GRS structures recently developed and constructed for railways and roads in Japan

F. Tatsuoka
Tokyo University of Science, Japan

M. Tateyama
Railway Technical Research Institute, Japan

J. Koseki
Institute of Industrial Science, University of Tokyo, Japan

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A GRS RW with a full-height rigid (FHR) facing supporting a very busy urban train line in Tokyo

Near Shinjuku Station, Tokyo, constructed during 1995 – 2000
Geosynthetic-reinforced soil retaining wall

Composite soil retaining structures:
Three main elements: soil, reinforcement, and facing.

If material characterization, design, and construction are properly done, such walls will exhibit excellent performance while being economical.

What is the basic difference?

Conventional type RWs
- (gravity)
- (cantilever)
- (T-shaped)

GRS RW

Conventional cantilever RW vs. GRS RW with a FHR facing for a highway in Yamagata, 1995

Previously constructed
- Canti-lever RC RW
- Backfill
- Tie rod
- RC anchorage
- Existing slope
- FHR facing
- Large diameter bored piles
- Rather stable supporting ground

Newly constructed
- Large diameter bored piles
- Limited excavation
- Geotextile
- Full height rigid facing
- Limited excavation
- Existing slope
Cantilever RC RW (constructed previously)

Two basic force equilibriums with reinforced soil walls:
(A) along the potential active failure plane (always considered in design)
(B) at the facing (very important, but often ignored)

Paramount importance of connection strength

Effects of connection strength on the tensile forces in the reinforcement & the stability of the active zone

→ Low earth pressure at the wall face
→ Low tensile forces in the reinforcement
→ In the active zone, low confining pressure, therefore, low stability
→ Low stability of the wall
Effects of connection strength on the tensile forces in the reinforcement & the stability of the active zone

High connection strength

→ High earth pressure at the wall face
→ High tensile forces in the reinforcement
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→ High stability of the wall

Graded Reinforcement Soil Wall (GRS) RW with a FHR facing:
The facing is “a continuous beam supported at many levels with a small span”

Very stable active zone

Well connected

High tensile force in the reinforcement

High confining pressure

→ High tensile force in the reinforcement

Rigid facing

Increased stability against concentrated load on the wall crest

Concentrated load

FHR facing

Failure plane when the facing is flexible or the connection strength is low

Failure plane forced to develop when using a FHR facing with high connection strength, resulting in a high wall stability

Tatsuoka et al. (1989) 12ISMFE, Rio de Janeiro

3D effects!

Against lateral load $H$, each unit of FHR facing together with reinforced backfill behaves as a monolith.

→ A FHR facing becomes a foundation for super-structures, such as electric poles, noise barrier walls, bridge girders etc.
1) The facing is only to prevent the spilling out of backfill.

2) The earth pressure at the facing should be made as low as possible.

3) The facing should be flexible enough to accommodate the deformation of supporting ground.

These explanations are wrong, or not accurate!

The correct and accurate explanations

1) The facing is an important and essential **structural component** confining the backfill and developing large tensile force in the reinforcement.

2) The earth pressure at the facing should be high enough to provide sufficient confining pressure to the backfill.

3) The facing should be flexible enough to accommodate the deformation of supporting ground during construction, but **should be rigid enough during service**. This can be achieved by staged-construction.

FHR facing contributes to the wall stability, but several problems during wall construction if constructed before, or simultaneously with, the construction of the backfill.

- Large load
- Difficulty in compacting the backfill behind the facing
- Need for a propping
- No tensile strains before removing the propping
- Damage to the connection due to relative settlement between the facing and the backfill.

□ Most of these problems can be solved by the staged construction procedure ….
**Staged construction - 1:**
- Construction with a help of gravel gabions placed at the shoulder of each soil layer

**Staged construction - 2:**
- Construction with a help of gravel gabions placed at the shoulder of each soil layer

**Staged construction - 3:**
- Construction with a help of gravel gabions placed at the shoulder of each soil layer

**Staged construction - 4:**
- After sufficient compression of backfill and supporting ground has taken place, a full-height rigid facing is constructed by casting-in-place concrete directly on the wrapped-around wall.

→ No damage to the connection between the facing and the reinforcement during and after construction.

→ Construction using compressive backfill on a compressive soil layer becomes possible.
A firm connection between the facing and the reinforcement by casting-in-place concrete directly on a geogrid-wrapping-around the wall face.

Adequate drainage by:
1) drain holes in the FHR facing;
2) gravel bags immediately behind the facing: a temporary facing before casting-in-place concrete and a vertical drain layer during service; and
3) if necessary, buried drain crossing the wall.

Staged construction - 5:
- Completed.

Re-construction of an existing slope to a vertical wall for a yard of high-speed train at Biwajima, Nagoya

Existing slope; large deformation is not allowed during reconstruction.
A yard of high-speed trains at Biwajima, Nagoya, 1989 - 1990
- Average wall height= 5 m & total length= 930 m

Amagasaki wall, directly supporting a very busy rapid railway, constructed 1991 - 1992
- Both sides of an existing railway embankment were reconstructed to GRS RWs having a FHR facing under a severe space restriction
- Average wall height= 5 m
- Total wall length= 1,300 m

History of elevated railway and highway structures in Japan

- Gentle slope
  - Low stability
  - High deformability
  - Large space occupied

- Conventional type RWs

New construction of RWs for railways:
- No conventional type RWs
- No Terre Armée RWs
- GRS RWs with a FHR facing in nearly all cases

- GRS-RW
  - (basically no piles)
  - High cost-effectiveness
  - Sufficiently high stability & stiffness

The total wall length= 136 km at 910 sites
- Zero problematic case

Locations of GRS RWs with a stage-constructed FHR facing as of June 2012
Earthquakes

1995 Kobe Earthquake
Failure of gravity type wall at Ishiyagawa site

Restart of construction of new high-speed train lines (Shin-kan-sen)

From 1982: research at the University of Tokyo & Railway Technical Research Institute
1995 Kobe Earthquake
Failure of leaning (gravity) type wall at Sumiyoshi site

Reconstruction

Why are GRS RWs much more stable than conventional type RWs?
→ Evaluation by shaking table tests

Why are GRS RWs much more stable than conventional type RWs?
→ Evaluation by shaking table tests

Gravity type: less ductile failure

Gravity type: more ductile failure

Performance of RWs during the 1995 Kobe EQ.

(Koskki et al., 2003)
Different resistance mechanisms

- Seismic force
- Bearing capacity, P
- Tensile force, T

(Koseki et al., 1997)

Seismic Force

Less ductile

Seismic Force

More Ductile

Total normal force, P (kN/m)

G: gravity
C: cantilever
L: leaning

R2: very ductile & most cost-effective → current design practice

2004 Niigata-ken Chuetsu Earthquake

GRS-RW with a FHR facing; slope: 1:0.3 (V:H); max. height= 13.2 m, vertical spacing of geogrid= 30 cm

Before failure: sand backfill including round-shaped gravel on sedimentary soft rock (weathered, more at shallow places)

After remedy work: Silt rock

Shinano river

1.4 (V:H)

Gravel-filled steel wire mesh basket

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Gravel-filled steel wire mesh basket
Another site

GRS RWs having FHR facing for railways, including high-speed trains, constructed before the 2011 Great East Japan Earthquake

Aomori: 58
Iwate: 23
Akita: 1
Yamagata: 3
Fukushima: 1
(total) 95

Adjacent to Natori River, Sendai City
Completed 1994
Wall length= 400 m

Collapse of a wing RW for a bridge abutment (JR East)

- Nagamachi → Higashi Sendai

- Unreinforced backfill (H= 5 m)
- Gravelly sandy soil
- Masonry RW

(by the courtesy of the East Japan Railway Co.)

Reconstruction of collapsed RW to GRS-RW

- Very fast reconstruction
- Emergent opening of service before the construction of a FHR facing

(by the courtesy of the East Japan Railway Co.)
Failure of railway embankment at three locations by the Nagano-Niigata Border Earthquake (12 March 2011)

Reconstruction to GRS-RWs having a FHR facing

(by the courtesy of the East Japan Railway Co.)

Reconstruction of railway embankments that failed by flood, 1991

Several railway embankments in Kyushu failed by a heavy rainfall and a flood in 1989 and reconstructed GRS-RWs in 1991

Locations of GRS RWs with a stage-constructed FHR facing as of June 2012
Reconstruction of embankment & RW that collapsed by heavy rain, Iiyama Line (JR East), July 2011

Locations of GRS RWs with a stage-constructed FHR facing as of June 2012

Key design factors in the reconstruction

- 14 days until the re-open of service required
- Minimized imported backfill (gravelly soil: C-40)
  → GRS RW

Collapse of a masonry RW by scouring of supporting ground and associated erosion of the backfill

Failure of the fill constructed by cut & fill

(Takisawa et al., 2012, JR East)

(Takisawa et al., 2012, JR East)
Reconstruction of RW to GRS RW with a FHR facing

- FHR facing, staged-constructed after emergent train operation upon the completion of the GRS wall (w/o FHR facing)

Approach fill (cement-mixed gravelly soil, M-40; cement 50 kg/m³) to minimize the settlement of the approach fill

(Takisawa et al., 2012, JR East)

Key design factors in the reconstruction

- 10 days until the re-opening of service required: the original masonry RW needs a long construction period → GRS RW
- Re-opening of service (with slowed-down running of trains) before constructing of FHR facing

Completed GRS RW

Staged construction of FHR facing

(Takisawa et al., 2012, JR East)

Failure of RW and backfill by scoring

1. Scouring
2. Over-turning of RW
3. Collapse of embankment

GRS-RWs with a FHR facing has a high resistance against scouring

Failure of seawall for National Road No. 1, Kanagawa Pref., southwest of Tokyo, by Typhoon No. 9, 8 Sept. 2007

GRS-RW having a full-height rigid facing

Better performance of GRS-RW with FHR facing
10 March 2010

Reconstruction to GRS RW with FHR facing

Summary:

A number of GRS RWs having a staged constructed FHR facing performed very well during the 1996 Great Kobe and the 2011 Great East Japan Earthquakes.

A number of conventional type RWs and embankments that failed during recent severe earthquakes, heavy rains, floods and storms were reconstructed to GRS RWs of this type soon after the failure.

It was proven that this technology can construct stable RWs under very difficult design conditions requiring:
1) a very short construction period;
2) severe construction conditions (e.g., on a steep slope at a water collecting place);
3) high stability against severe seismic loads, heavy rains, floods, storms; &
4) low construction cost.

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2. GRS integral bridge, comprising a girder integrated to the facings with the backfill reinforced with reinforcement connected to the facings

Technical problems with conventional type bridges

- 1. Piles
- 2. RC abutment
- 3. Backfill
- 4. Bearings (fixed or movable) → High cost for construction & long-term maintenance
- 5. Girder
- Displacement by earth pressure
- Ground settlement & lateral flow due to the weight of backfill, and associated negative friction & bending of the piles.
Technical problems with conventional type bridge

- Long-term settlement by self-weight, traffic load & seismic load
- Low seismic stability
- Displacement by seismic earth pressure

What is a solution?

- Ground settlement & lateral flow due to displacements by seismic load
- Ground pressure
- Earth pressure

Towards GRS Integral bridge:

- Problems with conventional type bridges
- Integral bridge; a structural engineering solution
  - GRS RW bridge; a geotechnical engineering solution
  - GRS Integral bridge; the solution
    - Importance of strong connection between the reinforcement and the facing

Conventional type

GRS RW

Combined

Integral

To solve several problems with backfill

To solve several problems with RC structures

1. Piles
2. RC facing (abutment)
3. Continuous girder
4. Backfill

Integral bridge

- Low construction & maintenance cost of the structural part, due to:
  a) no use of girder bearings &
  b) the use of a continuous girder

Integral bridge

- 2a. Concrete framework and propping
- 2b. RC facing (abutment)
However, several unsolved old problems!

Long-term service issue:
- settlement by self-weight & traffic load
- large deformation by seismic load

3. Continuous girder Integration
4. Backfill

2. RC facing

Displacement due to earth pressure
Earth pressure (static & dynamic)

Ground settlement & lateral flow due to the weight of backfill, and associated negative friction & bending of the piles.

A new problem with integral bridges!

Seasonal thermal expansion & contraction of the girder
Lateral cyclic displacements
Settlement

Backfill
Continuous girder
RC facing

Increase in the earth pressure

Static lateral cyclic loading tests under plane strain conditions in 1g (considered model scale: 1/10)

Wall height: 50.5 cm

D
L
H=50.5 cm

K

Unreinforced backfill:
A significant increase in the passive earth pressure with cyclic loading

Total earth pressure coefficient, $K$

Constant amplitude, $D/H$

Elapsed time (second)

Initial state ($K_0=0.5$)
Dual ratchet mechanism

Unreinforced backfill:
Significant settlement in the backfill with cyclic loading

Why?

Dual ratchet mechanism

Formation of active wedge

No major deformation outside the active wedge

Active wedge deforms as part of passive wedge, not recovering the active displacement during S→A1

Formation of passive wedge

Towards GRS Integral bridge:

- Problems with conventional type bridges
- Integral bridge; a structural engineering solution
- GRS RW bridge; a geotechnical engineering solution
- GRS Integral bridge;
  • the solution
  • Importance of strong connection between the reinforcement and the facing
After sufficient deformation of backfill and supporting ground, construction of full-height rigid (FHR) facing. Staged construction.

A high cost/performance ⇒ about 20 abutments constructed. However, new problems by a relatively low seismic stability of sill beams and relatively low stiffness of the backfill.

Modification: placing the girder on the top of the facing via bearings.

The first bridge abutment at Takada, completed March 2003.
Staged construction procedure for the new type bridge abutment (1)

To avoid the damage to the connection between the reinforcement and the facing due to relative settlement

A 15 m-high GRS-RW bridge abutment at Mantaro for a new high-speed train line, the south end of Hokkaido

Why not removing the bearings?

The total number of GRS RW bridge abutments completed or designed (as of June 2012): 59

- Despite a high cost-effectiveness, still serious problems by using bearings (i.e., high cost for construction & low seismic stability)

Towards GRS Integral bridge:

- Problems with conventional type bridges

- Integral bridge; a structural engineering solution

- GRS RW bridge; a geotechnical engineering solution

- GRS Integral bridge;
  - the solution
  - Importance of strong connection between the reinforcement and the facing
Firmly connected

1. GRS wall
2. FHR facing
3. Girder

0. Ground improvement (when necessary)

Gravel bags

Reducing the effects of thermal deformation of the girder by:
1) reinforcing the backfill; and
2) connection between reinforcement and facing

Displacement-controlled loading system
Lateral displacement

Distance (cm) from the back of the facing
Settlement of the crest
Box width: 40

Air-dried Toyoura sand
(D_r = about 90%)

8 polyester reinforcement layers

NR (no reinforcement):
D/H = 0.2 or 0.6 %

Hinge-support: or no support with a depth of 3 cm

NR: not reinforced
NR: not reinforced  
R&NoC: reinforced, but no connection  

This is *not* a solution!

NR (no reinforcement): D/H = 0.2 %
R & NoC: D/H = 0.2 %

Residual settlement of the backfill at 5 cm back of the facing, Sg/H (%)

Number of loading cycles, N (cycles)

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Shaking table tests in 1g  
(considered model scale: 1/10)

D: displacement transducer  
M: movable (sliding) shoe  
F: fixed (hinged) shoe  
L: L shaped metal fixture

Conventional type bridge 'CB'  
Integral bridé (IB)

Lateral displacements

Conventional  
Integral  
GRS RW  
GRS Integral

Dislodging of girder

Base acceleration, $\alpha_{\text{max}}$ (gal)
Response of GRS Integral Bridge

- Increase in the number of loading cycle & base acceleration → Structural softening
- Decrease in the natural frequency $f_0$ → increase in $\beta$
- Increase in the response ratio $M$ and the phase difference $\phi$
- Approaching the resonant state → failure

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

- Response acceleration (amplitude: $\alpha_i$)
  - Measured
    - Acceleration magnification ratio: $M = \alpha_t/\alpha_b$
    - Phase difference: $\phi$
  - Back-calculated
    - Natural frequency: $f_0$
    - Tuning ratio: $\beta = f_i/f_0$
    - Damping ratio: $\xi$

Four reasons for a very high seismic stability of GRS IB among the different bridge types

1) The the largest initial value of $f_0$ (i.e., smallest initial value of $\beta$) → the smallest initial response

2) The smallest decreasing rate of $f_0$ (i.e., the smallest increasing rate of $\beta$) → the smallest possibility to reach the resonance

3) The largest damping ratio at failure → the smallest response

4) The largest response acceleration at failure (i.e., the largest strength)
Four reasons for a very high seismic stability of GRS IB among the different bridge types

1) The largest initial value of $f_0$ (i.e., smallest initial value of $\beta$) → the smallest initial response

2) The smallest decreasing rate of $f_0$ (i.e., the smallest increasing rate of $\beta$) → the smallest possibility to reach the resonance

3) The largest damping ratio at failure → the smallest response

4) The largest response acceleration at failure (i.e., the largest strength)

Implications of the test results in the seismic design

Very high strengths & very high damping ratios

Acceleration response spectra of NS component of the earthquake motion recorded at JMA Kobe, 1995 Kobe Earthquake (by the courtesy of Dr Izawa, J., RTRI Japan).
A full-scale model of GRS integral bridge, completed Feb. 2009 at Railway Technical Research Institute, Japan

The initial natural period of the full-scale model: $T_0 = 0.046$ sec (Yokoyama et al., 2012); much smaller than $T_p$ of ordinary strong seismic motions ($T_p = 0.35$ sec in this case)

Implications of the test results in the seismic design

1) Lower initial response acceleration of GRS IB than CB
2) A smaller increase in the natural period $T_0$ of GRS IB than CB
3) A higher damping ratio of GRS IB than CB
4) A higher strength of GRS IB than CB

The four reasons, all due to the integration of the girder, abutments and approach fills.
First full-scale GRS integral bridge, for a new high-speed train line, Kikonai at the south end of Hokkaido (14th Oct. 2011).

GCM: Ground improvement by cement-mixing

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<td>GCM GL = 5.0</td>
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<td>[All units in m]</td>
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</tbody>
</table>

(14th Oct. 2011).

First full-scale GRS integral bridge, for a new high-speed train line, Kikonai at the south end of Hokkaido (31 July 2012).

Not long, but the beginning of a long history (I hope)

(31 July 2012).

Great tsunami
2011 Great East Japan Earthquake

Total collapse of coastal dykes by overflow of tsunami

Flowing down of tsunami current along the down-stream slope:
(1) Scouring in the ground; and strong uplift forces
(2) Loss of the stability of concrete slab (not fixed) of the down stream slope.
(3) Erosion and wash away of the backfill
(4) Loss of full-section
Total collapse of coastal dykes by overflow of tsunami

- Flowing down of tsunami current along the down-stream slope:
  1. Scouring in the ground; and strong uplift forces
  2. Loss of the stability of concrete slab (not fixed) of the down stream slope.
  3. Erosion and wash away of the backfill
  4. Loss of full-section

Model tests at Tokyo University of Science

Conventional type
- unreinforced backfill
- discrete concrete panels on slopes and top

Model tests at Tokyo University of Science

GRS coastal dyke
- reinforced backfill
- continuous panels connected to the reinforcement
Various types of GRS coastal dike proposed as a barrier for over-flowing tsunami

- Concrete facing (connected to reinforcement)
- Planar reinforcement (e.g., geogrid)
- Foot protection to prevent scouring

Flow-away of bridge girder by great tsunami
2011 Great East Japan Earthquake

A railway bridge (Tsuyano-gawa bridge) that lost multiple simple-supported girders by tsunami forces

Over 340 bridges collapsed by tsunami, mostly by flow-away of girder and/or backfill

Both bearings & backfill are weak components for seismic & tsunami forces

A solution by GRS integral bridge

Railway that can survive a great tsunami

Sanriku Railway (under restoration)

Haipe at Sanriku Railway (August 2011)
Summary

The GRS integral bridge:
1) no use of girder-bearings;
2) use of a continuous girder integrated to the facings;
3) reinforcing the backfill with reinforcement connected to the facing; and
4) after the completion of reinforced backfill, construction of a full-height rigid facing then the girder.

The backfill may be cement-mixed appropriately to increase the seismic stability and to decrease the residual deformation.
Conclusions

1. Geosynthetic-reinforced soil retaining walls (GRS RWs) having a stage-constructed full-height rigid (FHR) facing have been constructed as important permanent RWs for a total length of more than 135 km in Japan. It is now the standard RW technology for railways.

Many others were also constructed for highways and others.

Its current popular use is due to not only high cost-effectiveness, but also high performance, in particular during severe earthquakes.

(to be continued)

Conclusions (continued)

2. Many embankments and traditional type RWs that failed during recent severe earthquakes, heavy rains, floods and storms in Japan were reconstructed to GRS RWs with a stage-constructed FHR facing. It was proven that this technology is highly cost-effective.

(to be continued)

Conclusions (continued)

3. A new bridge type, called the GRS integral bridge, is proposed, which comprises an integral bridge and geosynthetic-reinforced backfill.

GRS integral bridges would exhibit essentially zero settlement in the backfill and no structural damage to the facing by lateral cyclic displacements of the facing caused by seasonal thermal expansion and contraction of the girder, while their stability against seismic loads and tsunami is very high.

Thank you for your kind attentions!