Geotechnical issues around ballasted track and slab track in Japan

Railway Technical Research Institute

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Contents

- Introduction
- Ballasted tracks in existing line
- Asphalt roadbed in design standard
- Slab track on earth structure
**Ballasted track and slab track**

**Ballasted track**
- Periodical maintenance work is necessary.
- Easy to correct track irregularity.
- Construction cost is relatively low.

**Slab track**
- Low maintenance work.
- Difficult to correct track irregularity.
- Construction cost is relatively high.
**Requirement for ballasted track**

- Supporting sleepers stably and uniformly.
- Distribute train load applied on roadbed.
Requirement for ballasted track

- Easy to correct track irregularity by tamping.
- Good drainage.
- **Requirement for ballasted track**
  
  - Lateral resistance against lateral train load and rail buckling.
  
  - Apply adequate elasticity on track (especially on bridge or viaduct)
Requirement for slab track

◆ Maintenance free.
◆ Not high construction cost.
Difficult circumstance for railway track in Japan

◆ Soft ground.

Alluvial clays are deposited at plains. Geological ages are young. (younger than 6000 years)
Difficult circumstance for railway track in Japan

◆ Heavy rain.

Rain fall in September (average)

[Map showing rainfall distribution with indications for China and Japan]

Typhoon

Ballasted track after rain
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Existing line and newly constructed line

- **Existing line**
  - Constructed before 1960’s
    Design standard was not regulated.

- **Newly constructed line**
  - Constructed after 1970’s
    Design standard was established in 1978

Most of railway lines in Japan were constructed before 1950’s
Roadbed and subgrade in existing line

- No specific roadbed layer
- Material is not regulated
- Insufficient drainage
- Low stiffness subgrade

- Penetration of ballast into roadbed
- Mud pumping
- Large dynamic deformation
- Increase of maintenance work
Penetration of ballast into roadbed

- **Existing line**
  - Ballast layer
  - SPT test N-value
  - Ballast penetration layer

- **Newly constructed line**
  - Depth (cm)
  - SPT test N-value
  - Roadbed
  - Subgrade
Depth of ballast penetration layer

\[ \log_{10} h = -0.019K_{30} + 5.02 \]

- Depth of ballast penetration layer (cm)
- \( K_{30} \) value of plate loading test (MN/m\(^3\))
Vertical stress in roadbed and subgrade

- Ballasted track
- Ballast
- Roadbed
- Subgrade

Vertical stress in roadbed and subgrade

0.0  0.5  1.0

3.0m
Settlement of ballasted tracks and track irregularity strongly depends on the stiffness of roadbed and subgrade.

![Graph showing the relationship between track irregularity and amplitude of roadbed displacement.](image)
**Roadbed improvement**

- Most of the roadbeds constructed before 1960’s do not have sufficient stiffness.

- Settlement of ballasted track becomes less after roadbed improvement.
Conventional roadbed improvement method: Crushed stone, steel slag, cement treated material.

Sufficient compaction work was necessary.
New roadbed improvement method

◆ Reusing degraded ballast mixed with cement grout.

Degraded ballast (Mixed with sand)
Cyclic loading test

Cyclic loading
5Hz, ΔP=80kN

Sleeper
Ballast
Roadbed
◆ Cyclic loading test results

![Graph showing cyclic loading test results with settlement of sleeper (mm) on the y-axis and number of cycles (x1000) on the x-axis. The graph compares different types of ballast and roadbed conditions, including Grouted deteriorated ballast, Grouted new ballast, and Sand roadbed. Notable features include water pouring events.]

- Water pouring
- Grouted deteriorated ballast
- Grouted new ballast
- Sand roadbed
Cyclic loading test results

Settlement after 750,000 cycles

- Grounded degraded ballast
- Grouted new ballast
- Sand roadbed

Cyclic loading test results

Settlement after 750,000 cycles

- Grounded degraded ballast
- Grouted new ballast
- Sand roadbed
Application at site

Before roadbed improvement

Degraded ballast

Grout material

Degraded ballast

Excavation of ballasted track

Preparation of grout

Liquid A

Liquid B
◆ Application at site

Laying degraded ballast

Injection of grout

Injection of grout

After roadbed improvement
◆ Track irregularity after the roadbed improvement

![Graph showing track irregularity before and after roadbed improvement](image-url)
## Issues around transition zone

<table>
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<tr>
<th>Concrete structure</th>
<th>Structural transition zone</th>
<th>Embankment</th>
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</table>

- Floating sleeper → large settlement
- No floating sleeper

- Embankment
- Concrete structure
- General section
Moving loading test

- Multi-actuator moving loading test apparatus

- Loading actuators
- Track model
  Scale: 1/5
- Embankment model
- Concrete structure model
- Load cells
- Moving train load

Multi-actuator moving loading test apparatus
Multi-actuator moving loading test apparatus

Load by each actuator

Vehicle

Unit: m
Multi-actuator moving loading test apparatus

- Actuator load
- Sleeper load
- Sleeper settlement
Moving loading test results

- Train load
- Concrete structure
- Embankment

- Sleeper load (kN)
- Sleeper position (mm)

- Settling of sleeper (mm)
- Position of sleeper (mm)

- Those sleepers are not supporting wheel load (Floating sleeper)

- Accelerate local settlement

- 10 trains
- 50 trains
- 100 trains
- 200 trains

- 4000 cycles
◆ Moving loading test results

Approach block (Design standard)

Concrete approach slab

Low stiffness roadbed

Concrete slab

Low stiffness mat
Moving loading test results

![Graph showing settlement of sleeper (mm) vs. position (mm)]

- Concrete approach slab
- Low stiffness roadbed
- Without counter measure
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Asphalt roadbed for newly constructed lines

- Asphalt roadbed became standard structure in Japan after 1978

Subgrade: $K_{30} \geq 70 \text{MN/m}^3$

- Sufficient bearing capacity.
- No ballast penetration.
- Good drainage.
Design of asphalt roadbed

Multi-layered elastic analysis

FEM analysis
Design of asphalt roadbed

Displacement at the surface of roadbed
Tensile strain at the bottom of asphalt concrete

Asphalt concrete
Well graded crushed stone
Subgrade

1/4 symmetric model
Design of asphalt roadbed

Settlement

Strain

Wheel load 80 kN
(bogie axle)

Thickness of crushed stone layer:
- 15cm
- 30cm
- 60cm

Displacement of asphalt roadbed surface (mm)

Position (cm)

Wheel load 80 kN
(bogie axle)

Beneath sleeper:
Tensile strain

Thickness of crushed stone layer
- 15cm
- 30cm
- 60cm

Between sleeper:
Compressive strain

Strain at the bottom of asphalt concrete (µ)

Position (cm)

Asphalt concrete
Well graded crushed stone
Subgrade

Railway Technical Research Institute
Design of asphalt roadbed

- Tensile strain at the bottom of asphalt concrete $\varepsilon_t$
  \[ N_A = 0.6 \times 18.4 \times C \times 6.167 \times 10^{-5} \varepsilon_t^{-3.291} E_A^{-0.854} \]

Where $N_A$ : Allowable number of cyclic loading for Fatigue failure
$\varepsilon_t$ : Tensile strain
$E_A$ : Young’s modulus (MN/m²)
$V_v$ : void ratio
$V_b$ : asphalt volume
\[ C = 10^M \quad M = 4.84 \left( \frac{V_b}{V_v + V_b} - 0.69 \right) \]

- Vertical displacement at the surface of asphalt roadbed
  \[ \text{Less than 2.5mm considering impact load} \]
### Design of asphalt roadbed

#### Fatigue life

- **Subgrade:** $K_{30} = 70 \text{ MN/m}^3$
  - 60 cm (Settlement)

- **Subgrade:** $K_{30} = 110 \text{ MN/m}^3$
  - 40 cm (Fatigue life)

#### Displacement

- **Subgrade:** $K_{30} = 70 \text{ MN/m}^3$
  - 2.5 mm

- **Subgrade:** $K_{30} = 110 \text{ MN/m}^3$
  - 40 years (Settlement)

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**Fatigue life of asphalt concrete (year)**

- **Subgrade:** $K_{30} = 70 \text{ MN/m}^3$
  - 60 cm (Settlement)

- **Subgrade:** $K_{30} = 110 \text{ MN/m}^3$
  - 40 cm (Fatigue life)
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Slab track

- Rail Fastener
- Rail
- Slab
- Circular stopper
- Cement asphalt mortar
- Concrete trackbed
History of slab track

Tokaido Shinkansen (1964):
Ballasted track on embankment

Bearing capacity of embankment was not very high.
(using clay, compaction control etc)
Settlement of ballasted track became very large after the start of train operation.

Sanyo Shinkansen
Okayama-Hakata (1975):
Slab track on viaduct.

Hokuriku Shinkansen
Takasaki-Nagano (1997):
Slab track on high quality embankment

Life cycle cost of slab track is lower than that of ballasted track.
Percentage of slab track in Shinkansen
Slab track on earth structure

- **Required specification for subgrade**

  - **Stiffness:** $K_{30} \geq 110 \text{MN/m}^3$

  - **Density:** Higher than 95% of maximum dry density

  - **Material for embankment:**
    - Gravel, Sandy gravel, Gravelly sand, sand
Subgrade improvement for slab track

- Subgrade of natural ground should be improved to satisfy $K_{30}$ value.

![Diagram of multi-layered elastic analysis](image)

- Improved layer
- Subgrade
- $E_1$, $\mu_1$
- $E_2$, $\mu_2$
- Depth for improvement (m)
- $K_{30}$ value of natural ground (MN/m$^3$)
Numerical analysis for the design

(a) Parallel to rail direction

(b) Perpendicular to rail direction
Cross section of slab track on earth structure

Slab track on earth structure (Cutting)

Concrete roadbed

- Slab
- Slab track on earth structure (Cutting)
- Concrete roadbed

Cross section diagram:
- Slab
- Filling layer (CA mortar)
- Reinforced concrete
- Well graded crushed stone
- Subgrade (embankment)
- Drainage Layer
- Subgrade (Groundwork or cutting)
- CA mortar
- Prime coat
- Reinforced concrete
- Well graded crushed stone
Subgrade with N value less than 4

- If N value of subgrade by SPT test is less than 4, ground improvement is required.
Integrated RC roadbed

Investigation was carried out to apply integrated RC roadbed on soft diluvial clay subgrade.

Diluvial clay: Ageing effect, pre-loaded(cutting)
Ground investigation method

- Standard penetration test
- Electric cone penetration test
Ground investigation result

**SPT**

- **N-value**

**Electric cone penetration test**

- Point resistance $q_t$ (MN/m$^2$)
- Pore water pressure $u_d$ (kN/m$^2$)
- Side surface friction $f_s$ (kN/m$^2$)

**Legend**

- **N value**
- **Point resistance**
- **Pore water pressure**
- **Side friction**

**Note:**
N-value must not be plotted in this area.
Triaxial test

Deviator stress $\sigma_1 - \sigma_3$ (kN/m$^2$) vs. Axial strain (%)

Young's modulus $E_{sec}$ (MN/m$^2$) vs. Axial strain
In-situ cyclic loading test

Subgrade improvement (crushed stone)
Crushed stone layer (150mm)
Base concrete (Thickness: 200mm)
Reinforced concrete (Thickness: 300mm)
Vibration machine
Integrated RC roadbed

Gauges:
- Acceleration
- Pore water
- Earth pressure
- Steel stress

Test site

Integrated RC roadbed
**Loading test results**

**120kN, 20Hz, 2x10^6 times loading**

**Acceleration**
- Clay subgrade surface (Just beneath loading point)
- Concrete roadbed surface (Just beneath loading point)

**Displacement**
- Concrete roadbed surface (Just beneath loading point)
- 2,700 mm distant from loading point

**Reinforcing steel stress**
- Edge of concrete base
- 2,700 mm distant from loading point

**Subgrade vertical stress**
- Surface of subgrade improvement
- Clay subgrade surface
FEM to simulate the loading test

- Reinforced concrete (Integrated RC roadbed)
- Vibration machine
- Well graded crushed stone
- Clay subgrade

Displacement
- RC roadbed displacement (mm)
  - Longitudinal direction of track (m)
  - Transverse direction of track (m)

Reinforcing steel stress
- Reinforcing steel stress (N/mm$^2$)
  - Transverse direction of track (m)

Vertical stress
- Vertical stress (kN/m$^2$)
  - Depth from RC roadbed surface (m)
  - Surface of subgrade improvement

Loading test vs FEM analysis graphs for each category.
Deformation of RC roadbed

- **Standard RC roadbed**
- **Integrated RC roadbed**

Integrated RC roadbed distributes train load widely.
**Vertical stress on subgrade**

- Standard RC roadbed
- Integrated RC roadbed

**Integrated RC roadbed reduces stress applied on subgrade.**
## Comparison between Standard RC roadbed and integrated RC roadbed

<table>
<thead>
<tr>
<th></th>
<th>Integrated RC roadbed</th>
<th>Standard RC roadbed</th>
<th>Integrated / Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical displacement</td>
<td>0.60 mm</td>
<td>0.71 mm</td>
<td>0.85</td>
</tr>
<tr>
<td>Reinforcing steel stress</td>
<td>2.08 MN/m²</td>
<td>2.33 MN/m²</td>
<td>0.89</td>
</tr>
<tr>
<td>Subgrade surface stress</td>
<td>10.5kN/m²</td>
<td>28.6 kN/m²</td>
<td>0.37</td>
</tr>
<tr>
<td>Clay subgrade surface stress</td>
<td>6.89 kN/m²</td>
<td>9.02 kN/m²</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Summary

- Bearing capacity of roadbed and subgrade is an important factor to reduce the maintenance work of ballasted track.

- To reduce the settlement of ballasted track at transition zone is an important issue.

- Asphalt roadbed is widely applied to ballasted track.

- Slab track is widely constructed on the earth structure in these 20 years.

- Integrated RC roadbed is a new method to apply slab track on relatively soft subgrade, such as aged diluvial clay.