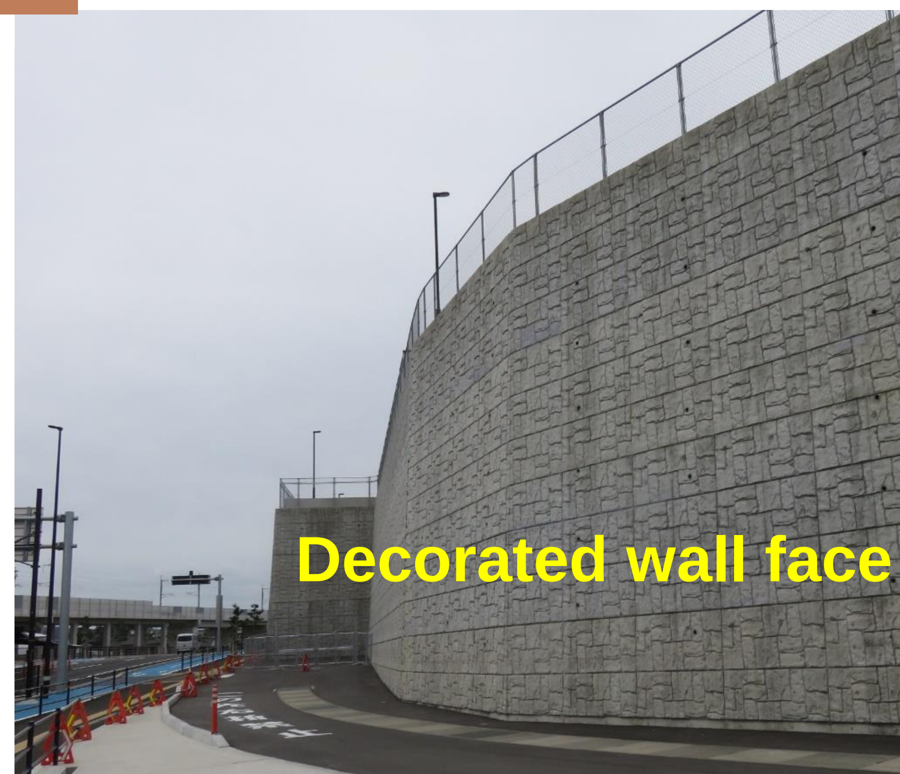
(black-and-white line)	In service		2,830.5 km (since 2000, 995.4 km)
(red line) Under construction	Hokkaido (extension)		211.5 km
	Hokuriku (extension)		125.2 km



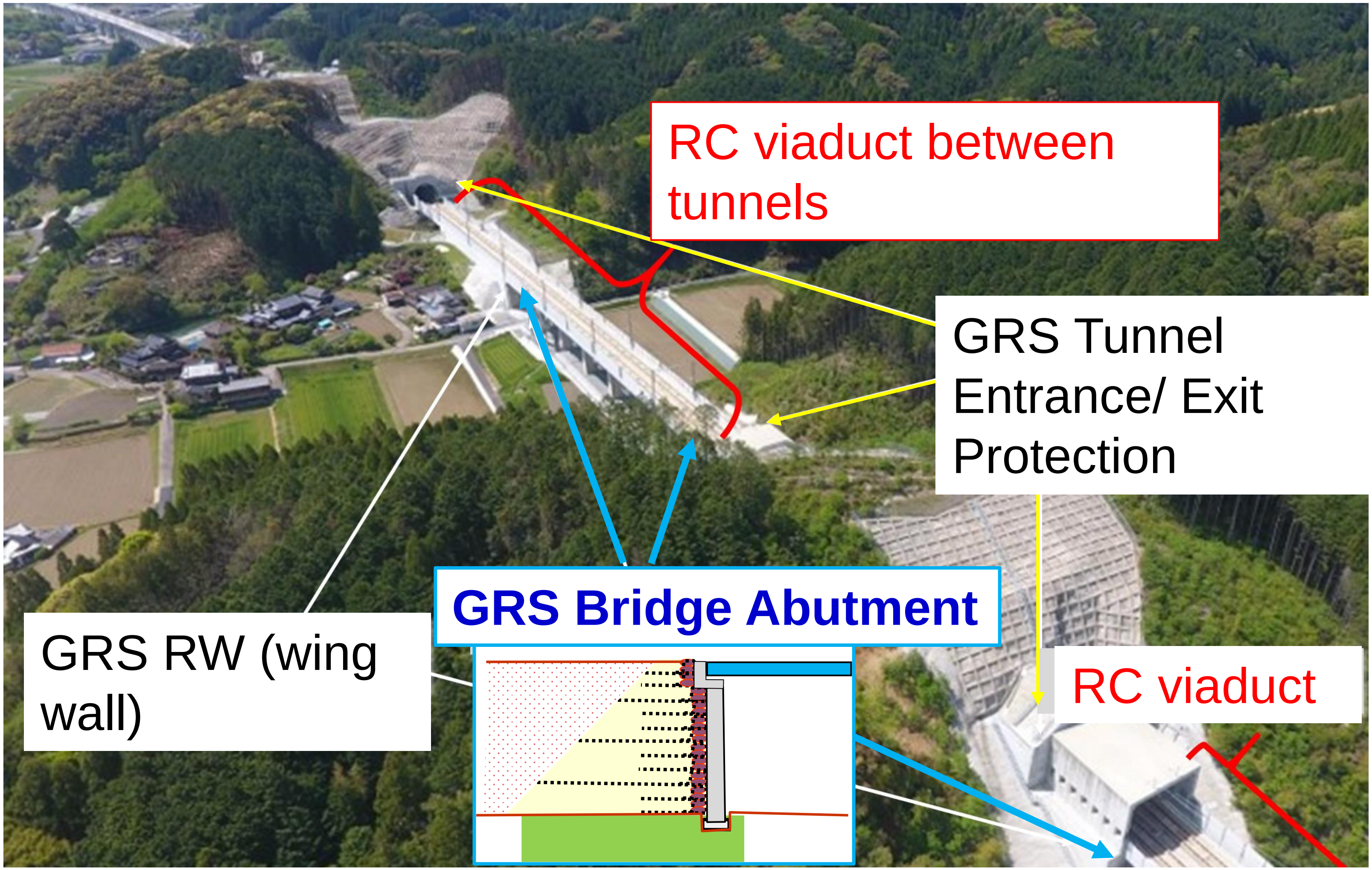
GRS RWs at Omura Depot



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,
Among 88 bridge abutments constructed at the tunnel exits,
78 (i.e., 89 %) are GRS Bridge Abutments !



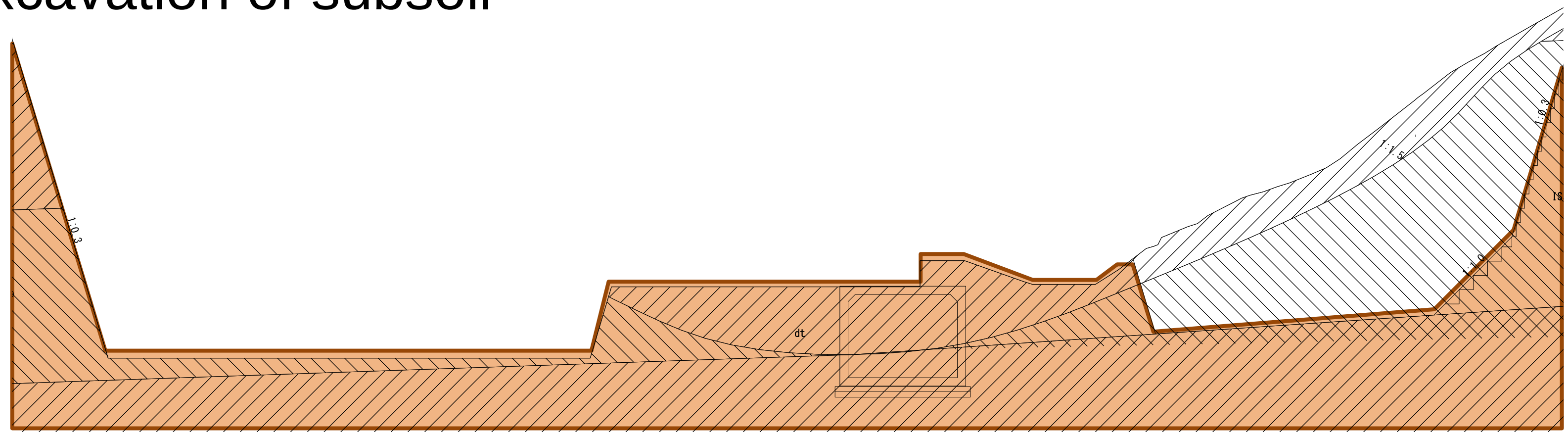
(By the courtesy of JRTT)

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


GRS Bridge
Abutment

GRS Integral Bridge at Genshu

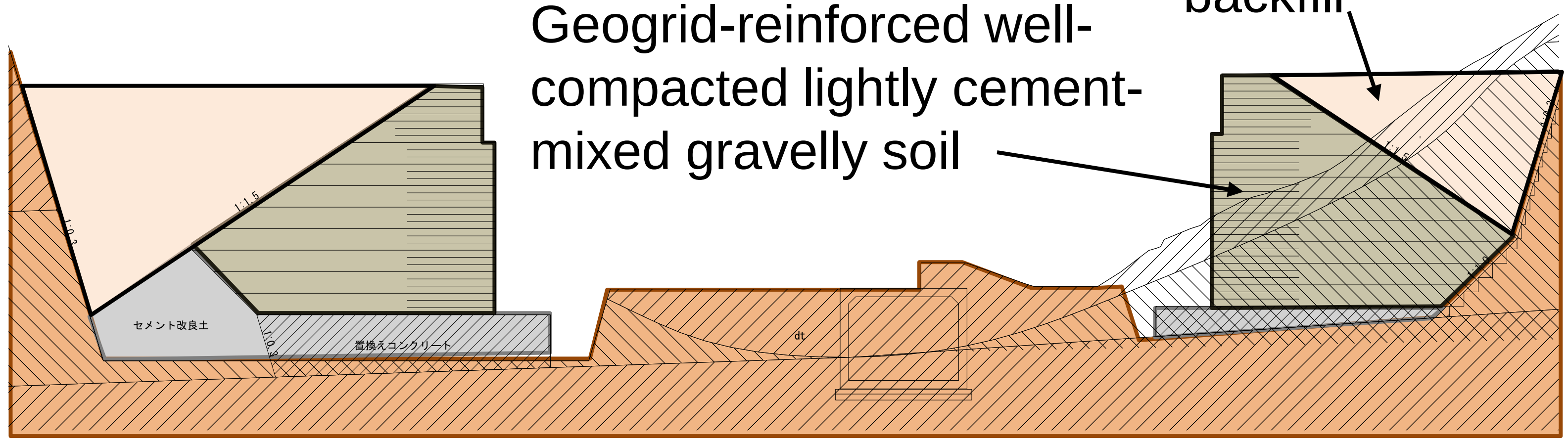
1. Excavation of subsoil



2. Construction of approach fills

Unreinforced backfill

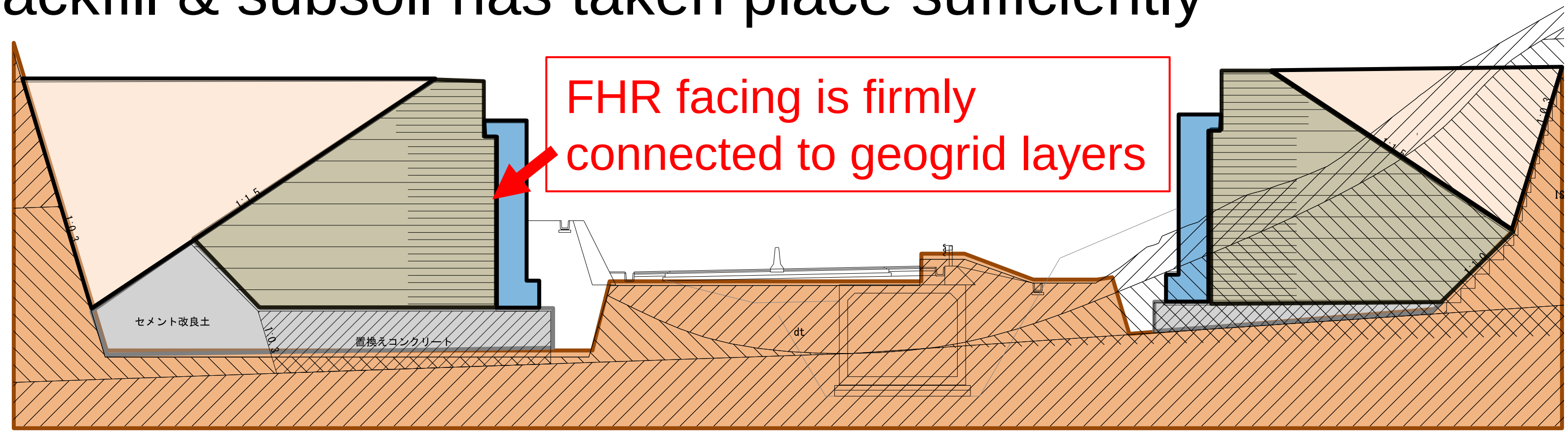
Geogrid-reinforced well-compacted lightly cement-mixed gravelly soil



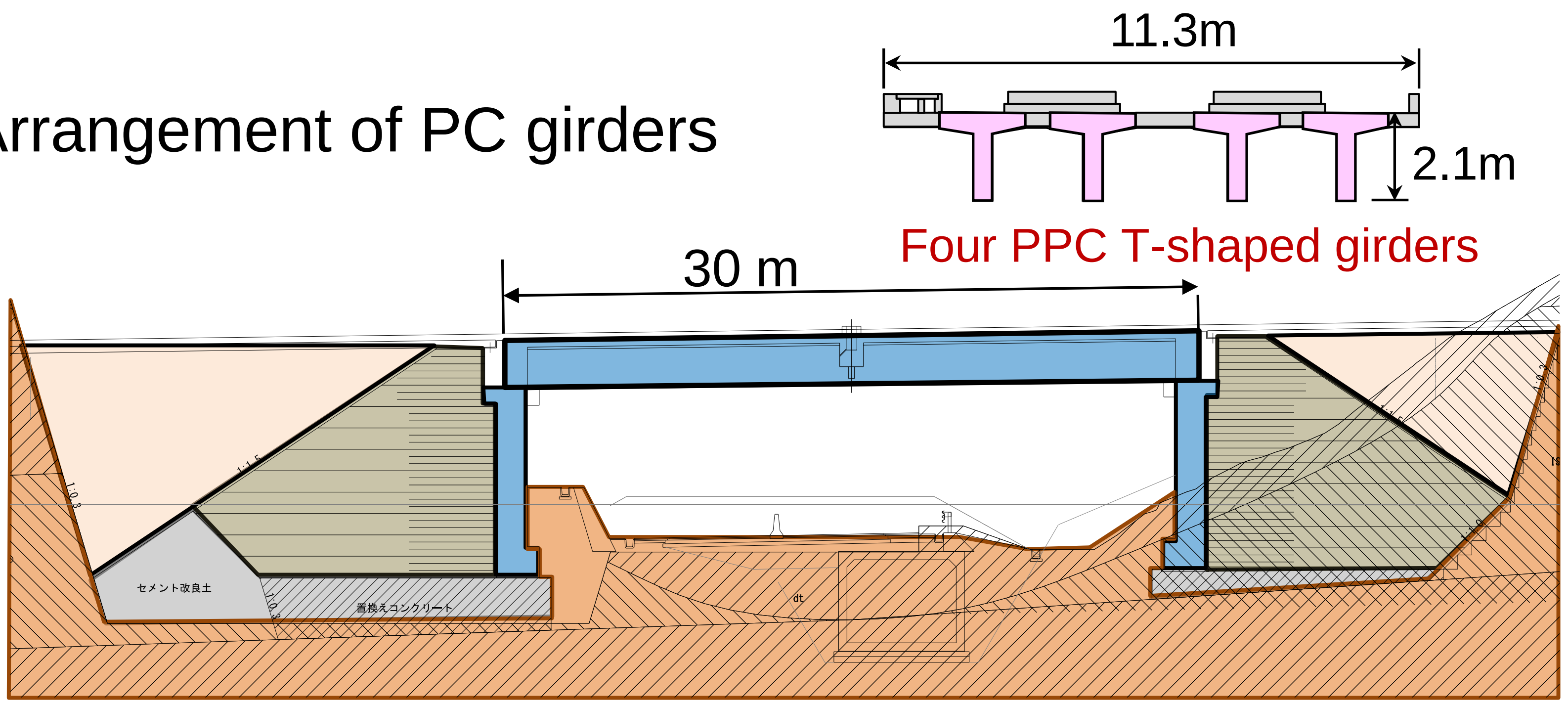
Soga et al. (2018) & JRTT

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

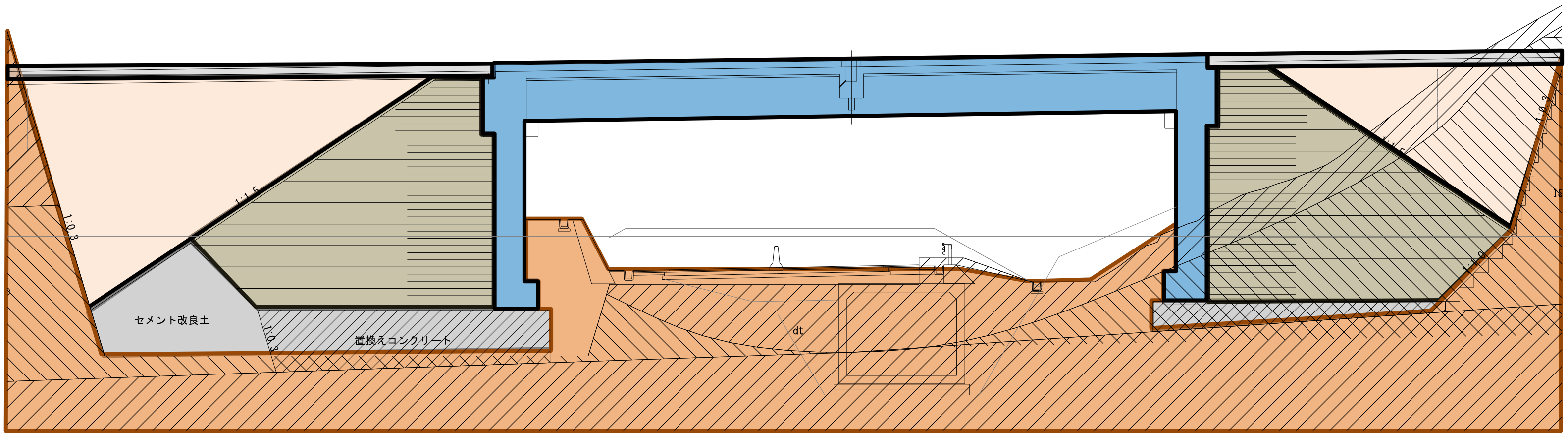


Arrangement of a 30 m-long PC girder

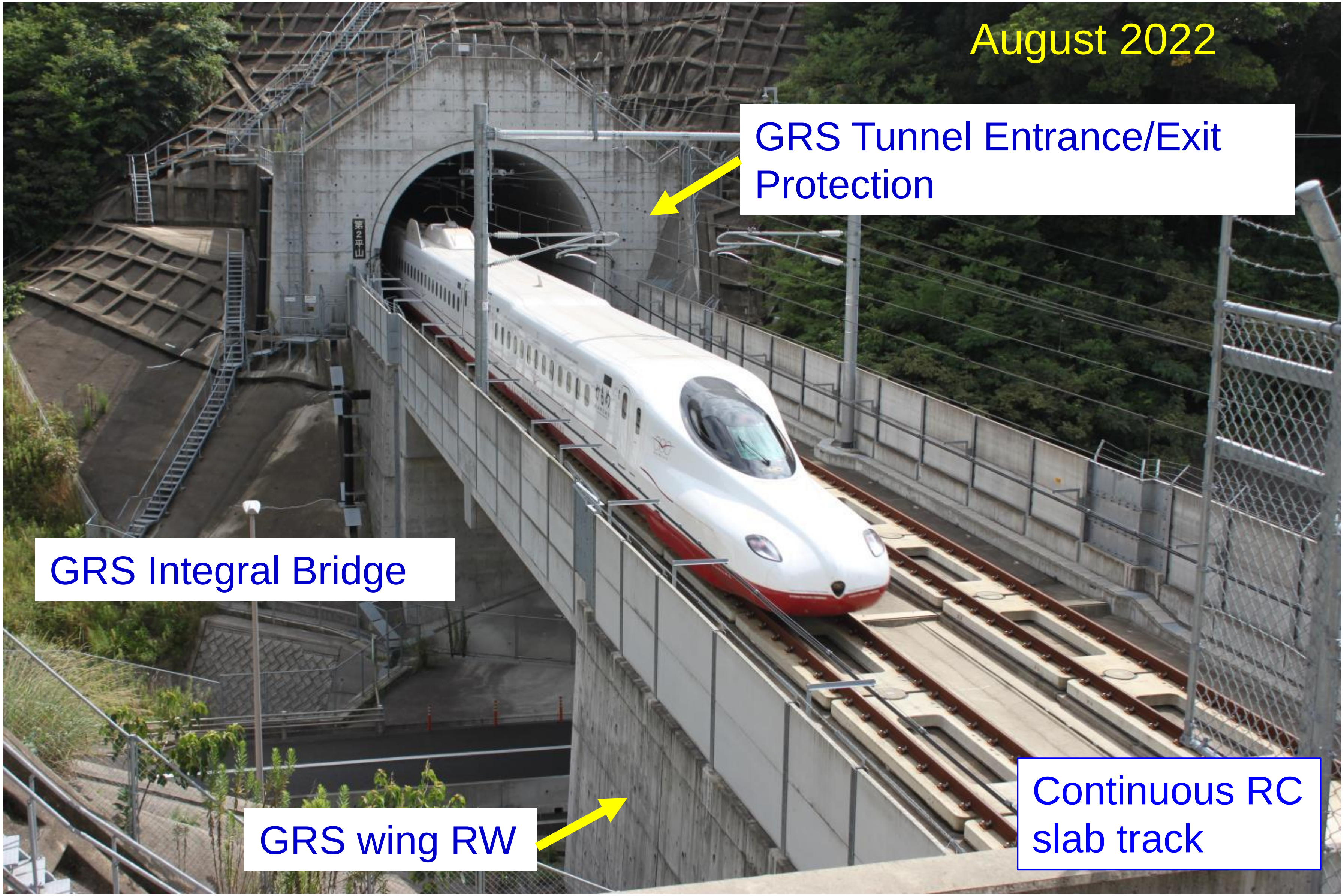
(By the courtesy of JRTT)

GRS Integral Bridge at Genshu

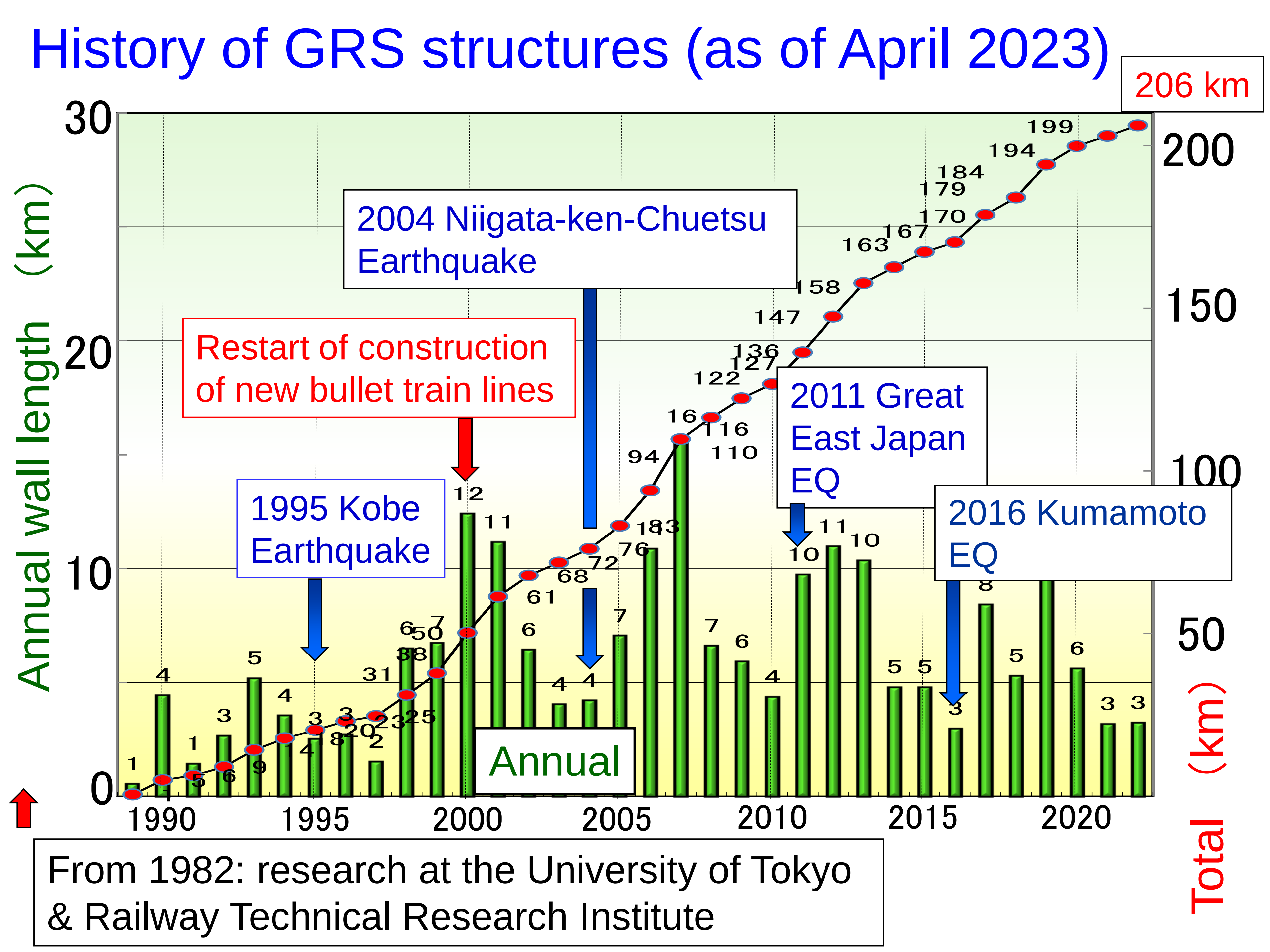
5. Structural integration of both ends of the girders to the FHR facings, then construction of slab & others to complete the bridge



Completed GRS Integral Bridge at Genshu



By the courtesy of JRTT

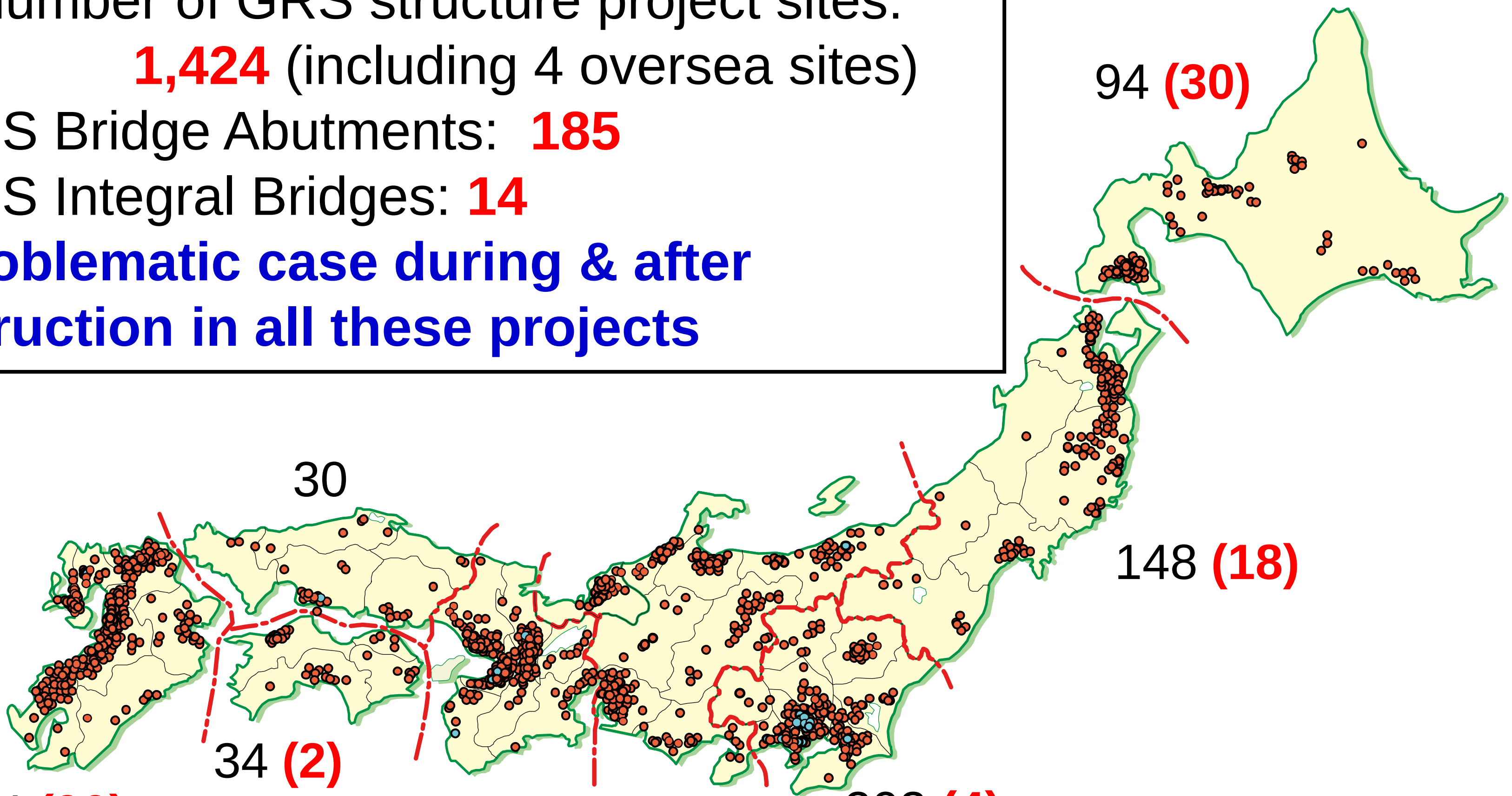


History of GRS structures (as of April 2023)
206 km
2004 Niigata-ken-Chuetsu Earthquake
Restart of construction of new bullet train lines
1995 Kobe Earthquake
2011 Great East Japan EQ
2016 Kumamoto EQ
Annual
Annual wall length (km)
Total (km)
1990
1995
2000
2005
2010
2015
2020
From 1982: research at the University of Tokyo & Railway Technical Research Institute

Locations of completed GRS RWs with FHR facing, GRS Bridge Abutments, GRS Integral Bridges etc. (April 2023)

Total completed wall length: **206** km
Total number of GRS structure project sites:
1,424 (including 4 oversea sites)
GRS Bridge Abutments: **185**
GRS Integral Bridges: **14**

No problematic case during & after construction in all these projects



No. of GRS structure sites

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

Concluding remarks – 1/6

A number of problems with conventional type RWs
- basically, low performance & low cost-effectiveness

Specifically ……

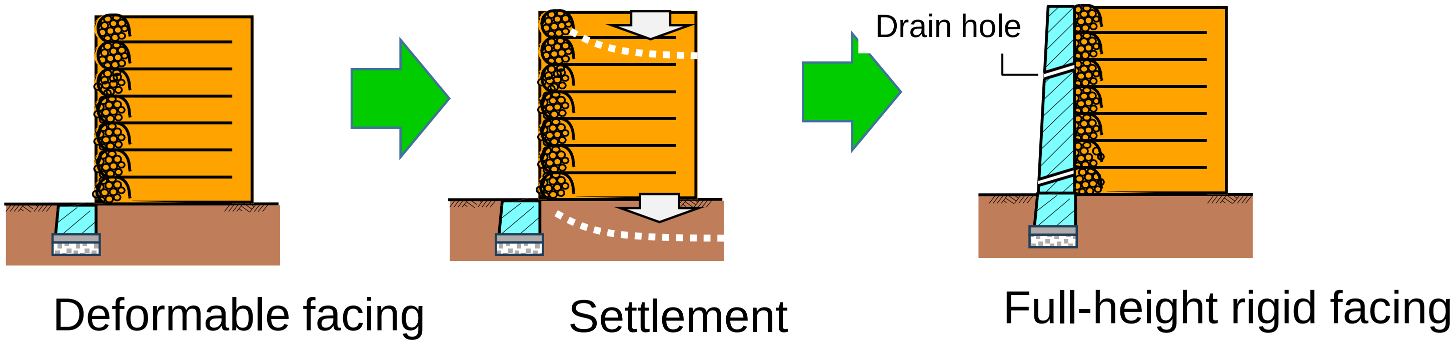
1) Need for a costly pile foundation to ensure sufficient stability.
2) Too large post-construction deformation/settlement.

Furthermore, Japan is congested & narrow with frequent severe natural disasters and a strong need for renewal of many old soil structures. So, we also have the following problems with conventional type RWs…

3) Narrow space available during & after construction.
4) Cost-ineffective construction of facing supporting other structures, including many problems with bridge abutments.
5) Cost-ineffective construction of stable RW on slope.
6) Low stability against severe seismic load, scouring, erosion, tsunami etc.
7) Not reliable for High-Speed Railways.

Concluding remarks – 2/6

The solution by three technical breakthroughs:



1) The use of full-height rigid (FHR) facing for changes:
a) from low earth pressure to high earth pressure on the facing; &
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.

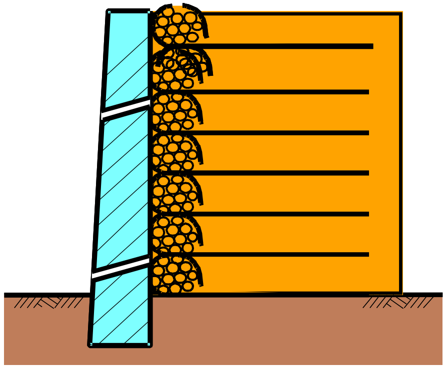
3) Staged construction for a change of construction sequence:
from the facing before the backfill to the facing after the backfill.

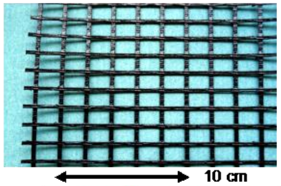
Concluding remarks – 3/6

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 206 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 seismic load, heavy rainfall, strong flood and tsunami; and
- **low cost** for construction and long-term maintenance.

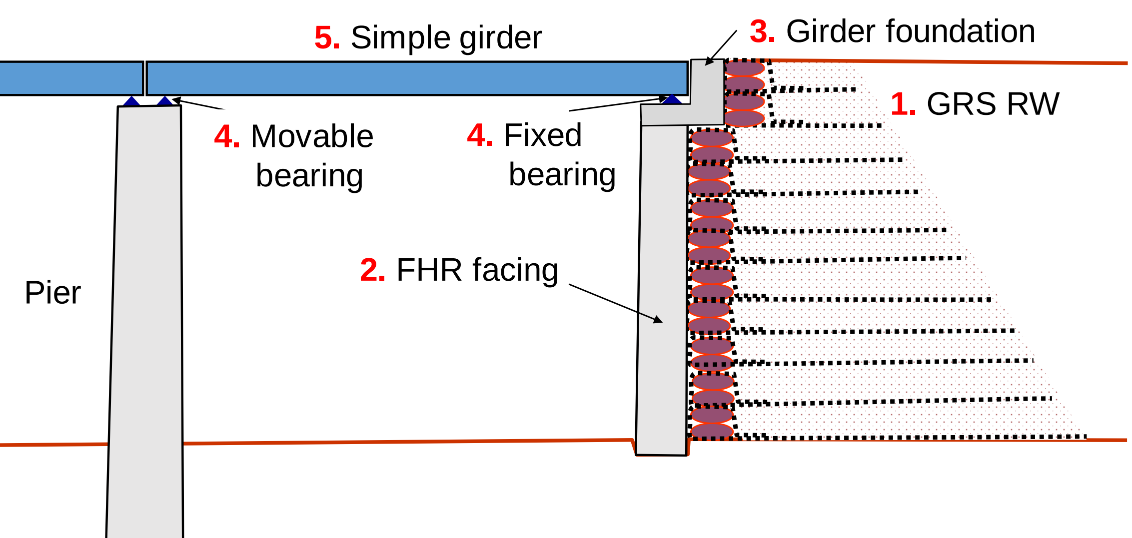




Typical polymer geogrid

Concluding remarks – 4/6

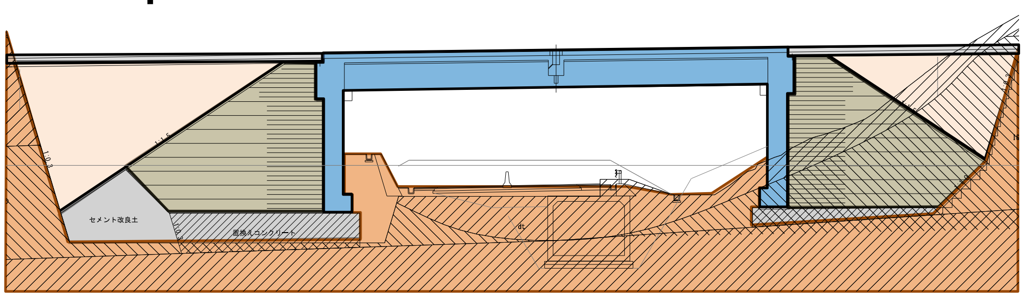
GRS Bridge Abutment is often used to support one end of a simple girder on a fixed bearing arranged at the top of FHR facing of a GRS RW. This is much more cost-effective and much more stable than conventional type bridge abutments. In total 185 have been constructed. All have been performing satisfactorily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



Concluding remarks – 5/6

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 – 6/6

Many of the conventional type embankments, RWs and bridges that collapsed by recent severe seismic load, heavy rainfall, strong flood, high ocean storm wave, tsunami etc. were restored to GRS structures having FHR facing.

Acknowledgements

Sincere appreciation for great contributions of a number of students, researchers and engineers, who jointed this very long-term research project performed 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.

Thank you 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/AACTs1F2AEl0gOjhn1IgcFMla?dl=0