Frost Heave Properties in Ballast Tracks

Field Observations and Laboratory Experiments

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Topics

- What is Frost Heaving
- Field Works
  Monitoring at railway tracks
- Laboratory Works
  Frost heave tests of crushed rock with different fines content
Topics

- **What is Frost Heaving**
- **Field Works**
  Monitoring at railway tracks
- **Laboratory Works**
  Frost heave tests of crushed rock with different fines content
What is frost heaving.

Black horizontal lines are ICE LENSes
Ice Lens Segregates at Negative Temp.

Temperature (°C)

-6  -4  -2  0  2  4

Tc: -5.1°C

Ts

Frozen Fringe

Frozen

Lead sphere + TC

Unfrozen

Tw: 2.9°C

t=118 hr

Surface of Segregating Ice Lens

0 °C

130mm
Crystal Structure of Ice Lens

Thin section of frozen soil
Schematic Drawing of Ice Lens

Temperature (°C)

- Ts 0

Frozen Soil

Monocrystal

Monocrystal

Growing Surface of Ice Lens

0 °C

Frozen Fringe

Unfrozen Soil

Ice Lens
How Pore Water Freezes
Distribution and Thickness of Unfrozen Water

Distribution of Unfrozen Water

Temperature Dependence of Unfrozen Water Thickness

Thickness of Unfrozen Water (nm: 1x10^{-9} m)

Temperature (°C)
Field Observation
Our Test Fields

Washibetsu (Muroran line)

Fuhrren (Sohya line)

Shizukuishi (Tazawako line)
Ballast Track Structure
What is the uncertainty?

Dose ballast which contains fines frost heave?
Temperature Measurement in Railway Track Layers

Ballast Layer 20-10 cm
Ballast Layer 20-30 cm
Subgrade Layer 0-10 cm
Subgrade Layer 10-20 cm
Frost Heave Measurement in Railway Track Layers

Top View of LVDT utilized in Ballast

Truncated cone

Ballast Layer 10-20cm

Ballast Layer 20-30cm

Subgrade Layer 0-10cm

Subgrade Layer 10-20cm
What items have monitored

Field Monitoring

Monitor items:
- Temp. profile
- Heave amounts,
- Moisture contents

Plane View

Vertical View
Frost Heave Monitored in Ballast Track

Data of Furen

Cryosphere Engineering Laboratory
Laboratory Observation
Grain Size Distribution of Ballast Track

Fhuren

Shizukuishi
Textures of Real Ballast

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Sample Name</th>
<th>Specific Gravity of Soil Particle (g/cm³)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gravel (%)</td>
</tr>
<tr>
<td>Fhuren</td>
<td>Ballast Layer 0~10cm</td>
<td>2.465</td>
<td>99.5</td>
</tr>
<tr>
<td></td>
<td>Ballast Layer 10~20cm</td>
<td>2.747</td>
<td>98.5</td>
</tr>
<tr>
<td></td>
<td>Ballast Layer 20~30cm</td>
<td>2.744</td>
<td>88.4</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>2.808</td>
<td>73.2</td>
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<tr>
<td>Shizukuishi</td>
<td>Ballast Layer 0~10cm</td>
<td>2.671</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>Ballast Layer 10~20cm</td>
<td>2.671</td>
<td>86.8</td>
</tr>
<tr>
<td></td>
<td>Ballast Layer 20~30cm</td>
<td>2.676</td>
<td>70.2</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>2.676</td>
<td>61.8</td>
</tr>
</tbody>
</table>
Mineral compositions of ballast and subgrade at Fhuren and Shizukuishi

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample Name</th>
<th>Mineral Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fhuren</td>
<td>Ballast Layre 0-10cm from Surface</td>
<td>Quartz, Anorthite, Albite, Montmorillonite, Corrensite, Biotite</td>
</tr>
<tr>
<td></td>
<td>Ballast Layre 10-20cm from Surface</td>
<td>Quartz, Anorthite, Albite, Montmorillonite, Corrensite</td>
</tr>
<tr>
<td></td>
<td>Ballast Layre 20-30cm from Surface</td>
<td>Quartz, Anorthite, Albite, Montmorillonite, Corrensite</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Quartz, Anorthite, Albite, Corrensite, Kaolinite</td>
</tr>
<tr>
<td>Shizuku-ishi</td>
<td>Ballast Layre 10-20cm from Surface</td>
<td>Quartz, Anorthite, Albite, Kaolinite, Vermiculite, Crossite</td>
</tr>
<tr>
<td></td>
<td>Ballast Layre 20-30cm from Surface</td>
<td>Quartz, Anorthite, Albite, Kaolinite, Vermiculite, Crossite</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Quartz, Anorthite, Albite, Kaolinite, Vermiculite, Crossite, Pargasite</td>
</tr>
</tbody>
</table>
## Frost Heave Test Results (Shizukuishi)

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Fines Content (%)</th>
<th>Specimen Height (mm)</th>
<th>Heave Amount (mm)</th>
<th>Heave Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast Layer 0 ~ 10cm</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ballast Layer 10~ 20cm</td>
<td>3.0</td>
<td>30.0</td>
<td>6.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Ballast Layer 20~ 30cm</td>
<td>1.5</td>
<td>33.0</td>
<td>6.1</td>
<td>18.3</td>
</tr>
<tr>
<td>Subgrade</td>
<td>4.5</td>
<td>28.0</td>
<td>7.5</td>
<td>26.8</td>
</tr>
<tr>
<td>Subgrade (Undisturbed &amp; saturated)</td>
<td>-</td>
<td>109.2</td>
<td>54.9</td>
<td>50.3</td>
</tr>
<tr>
<td>Subgrade (Undisturbed &amp; unsaturated)</td>
<td>-</td>
<td>109.2</td>
<td>5.1</td>
<td>4.6</td>
</tr>
</tbody>
</table>
A Model for Prediction of Ballast Frost Susceptibility
An Empirical Formula has been used in Japan for Frost Heave Susceptibility Prediction

\[ \xi = \xi_0 + \frac{\sigma_0}{\sigma} \left( 1 + \sqrt{\frac{U_0}{U}} \right) \]

where,  
\( \xi \); heave ratio,  
\( \sigma \); confining pressure,  
\( U \); freezing speed,  
\( \xi_0, \sigma_0, U_0 \); test constants

Heave amount

Original height

\[ \xi = \frac{\ell}{L} \]
How the Ballast Layer Frost Heaves

CASE-1

Heave in fines

\[ \xi_B = \xi_f \times \frac{h}{H} \]

where, \( \xi_f \) heave ratio of fines,
\( \xi_B \) heave ratio of track subgrade.

CASE-2

Heave in ballast with excess fines

\[ \xi_B = \xi_f \times \frac{h_1 + h_2 + h_3 + h_4}{H} \]

CASE-3

Heave in ballast with fines saturated

\[ \xi_B = \xi_f \times \frac{h_1 + h_2 + h_3}{H} \]

Heave in ballast with fines unsaturated

\[ \xi_B = \xi_f \times \frac{h_1}{H} \]

however \( \rightarrow h = 0 \),
then \( \rightarrow \xi_B = 0 \).

Heave in ballast with no fines

\[ \xi_B = \xi_f \times \frac{\text{total thickness of fines}}{H} \]
Confirmation of Proposed Formula
Utilized Ideal Ballast which contains Fines

Kaolinite $G_s = 2.54$ g/cm$^3$

Crushed Rock I
Grain Size Distribution;
2.5mm to 5.0mm

Crushed Rock II
Grain Size Distribution;
13mm to 20mm
Frost Heave Test Apparatus – I

Thermal Bath

LVDT

Valve

Pt Temp.

Valve

Φ=200mm
Frost Heave Test Apparatus—II

ϕ = 50mm

L = 20 to 100mm

Weight

Pt Temp.

Thermal Bath

LVDT

Valve for PW

ϕ = 50mm
Frost Heave Test Conditions

**Confining Pressure**
- Overburden Pressure: 33.9 kPa
- Pore Water Pressure: 0 kPa

**Specimen Size**
- **Apparatus I**
  - Height: 92 ~ 111 mm
  - Diameter: 200 mm
- **Apparatus II**
  - Height: 38 ~ 47 mm
  - Diameter: 50 mm

**Thermal Condition**
- Temperature Gradient: 0.5 °C/cm
- Freezing Speed: 0.10 cm/hr

Example: Specimen Height = 48 mm

- Boundary Temp. (°C)
- Time (hr)
- **Tw**
- **Tc**
Frost Heave Tests Result

CASE-3

Test Result with Apparatus - I
Test Result with Apparatus - II

CASE-2
CASE-1

Frost Heave Ratio (%)

$\sqrt[3]{V_f/V}$
How the Ballast Layer Frost Heaves

CASE-1

Heave in fines

\[ \xi_B = \xi_f \times \frac{h}{H} \]

where, \( \xi_f \) heave ratio of fines,
\( \xi_B \) heave ratio of track subgrade.

CASE-2

Heave in ballast with excess fines

\[ \xi_B = \xi_f \times \frac{h_1 + h_2 + h_3 + h_4}{H} \]

CASE-3

Heave in ballast

- with fines saturated
  \[ \xi_B = \xi_f \times \frac{h_1 + h_2 + h_3}{H} \]
- with fines unsaturated
  \[ \xi_B = \xi_f \times \frac{h_1}{H} \]
- with no fines
  \[ \text{however} \rightarrow h = 0, \]
  \[ \text{then} \rightarrow \xi_B = 0. \]

\[ \xi_B = \xi_f \times \frac{\text{total thickness of fines}}{H} \]

\[ \xi_B = \xi_f \times \sqrt[3]{\frac{V_f}{V}} \]

where, \( V_f \) : volum of fines in an unit volume of track substructure
\( V \) : an unit volume of track substructure
Anticipated Result

In the CASE-3, steeper reduction of HEAVE RATE was expected.

Because of the unsaturated pore condition with fines, frost heave of the fines may not contribute to the macroscopic frost heave in CASE-3.

- CASE-3
- \[ \sqrt[3]{\frac{V_f}{V}} \]
- CASE-2

Pores are not saturated with fines

Ballast

Pore

Finds

Piece of ballasts are floating in the pore fines
Horizontally elongated ice lenses which are normal to the heat flow are observed. Vertical ice veins which are developed by the shrinkage due to pore water pressure depression in frozen fringe is also observed.

Normal frost heaving has happened.
Even in the CASE-3, pores are filled with fines and ice lenses but no frozen balk water.
Fines between Piece of Ballasts may Segregate Thick Ice Lenses

Thick ice lenses have developed at the upper part of piece of ballasts (=cold side of piece of ballasts)

Thermal conductivity of rock is higher than soil.

0 isotherm in rock advances faster.

Heave at the rock-fines boundary lasts longer.

Thick ice lens may segregate.
Fins in pores frost heave higher than total heave

Microscopic frost heave ratio along the white dotted line was 32%, whereas average was 14%.

Fines in pores show higher frost heave ratio.

Microscopic heat flow may meander due to inhomogeneity of thermal conductivity.
Cause of Thick Ice Lenses in Pore in CASE-3

Initially total stress was supported by rock skeleton.

Then fins suffer almost no confinement.

Heave rate of fines under very low confinement is very high.
Again what was happened
One Evidence

**Graph**

- **Vf / V = 0.37**
- **Heave**
- **Power water**
- **Tw**
- **Tc**

**Images**

- **Initial View (t=0hr)**
- **Final View (t=110hr)**
Conclusions

- Ballast which contains fines may frost heave.
- Proposed empirical formula provides frost heave susceptibility of ballast which contains fines.
- However further researches will be required to refine the reliability of the proposed formula.
Thank you for your attention