Advanced laboratory tests on granular materials for transportation facilities in cold regions

The first China – Japan Mini Workshop on High Speed Railway Geotechnics
14 December 2015, Beijing, CHINA

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SIMSG ISSMGE
International Society for Soil Mechanics and Geotechnical Engineering

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TC202 Terms of Reference

The goal of TC202 is to apply broad engineering to bridge the gap between Pavement/Railway Engineering and Geotechnical Engineering. The main task is to promote co-operation and exchange of information and knowledge about the geotechnical aspects in design, construction, maintenance, monitoring and upgrading of roads, railways and airfields. The task also covers the related environmental aspects. For these purposes, several main topics were identified and materialized in the main Task Forces of the Committee as follows.

TF 1. Promote of use of nontraditional materials in embankments and structural layers.

TF 2. Reinforcement of geomaterials and its implications in pavement and rail track design.

TF 3. Earthworks design, technology and management

TF 4. Rail track substructures, including transition zones.

TF 5. Subsurface sensing for transportation infrastructure condition diagnostics among others.

TF 6. 3rd International Conference on Transportation Geotechnics (ICTG), Guimarães, Portugal, September 4-7, 2016. Chairman António Gomes Correia (University of Minho).

TF 7. Transportation Geotechnics; Elsevier journal of TC202. Editors-in-Chief: António Gomes Correia; Erol Tutumluer, and Yunmin Chen. http://www.journals.elsevier.com/transportation-geotechnics/

TF 6. 3rd ICTG

3rd ICTG
International Conference On Transportation Geotechnics

Portuguese Geotechnical Society
University of Minho

Guimarães, PORTUGAL
4–7 September 2016
Vila Flor Cultural Centre

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ISSMGE

3rd International Conference on Transportation Geotechnics

CALL FOR SPONSORS AND EXHIBITORS REGISTRATION

Deadline for paper submission (accepted abstracts), November 6, 2015

Contact

3rd ICTG Secretariat
University of Minho – School of Engineering
Campus de Azurém, 4800-058 Guimarães – PORTUGAL
Tel.: *(+351) 253 510 218*
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e-mail: *3ictrgeo2016@civil.uminho.pt*

Exhibit space is available to showcase your activities, products and services to Academics, Researchers and Professionals (more than 300 abstracts from representatives of 50 countries).

Conference Website: http://civil.uminho.pt/3rd-ICTG2016

Important Dates

~~**March, 2015:**~~	~~Call for abstracts~~
~~**May 15, 2015:**~~	~~Deadline abstract submission~~
~~**June12, 2015:**~~	~~Notify authors of accepted abstracts~~
Submission of papers:	After abstract acceptance
November 6, 2015:	Deadline paper submission
February 26, 2016:	Notify authors of accepted papers
March 25, 2016:	Submission of final camera-ready papers

Conference Themes / Chairpersons

updated on 2015/09/08

Theme 01: Optimized geomaterial (including hydraulically bound materials and asphalt mixtures) use, reuse and recycling – *T. Edil, N. Consoli, A. Dawson*
Theme 02: Unsaturated soil mechanics in transportation geotechnics – *D. Toll, E. Alonso*
Theme 03: Foundations and earth structures – *A. Gomes Correia, H. Brandl*
Theme 04: Slope stability, stabilisation, and asset management – *S. Glendinning*
Theme 05: Mechanistic-empirical design (road, railways and airfields) – *C. Schwartz, D. Brill, S. Costa d'Aguiar*
Theme 06: Rail track substructures, including transition zones – *W. Powrie, M. Shahim*
Theme 07: Subsurface sensing for transportation infrastructure – *S. Nazarian, A. Loizos*
Theme 08: Macro and Nanotechnology applied to transportation geotechnics – *M. Alves, J.M. Fleureau*
Theme 09: Sustainability in transportation geotechnics – *I. Al-Qadi, M. Winter*
Theme 10: Case histories – *J. Koseki, J. Oliveira, J. Liu*

Workshops Themes

Workshop 01: Geosynthetics in transportation geotechnics
Workshop 02: Harbour geotechnics
Workshop 03: Non destructive technologies
Workshop 04: Ground improvement and soil stabilization

Honour Lectures

ISSMGE – TC202: Proctor Lecture: Prof. Buddhima Indraratna (Australia)
IGS: Mercer Lecture: Prof. Jorge Zornberg (USA)

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TF 7. Issue of International Journal

ISSMGE TC 202

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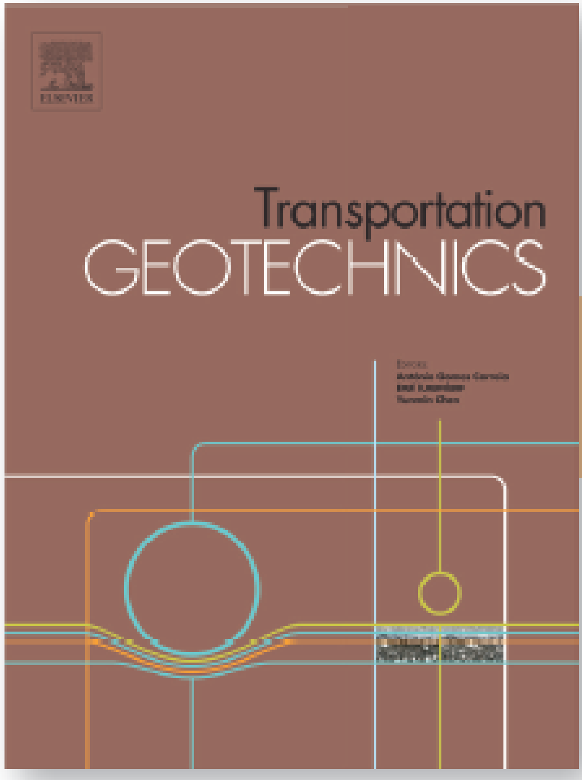

Transportation Geotechnics is a new journal publishing high quality theoretical and applied papers on all aspects of geotechnics for roads, highways, railways, airfields and waterways.

Editors:
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1st issue
03/2014

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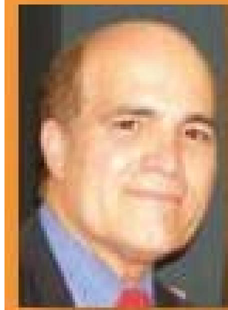

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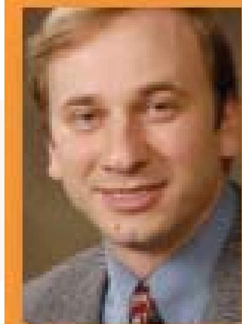

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TC202 Web Sites:

http://www.issmge.org/en/technical-committees/applications/147-transportation-geotechnics

http://www.eng.hokudai.ac.jp/labo/geomech/ISSMGE%20TC202/

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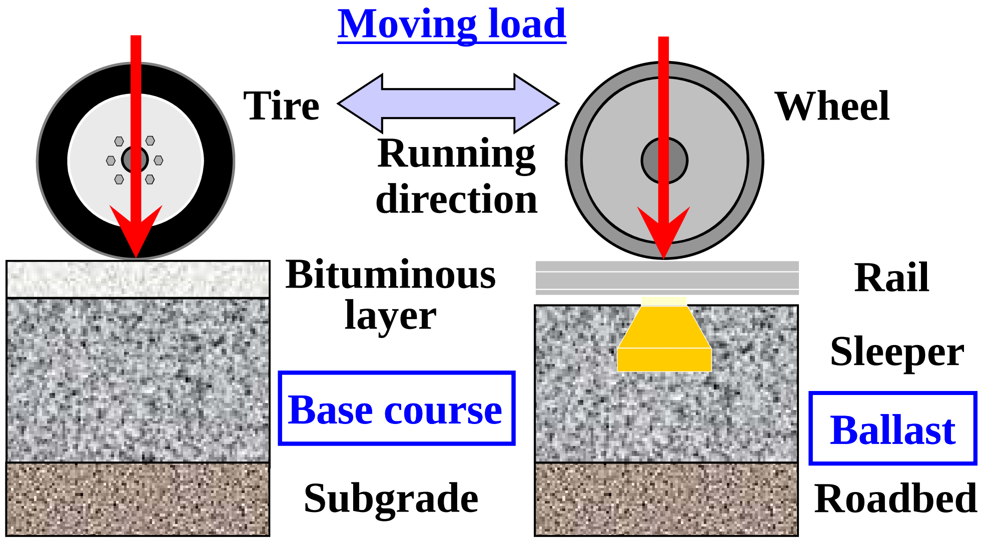
Background of research (1)

For saving maintenance costs of transportation facilities at road and railway, it is important to elucidate mechanical behavior of granular roadbed subjected to traffic loads.

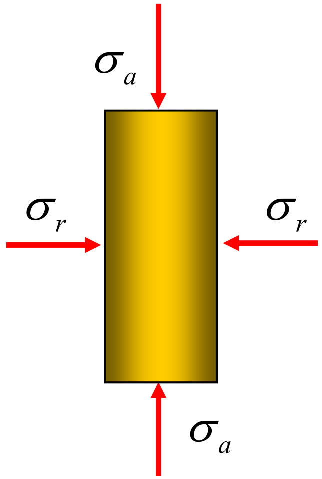


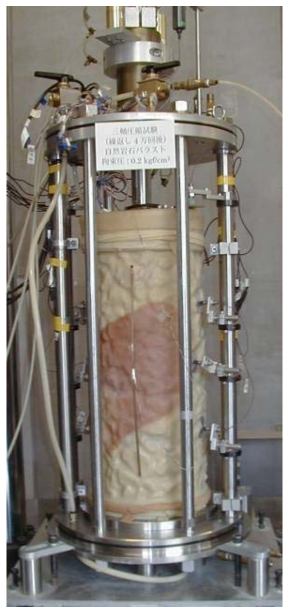
Conventional studies

Following loading tests have been performed in Japan;

Model test : fixed-point loading test

Element test : Triaxial test





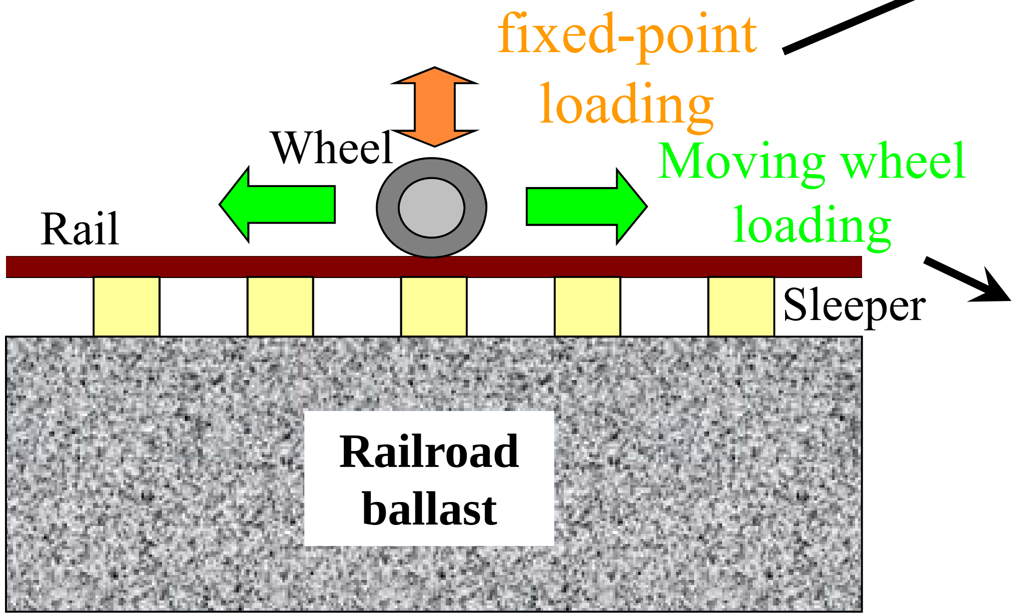
Effect of moving wheel loads

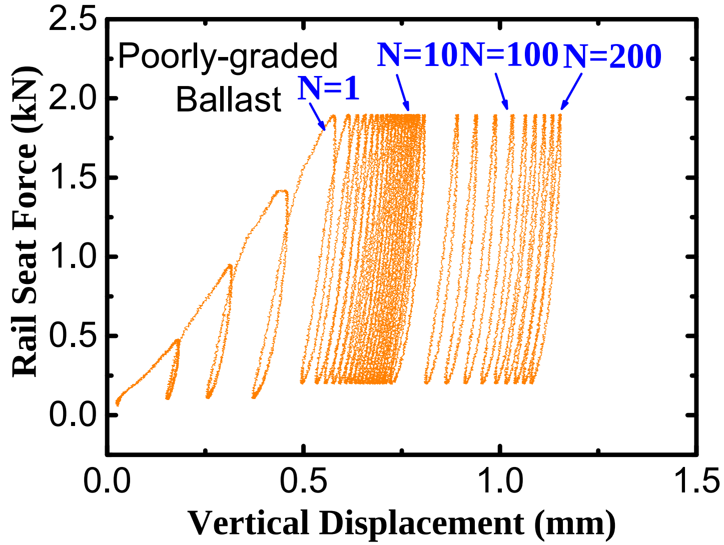
KEY POINTS

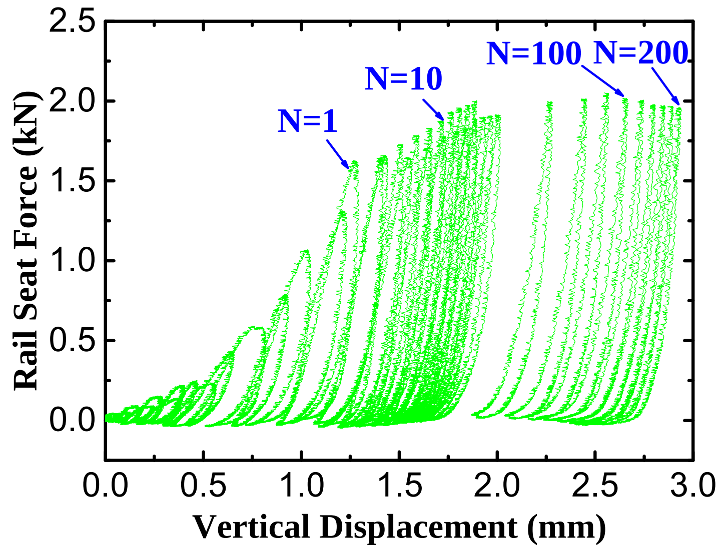
- **Can fixed-point loading tests simulate actual traffic loads ?**

Literature Review

Ishikawa & Sekine 2007



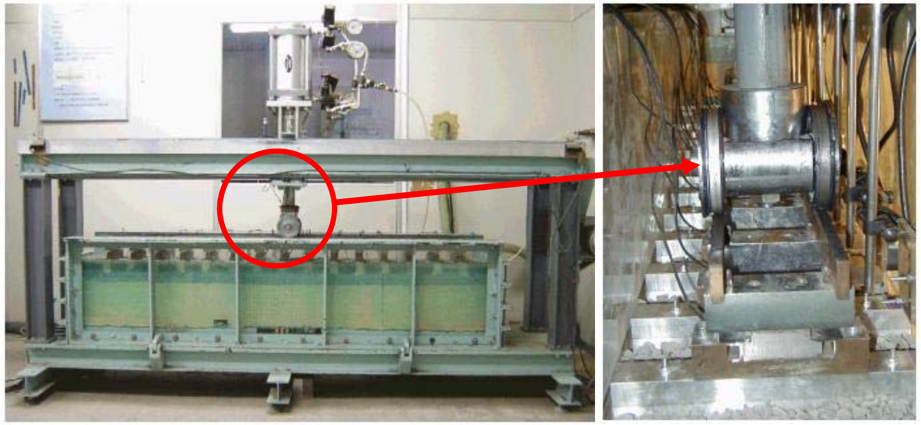


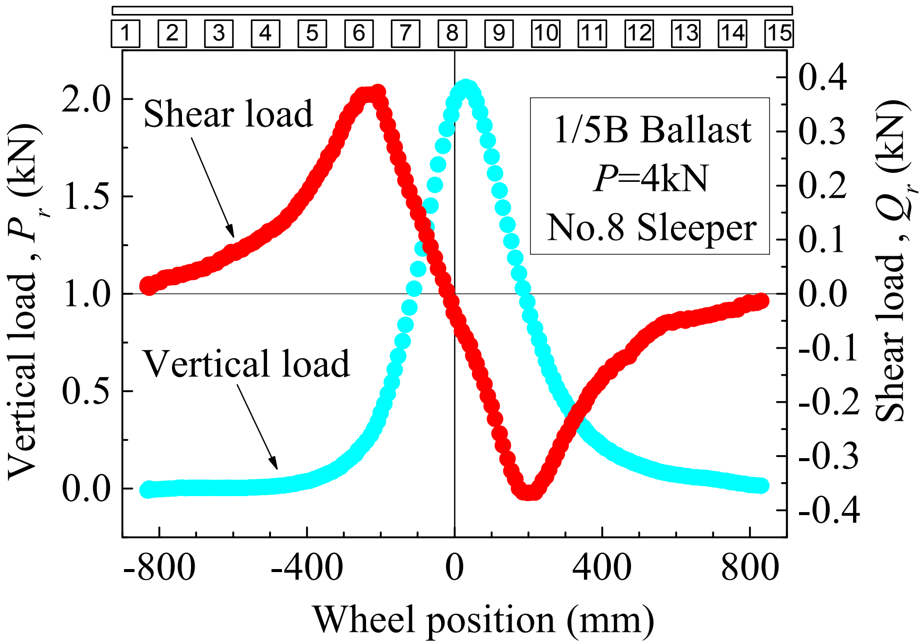


Moving wheel loads give a large residual settlement as compared with fixed-point cyclic loads.

Moving wheel load

Moving wheel loading test





Measured Ballast Pressure

- Normal component remains compression side through loading, while shear component changes the sign according to the position of a loading wheel.
- Principal stress axes rotate inside railroad ballast during train passage.

fixed-point loading

Increase & decrease of loads

⇔

Moving wheel loading

+ Principal stress axis rotation

Change in water content

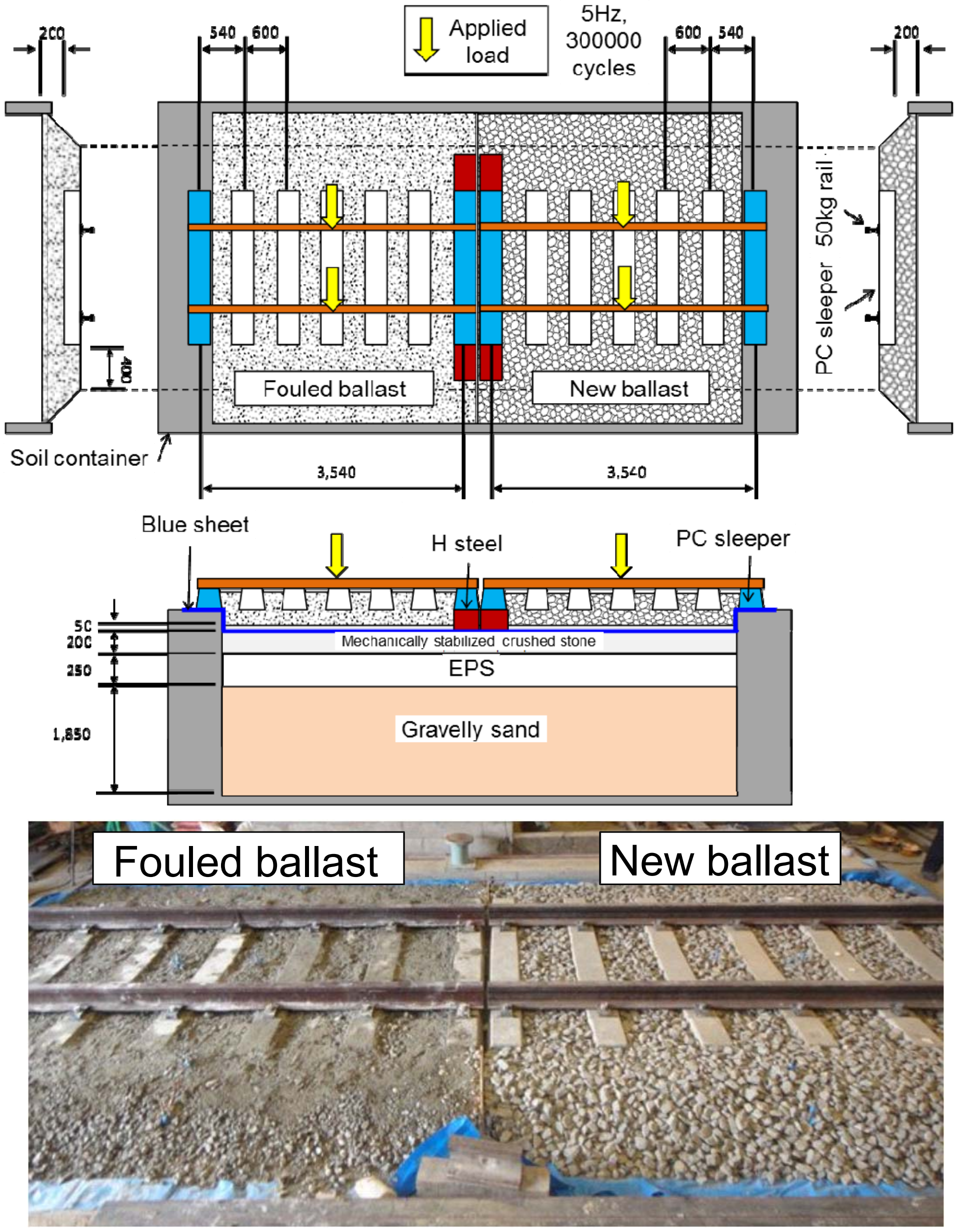
Literature Review

- In past studies, model and element tests have been performed mainly under air-dried condition.
- Deformation modulus of coarse granular materials decreases with the increase in water content. (Coronado et al. 2005, Ekblad & Isacsson 2006)

KEY POINTS

- **Does rainfall affect settlement of railroad ballast ?**

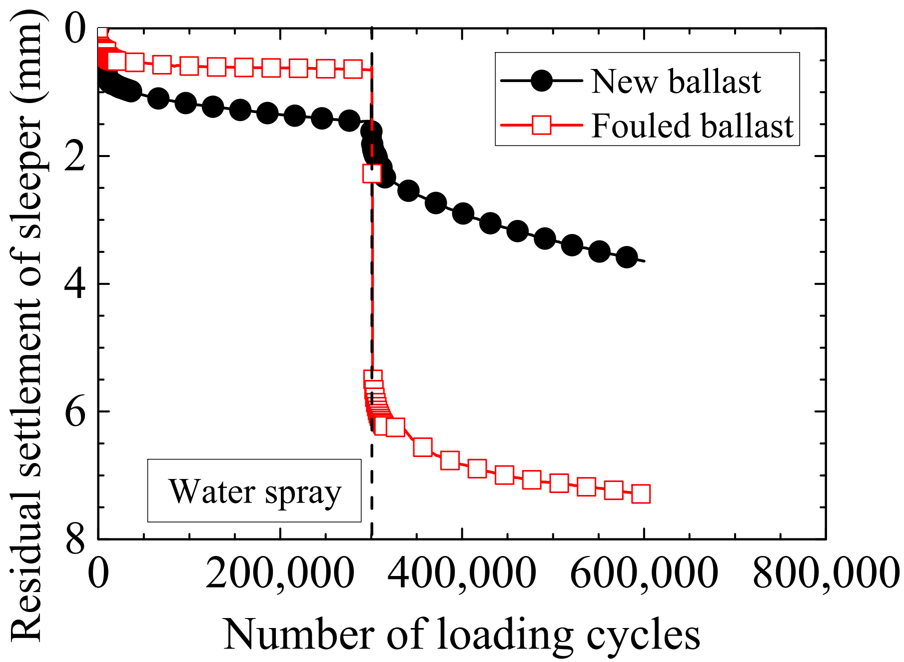
⇨ Itou et al. (2014) performed cyclic loading tests of full-scale model ballasted track before and after spraying water on the surface of railroad ballast (10 l/m^2).



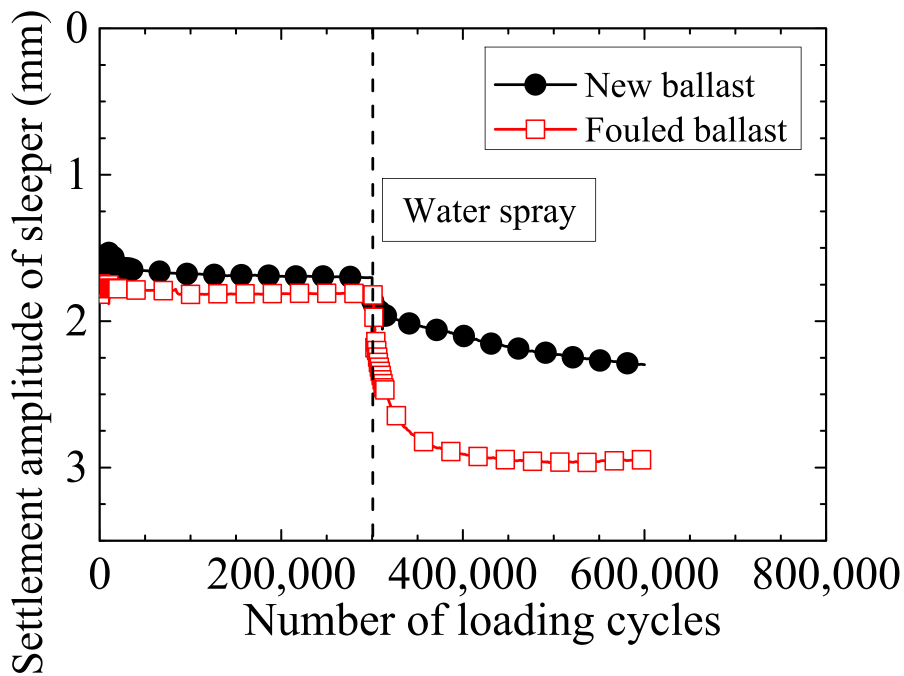
Full-scale model test

Results of full-scale model tests

Influence of water content



Residual settlement (Plastic behavior)

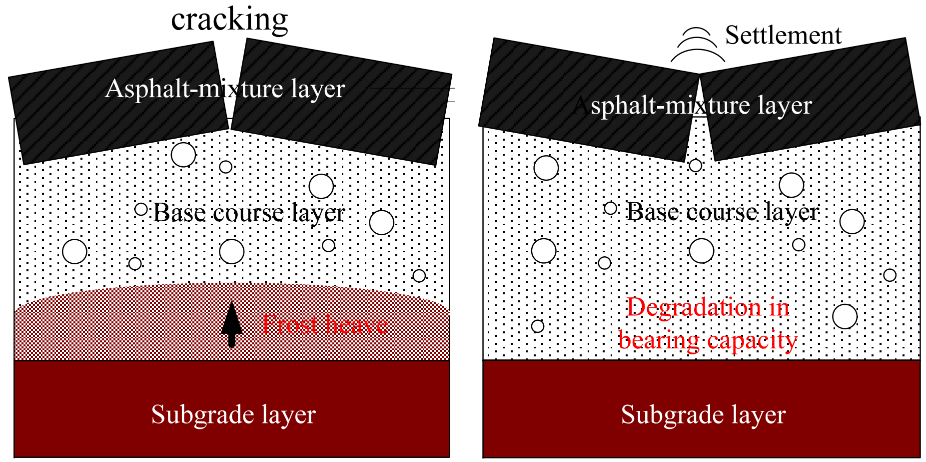


Settlement amplitude (Elastic behavior)

- Plastic deformation and elastic deformation of ballasted track during cyclic loading suddenly increase due to water spray.
- Wetting causes the sample to decrease the shear stiffness, thereby increasing residual settlement.

Background of Research (2)

In snowy cold regions, frost-heave phenomenon and temporary degradation in the bearing capacity during thawing season are thought to accelerate the deterioration of transportation facilities and losing of the functions.



Freezing season　　Thawing season

However, in Japan, such phenomena have not been sufficiently elucidated as well as modeling for theoretical design method of transportation facilities like railway track and pavement structures.

Research topics

To develop a rational design method of asphalt pavement and ballasted track in cold regions, we need to understand the mechanical behavior of subgrade and base course during freeze-thawing in detail.

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Objectives of Research

KEY POINTS

- **Are results obtained from conventional laboratory tests credible ?**
- **How about the synergistic effects of multiple factors ?**

Research objective

To evaluate effects of water content, principal stress axis rotation, loading rate, and freeze-thaw history on mechanical behavior of granular materials in terms of Transportation Geomechnics.

Research content

- Medium-size triaxial compression tests of coarse granular materials under various degrees of saturation and different loading rates
- Multi-ring shear tests of granular materials under various degrees of saturation subjected to principal stress axis rotation
- CBR tests and Multi-ring shear tests of freeze-thawed coarse granular materials under various degrees of saturation

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Medium-size triaxial test apparatus

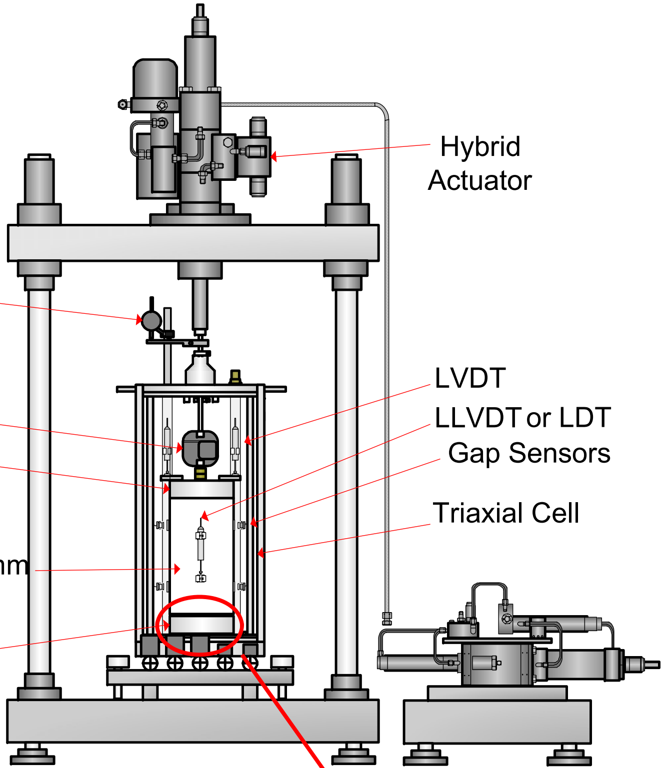
- Specimen size

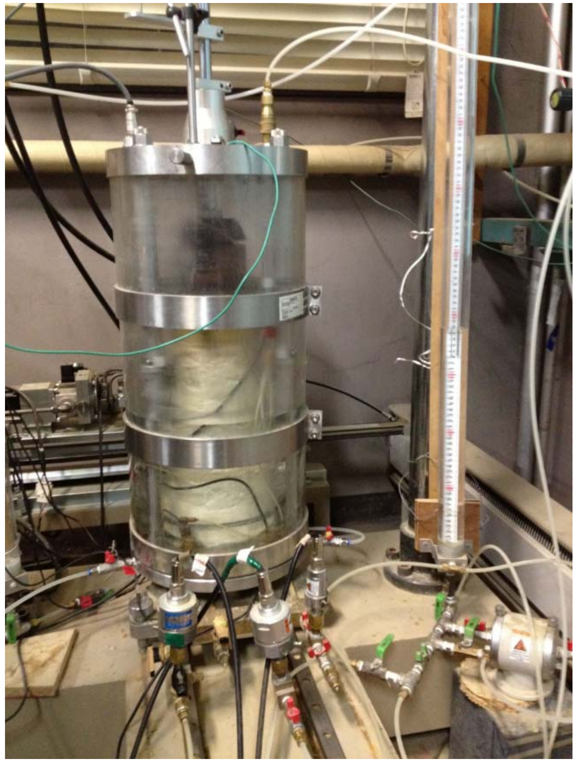
  Diameter : 150mm
  Height : 300mm

- Test condition

  Suction-controlled

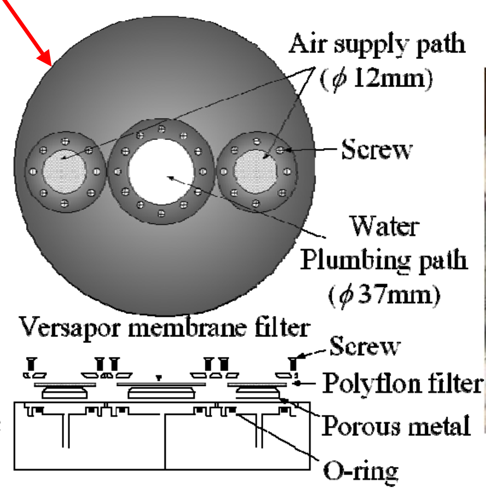
  - Monotonic loading with strain control method at very slow loading rate
  - Cyclic loading with stress control method at high loading frequency





- Remarkable Features

  - The apparatus can perform water retentivity tests, triaxial compression tests and resilient modulus test (MR test) for unsaturated soils to evaluate the deformation-strength characteristics of coarse granular materials.
  - The apparatus adopts pressure membrane method for reducing total testing time.



Multi-ring shear test apparatus

- Specimen size

  Width：60mm

  indside D=120mm

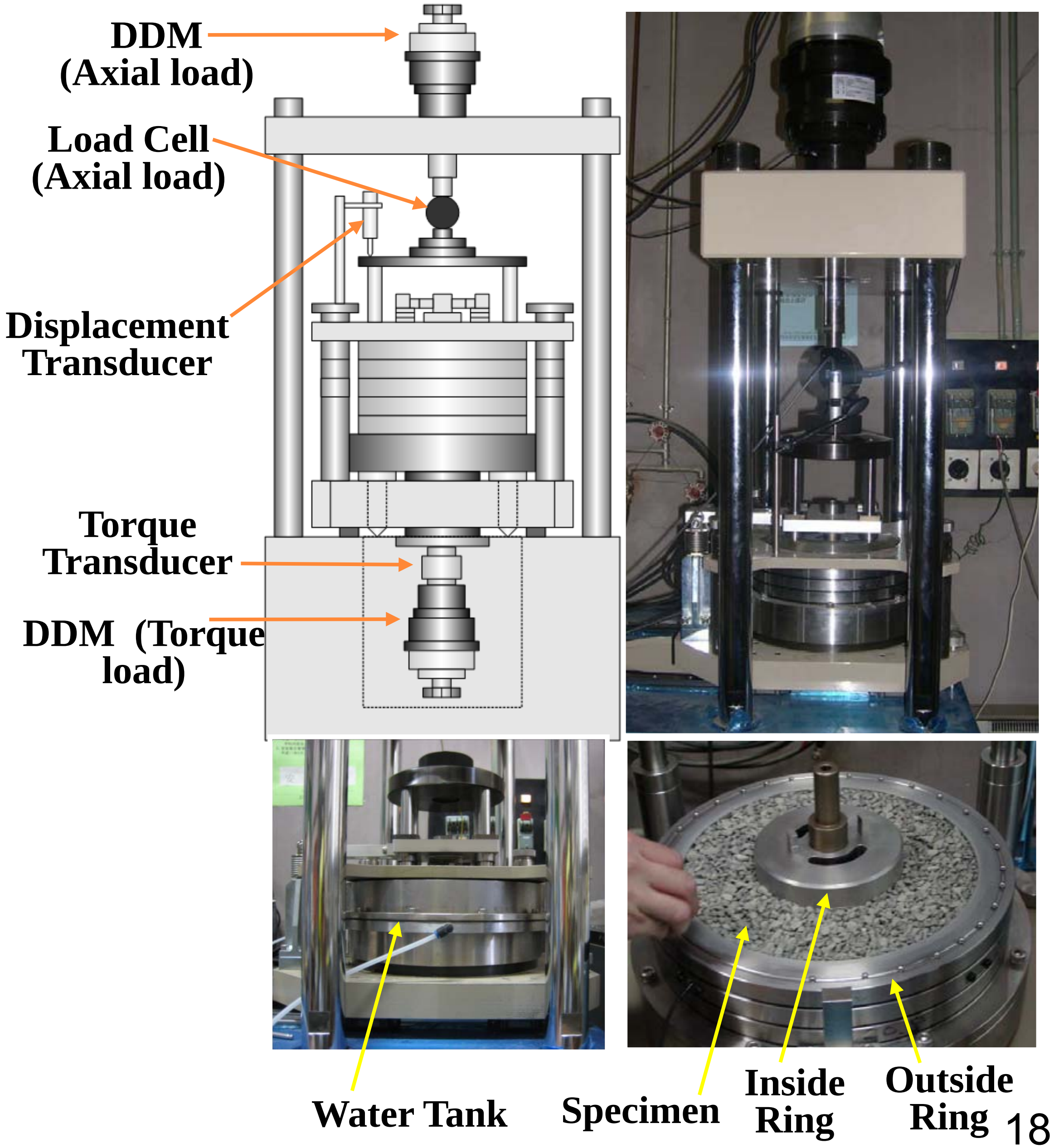
  outside D=240mm

  Height：60 - 100mm

- Test condition

  Torsional simple shear with strain-control and stress-control method using direct drive motor (DDM)

- Remarkable Features
  - It can evaluate the effects of rotating principal stress axes under shearing on the deformation-strength characteristics of granular materials.
  - It can perform monotonic and cyclic loading tests under various water contents and freeze-thaw history.



Freeze-thaw CBR test apparatus

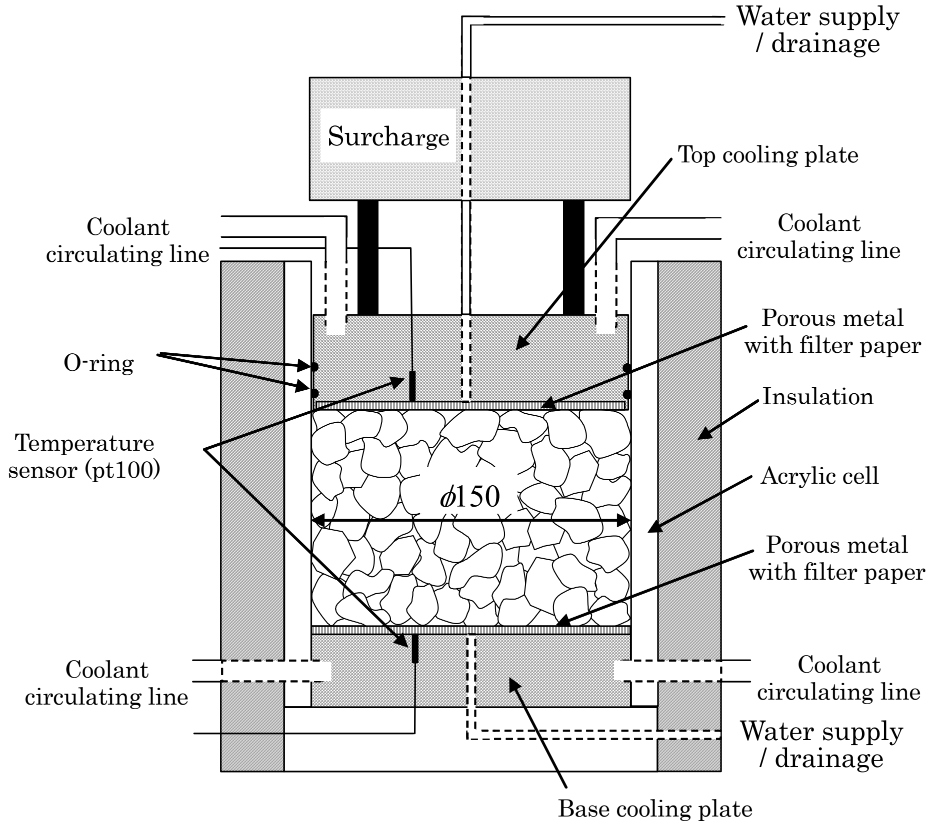
- **Specimen size**

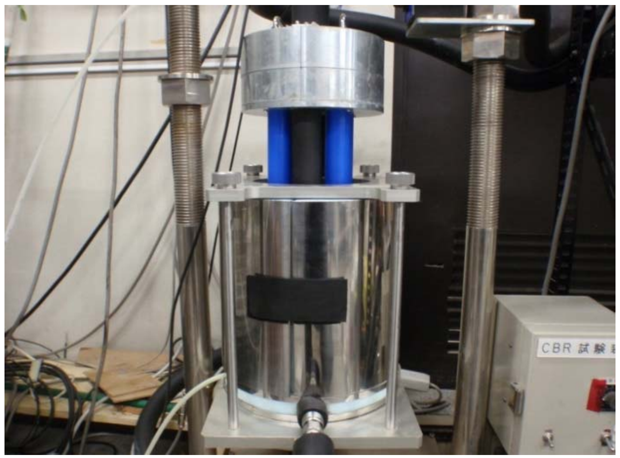
  Width: 60mm
  indside D=120mm
  outside D=240mm
  Height: 60 - 100mm

- **Test condition**

  It can conduct a CBR test as it is immediately after the freeze-thaw.

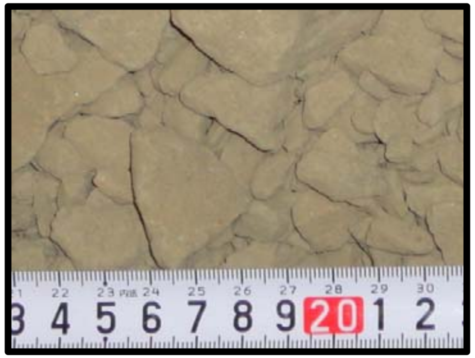
- **Remarkable Features**
  - It can subject a CBR test specimen (ϕ=15cm, H=12.5cm) to a one-dimensional desired freeze-thaw history at a constant freezing rate.
  - It allows open-system freezing or closed-system freezing.





Test Samples

C-40 Crusher-run | **1/5 ballast** | **C-9.5 gravel** | **Toyoura sand**




Sample	ρ_s (g/cm^3)	ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	D_{50}	U_c	$F_{cinitial}$ (%)
C-40 crusher-run	2.74			9.10	37.1	1.7
1/5 ballast	2.70	1.650	1.353	8.11	1.52	0.0
C-9.5 gravel	2.72	1.730	1.480	2.80	10.8	0.0
Toyoura sand	2.65	1.648	1.354	0.18	1.30	0.0

- Four types of test samples are employed to examine the mechanical behavior of railroad ballast and roadbed at ballasted tracks.
- To ensure experimental accuracy in terms of specimen size, 1/5 ballast and C-9.5 gravel have one-fifth and one-fourth similar grading of 1/1 ballast and base course material (C-40) used in Japanese railway and road, respectively.

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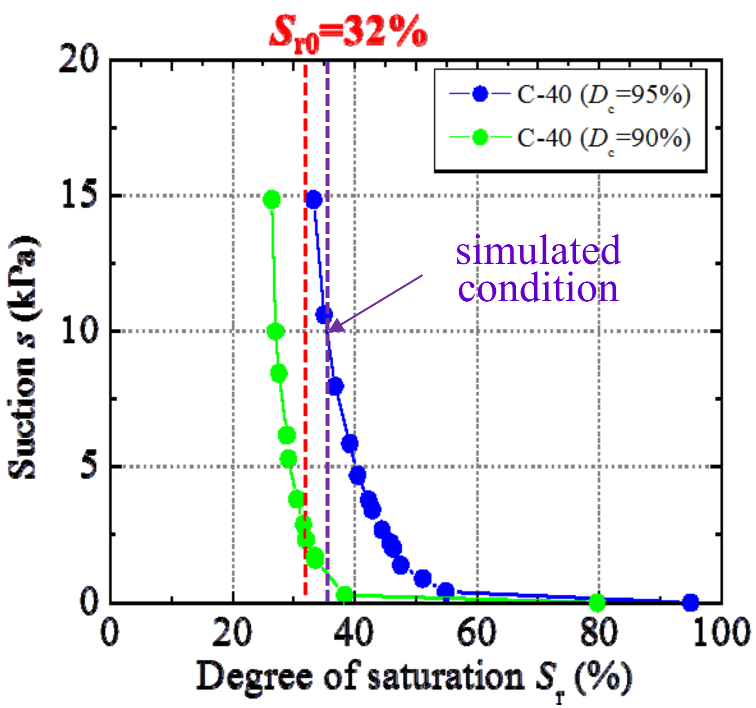
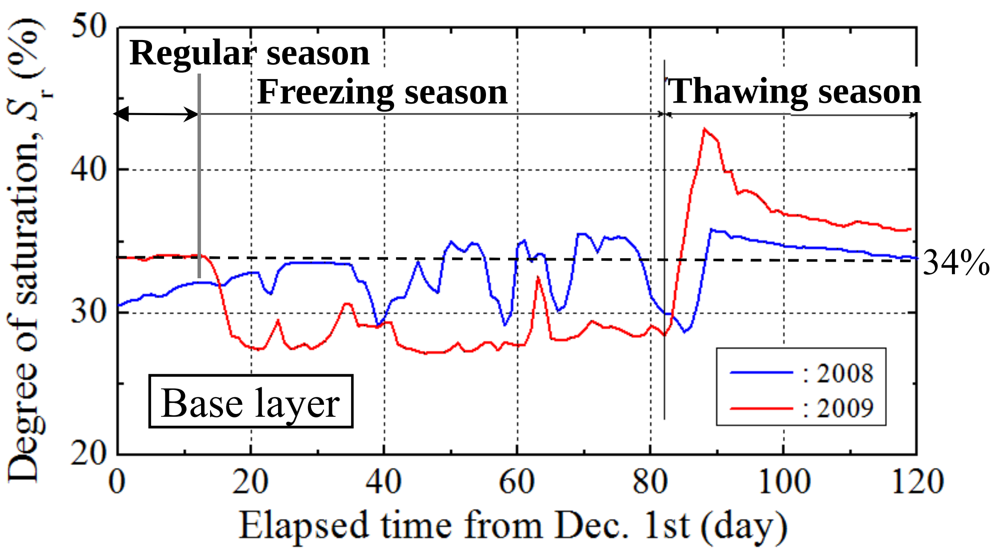
Testing Method

- Specimens were prepared by compacting with vibrator until reaching the D_c of 95 %, and they were kept throughout the test at a specified degree of saturation by controlling matric suction.
- Triaxail compression tests for air-dried (S_r=8.2%), simulated (S_r=36.7%), optimum (S_r=57.2%) and saturated (S_r=100%) specimens were conducted under fully drained condition, pursuant to JGS and AASHTO standards.



SWCC

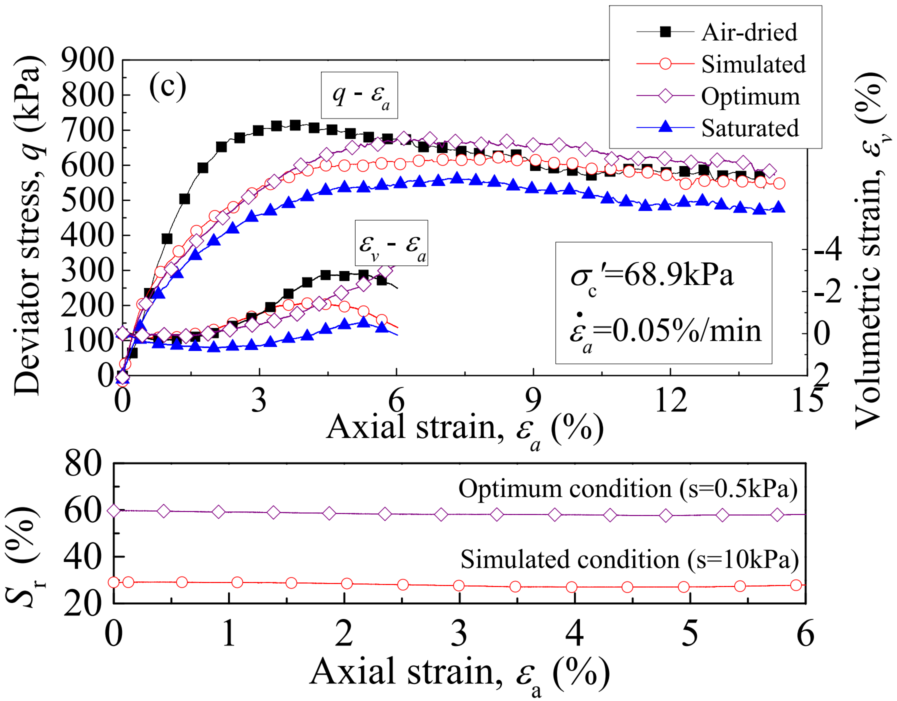


Long-term field measurement

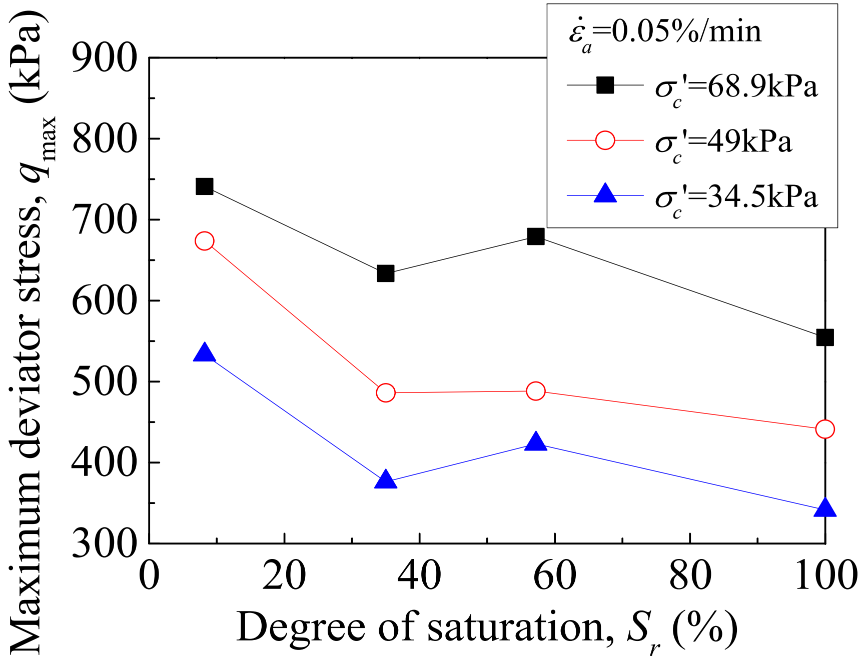
- We set the S_r for simulated specimens to the value close to S_r at the in-situ base layer during regular season.

Results of monotonic (static) loading tests

Influence of water content



Stress – strain relations under different S_r

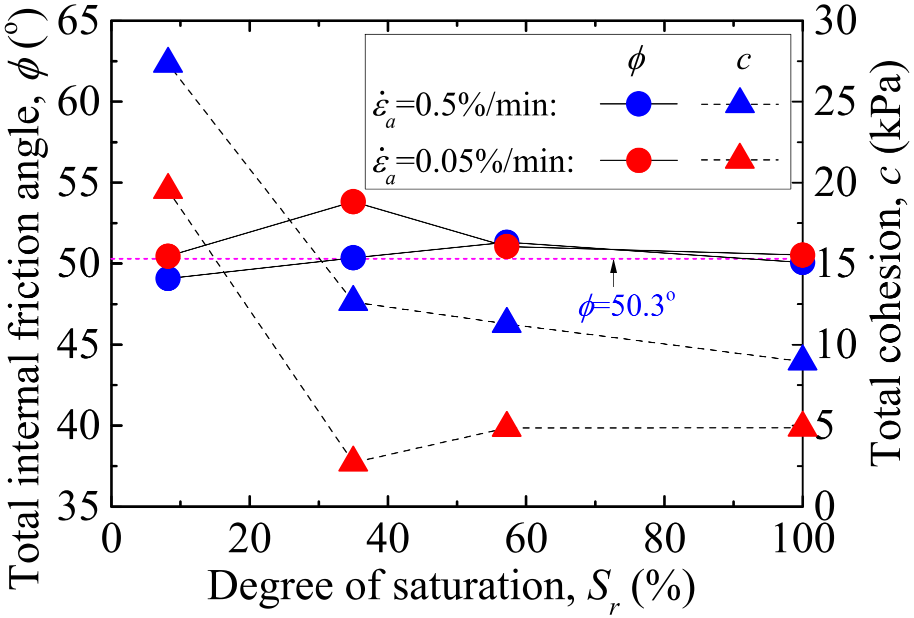


Peak strength at same strain rate under different confining pressures and S_r

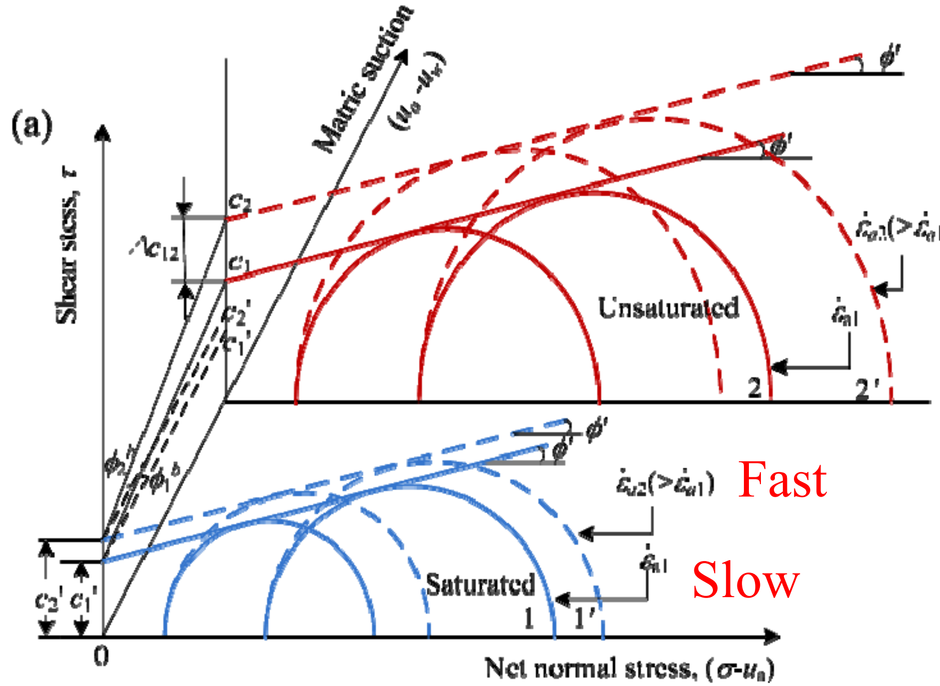
- Under same strain rate, air-dried sample has maximum peak strength, saturated sample has minimum one, and unsaturated samples have a peak strength between those two values, regardless of effective confining pressure.
- Wetting causes the sample to decrease the shear strength and stiffness.

Results of monotonic (static) loading tests

Influence of loading rate



Strength parameters under different loading rates and S_r

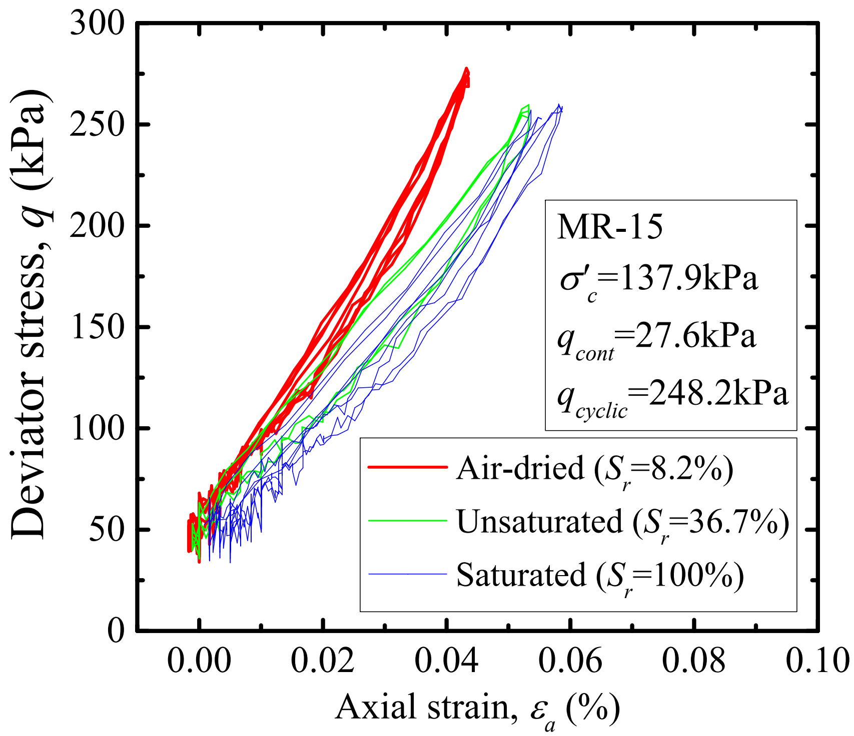


Three-dimensional failure surface for unsaturated soils

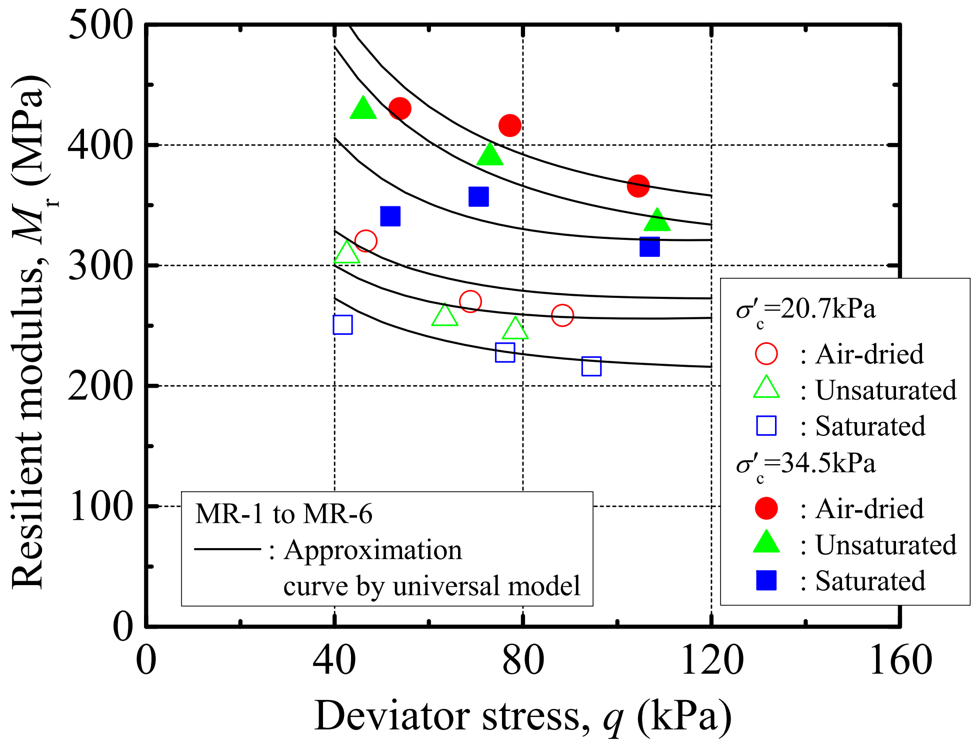
- At same water content, test results under fast loading rate has higher cohesion than test results under slow loading rate, while internal friction angle is almost constant, irrespective of loading rate and degree of saturation.
- The influence of loading rate on the strength parameter for crusher-run appears more clearly in unsaturated conditions.

Results of resilient modulus tests

Influence of water content



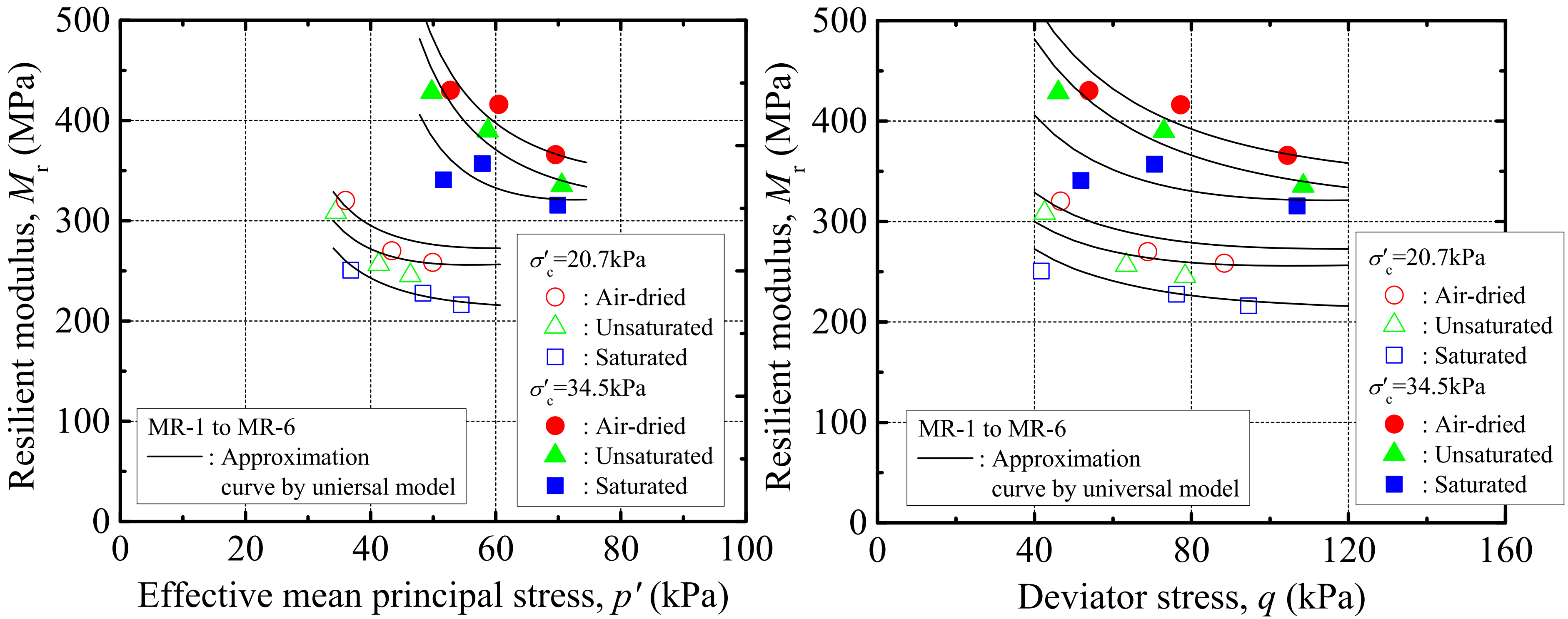
Stress – strain relations under different S_r



Resilient modulus under different S_r

- Stress-strain relationships varies depending on the water content, with a tendency for the stiffness to increase with the decrease in water content.
- For plots with the same q, resilient modulus decreases as the water content increases, regardless of σ'_c.

Stiffness estimation of unsaturated C-40



Influence of p' on M_r under different σ'_c Influence of q on M_r under different σ'_c

Universal model : $$M_r = k_1 p_a \left(\frac{\sigma_{ii}}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$ (Yan and Quintus 2002)

- Resilient modulus for unbound granular base course materials is greatly dependent on the stress conditions and the water content.
- Universal model given by above equation can be applied to the quantitative evaluation of resilient modulus for unsaturated base course materials.

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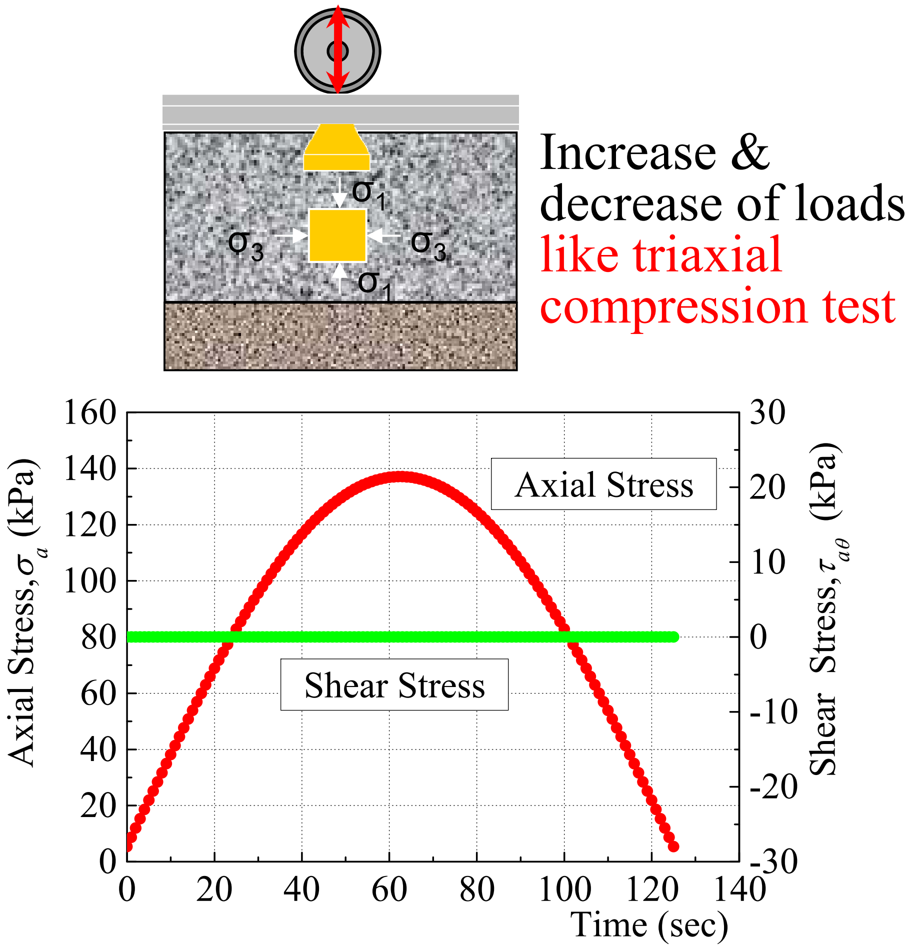
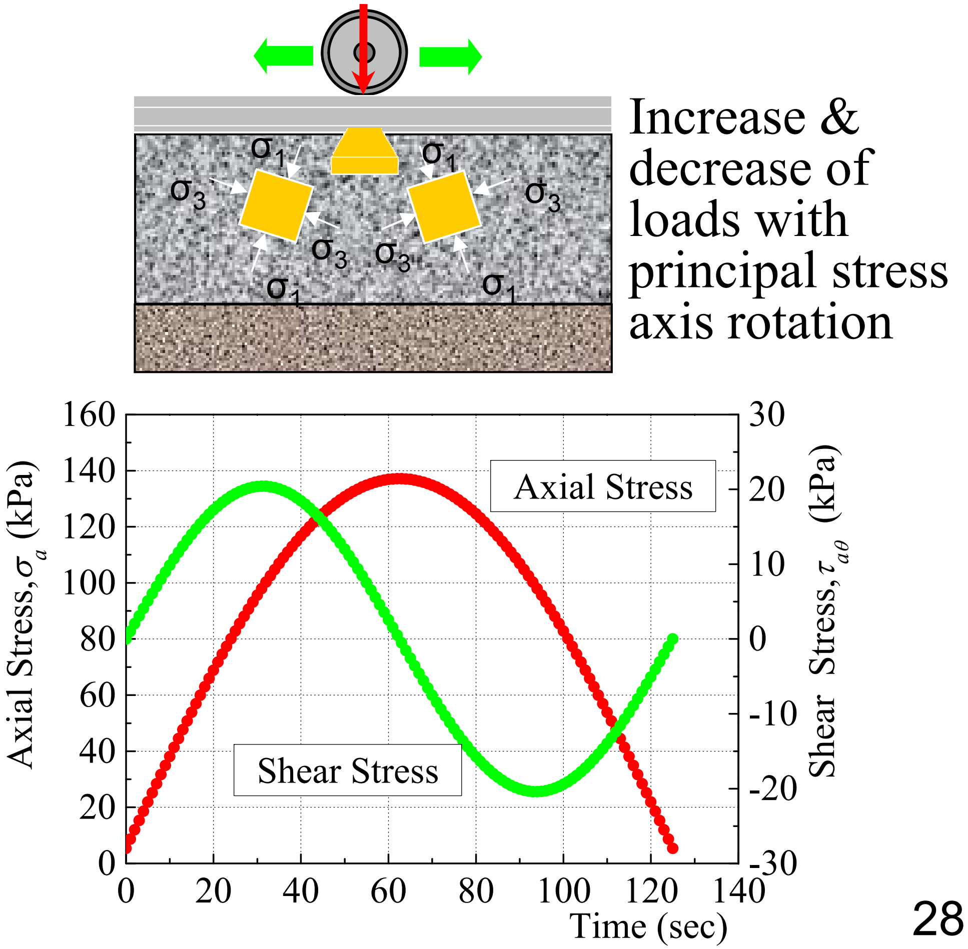
Testing Method

- Specimens were prepared by tamping a sample with prescribed water content, and a series of multi-ring shear tests was conducted by using fixed-point loading (FL) method and moving-wheel loading (ML) method.

Fixed-point loading (FL)



Moving-wheel loading (ML)



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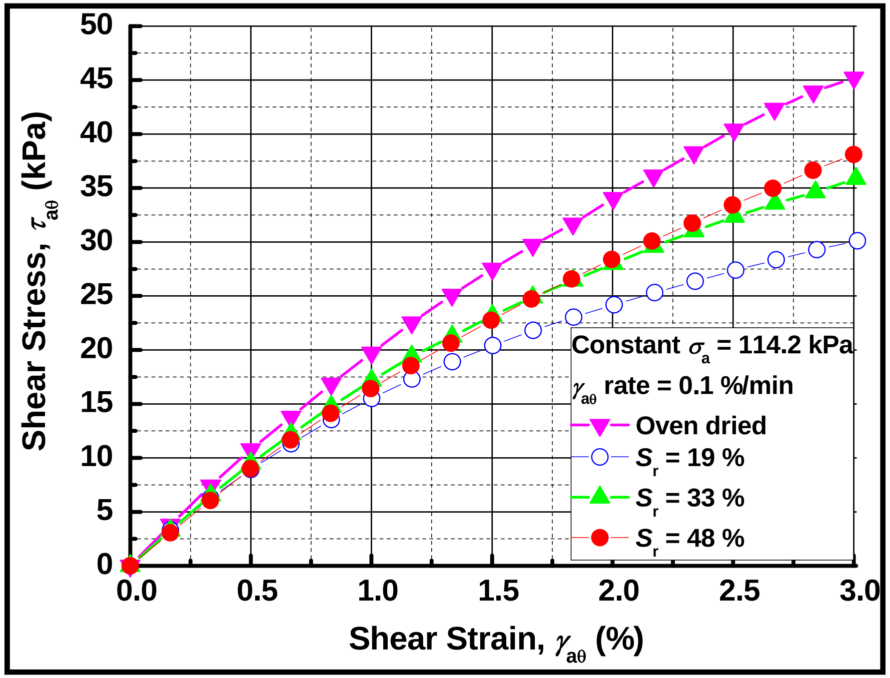
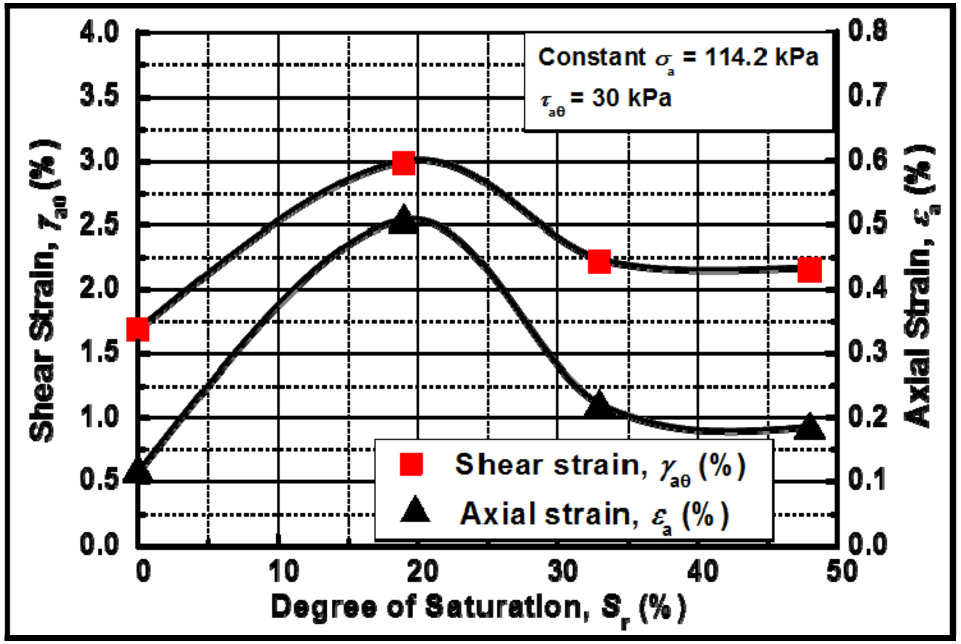
Results of monotonic (static) loading tests

Influence of water content



Stress – strain relations under different S_r

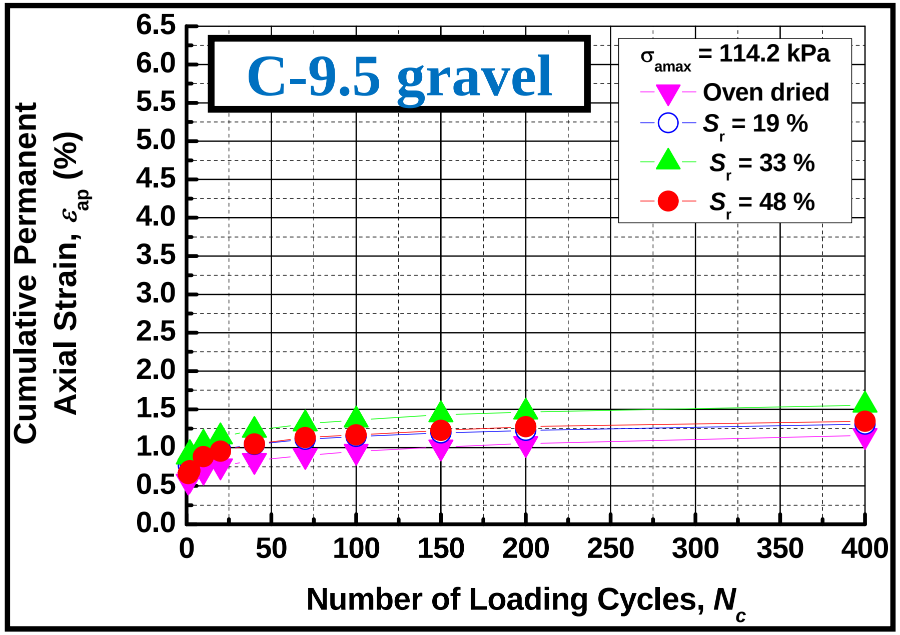


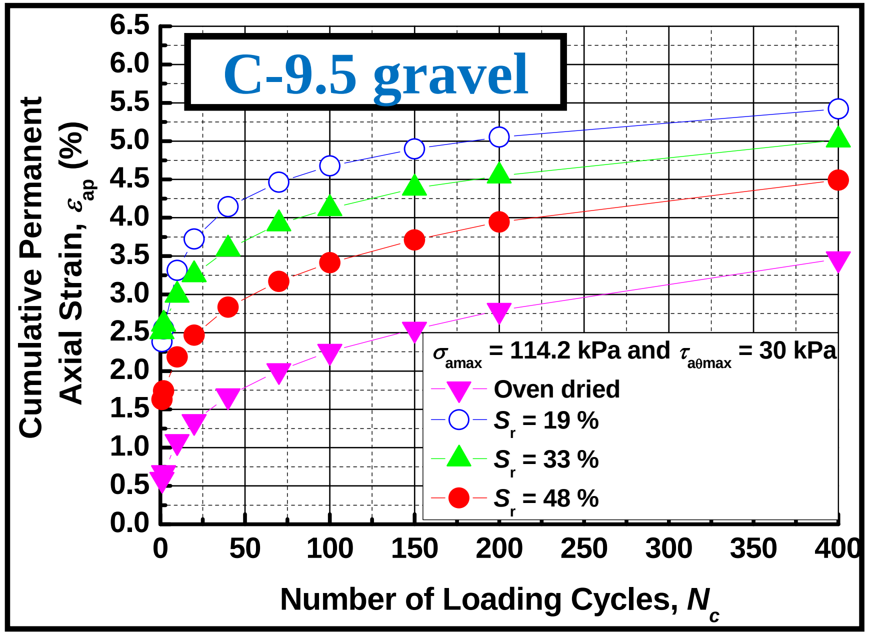
Strain at same loading conditions under different S_r

- Under same loading conditions, oven-dried sample has minimum shear and axial strains, thus indicating that it has maximum shear strength and stiffness.
- Wetting causes the sample to decrease the shear strength and stiffness, thereby increasing shear and axial strains.

Results of cyclic loading tests (1)

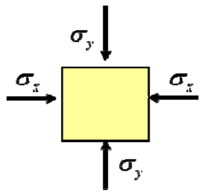
Influence of water content & loading method





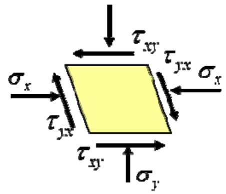
Fixed-point Loading

Increase & decrease of loads



Moving-wheel Loading

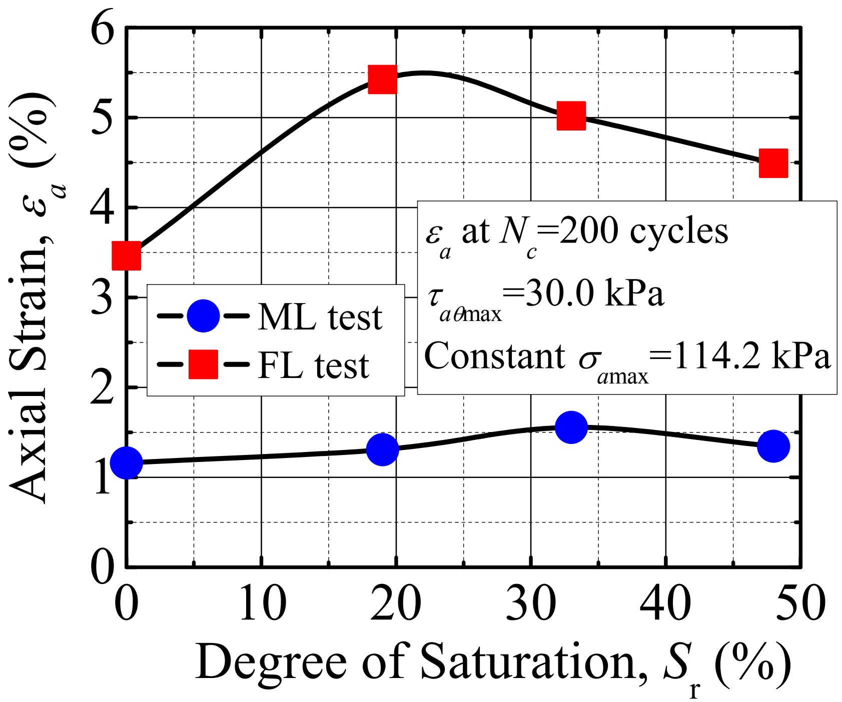
Increase & decrease of loads with principal stress axis rotation



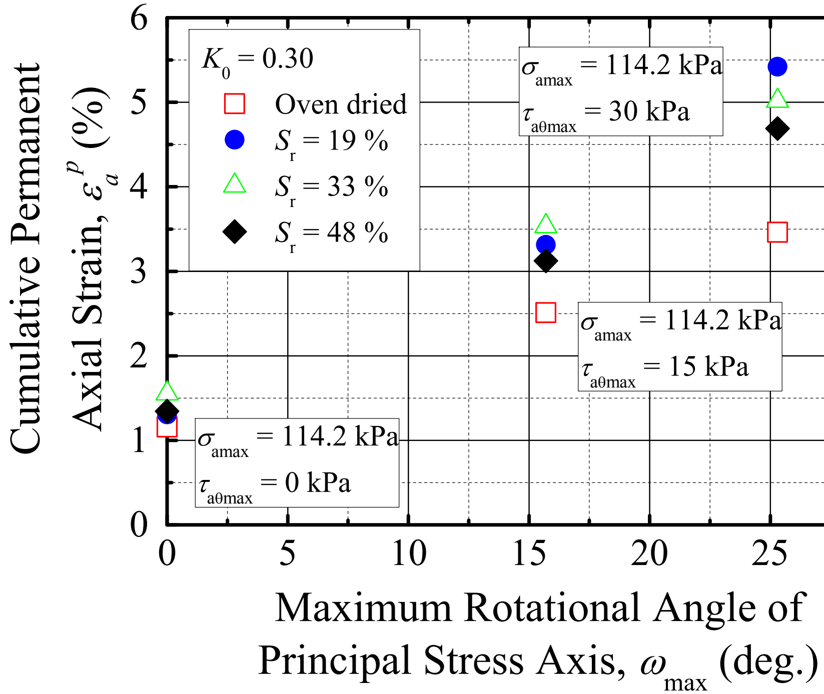
- Cyclic plastic deformation of wet gravel is more likely to increase with loading cycles than that of oven-dried gravel.
- The influence of water content on the cyclic plastic deformation for gravel appears more clearly in employing moving wheel loads.

Results of cyclic loading tests (2)

Influence of water content & loading method



Cyclic plastic deformation under different loading conditions and S_r



Influences of principal stress axis rotation on cyclic plastic deformation

- Wetting causes the sample to decrease the shear strength and stiffness, thereby increasing cumulative permanent strain during cyclic loading.
- When rotational angle of principal stress axis increases with the increase in shear stress amplitude, cumulative permanent axial strain also increases.

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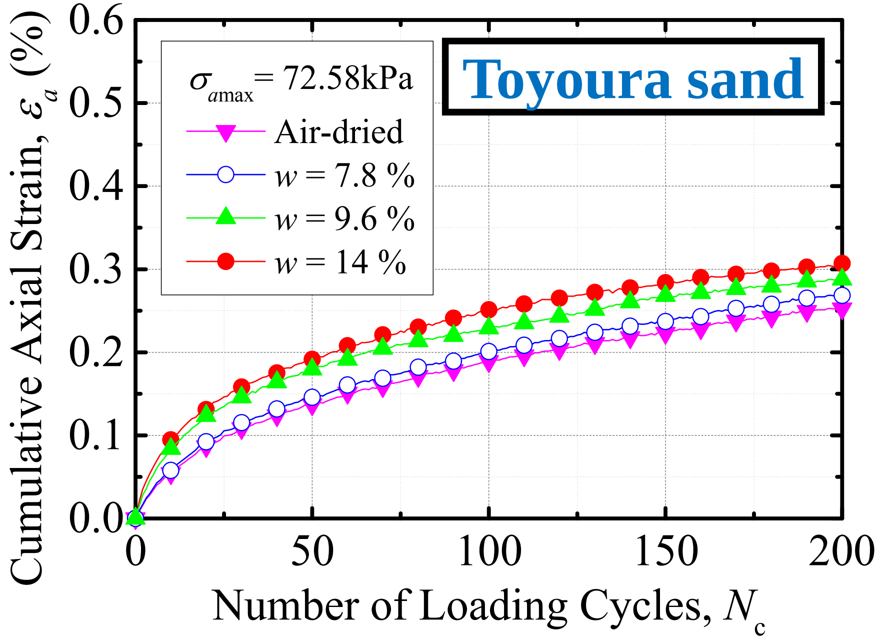
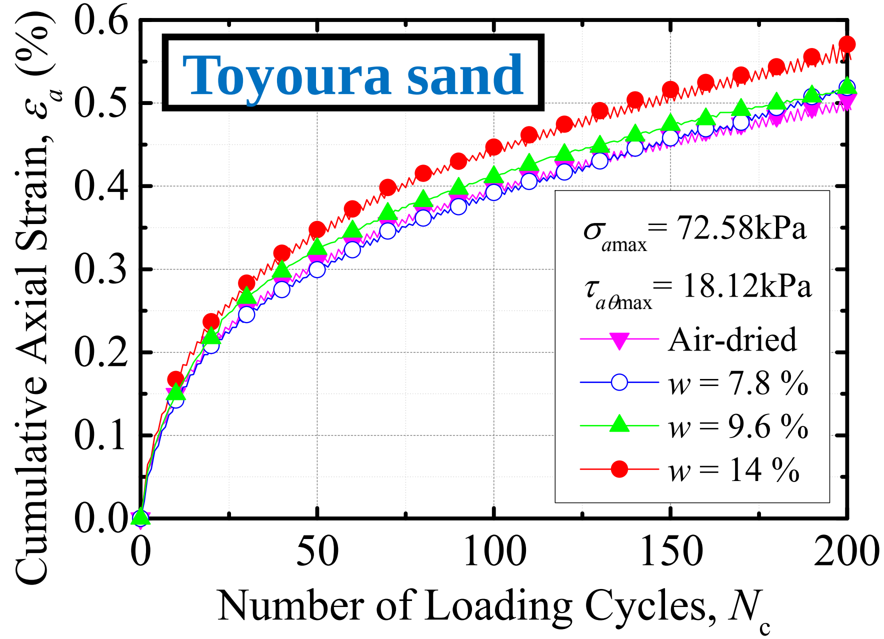
Results of cyclic loading tests (1)

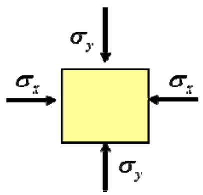
Influence of water content & loading method





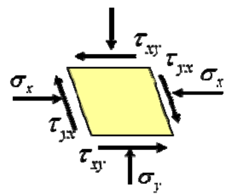
Fixed-point Loading

Increase & decrease of loads



Moving-wheel Loading

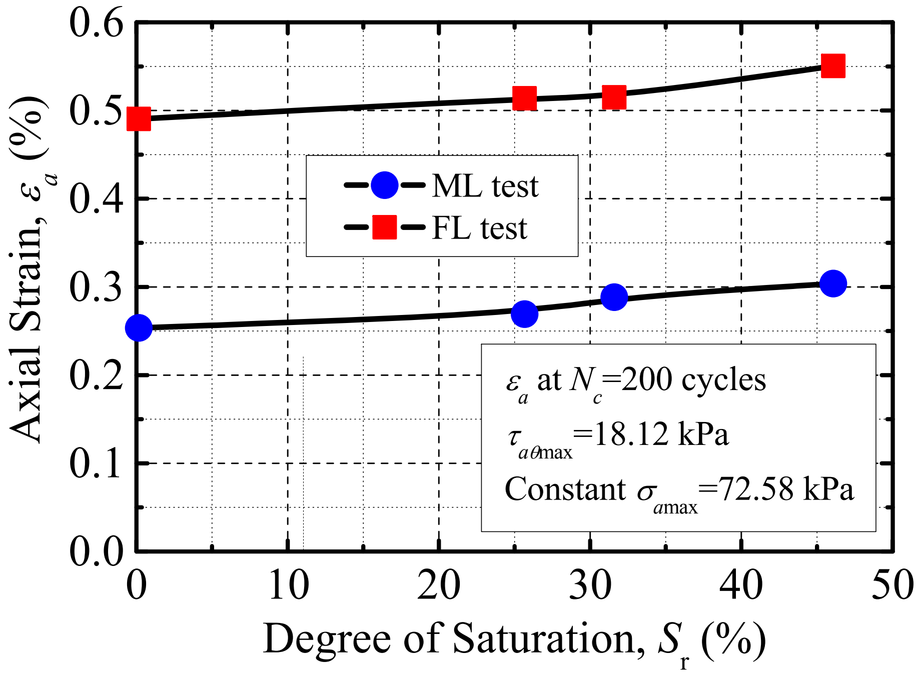
Increase & decrease of loads with principal stress axis rotation



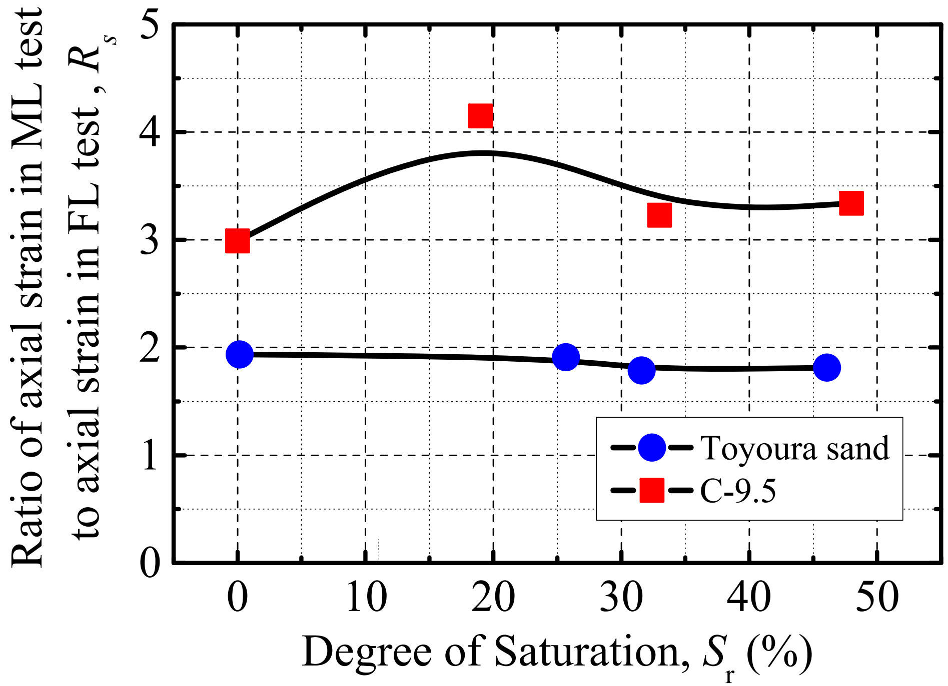
- As seen in the comparison for gravel, cyclic plastic deformation of sand in ML tests is larger than that in FL tests.
- Cyclic plastic deformation of wet sand is more likely to increase with loading cycles than that of air-dried sand.

Results of cyclic loading tests (2)

Influence of water content & loading method



Cyclic plastic deformation under different loading conditions and S_r



Influences of water content on cyclic plastic deformation of gravel and sand

- Wetting of sand increases cumulative permanent strain during cyclic loading, regardless of loading method.
- Effects of water content on cyclic plastic deformation under moving-wheel loads differ depending on soil types.

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Testing Method

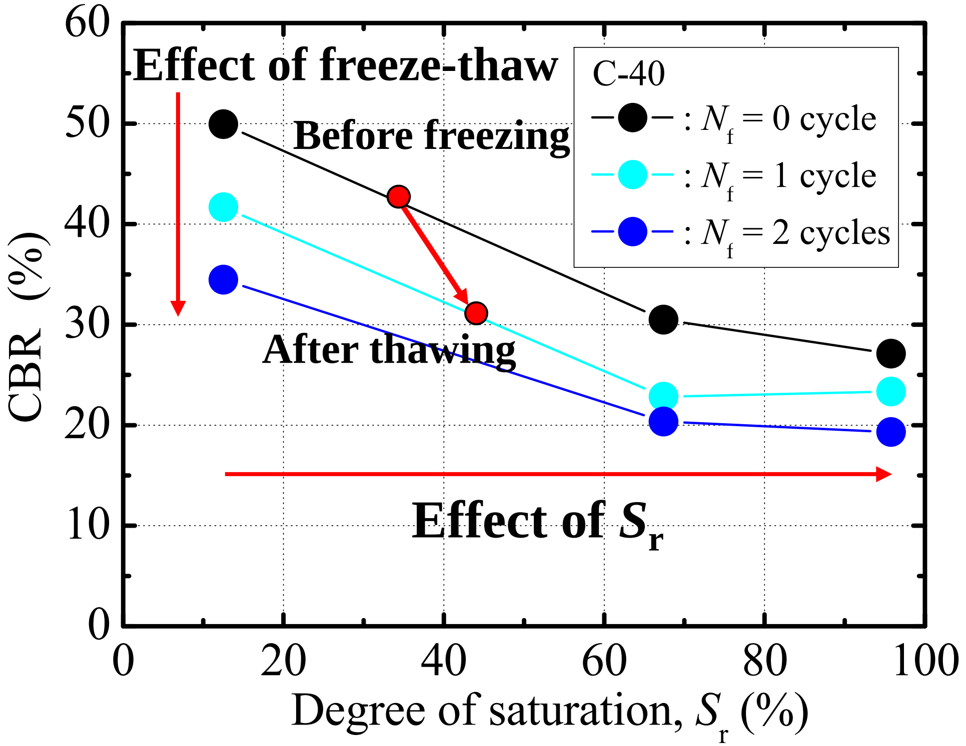
- Specimens in freeze-thaw CBR tests were prepared almost in the same manner as specimens in triaxial tests, except that the wet (S_r=67.6%) specimen was prepared by gravity drainage of saturated specimen.
- Freeze-thaw tests under the following experimental conditions, that is various freeze-thaw histories and water contents, were conducted in closed-system without water supply and drainage.
- After the freeze-thaw process, CBR tests for air-dried, wet and saturated specimens were carried out.
- Based on results of frost heaving tests, frost-susceptibility of natural crusher-run is low, regardless of freeze-thaw history and water content.

Experimental conditions of freeze-thaw CBR tests

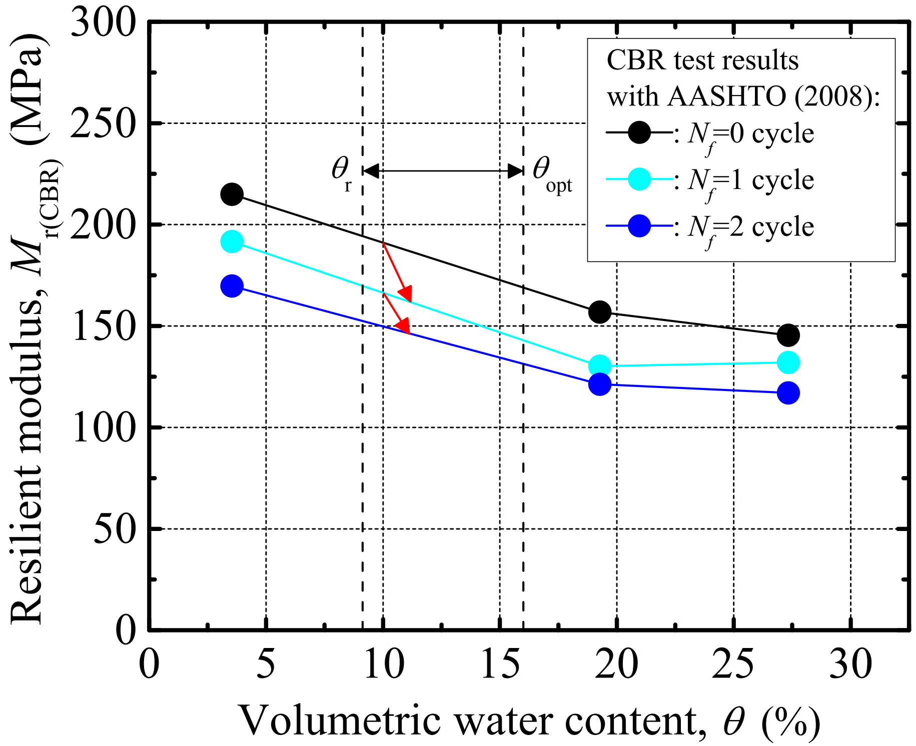
Name	Initial S_r	Initial w	Initial θ	Freeze-thaw history
air-dried	8.2 %	1.2 %	2.3 %	0 (no freeze-thaw), 1, 2 cycle
wet	67.6 %	9.8 %	19.3 %	0 (no freeze-thaw), 1, 2 cycle
saturated	100 %	14.3 %	28.2 %	0 (no freeze-thaw), 1, 2 cycle

Note : under optimum water content (w =8.2 %), S_r =57.0 % and θ =16.2 %.

Results of freeze-thaw CBR tests



CBR under different freeze-thaw histories & S_r

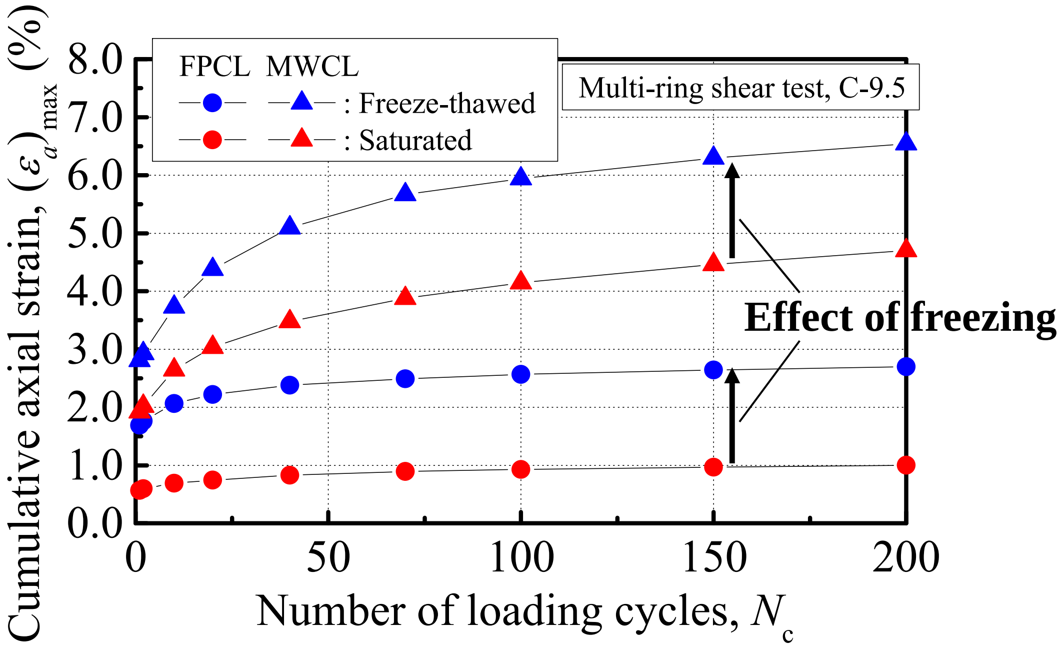


M_r estimated using M_r=17.6 CBR$^{0.64}$

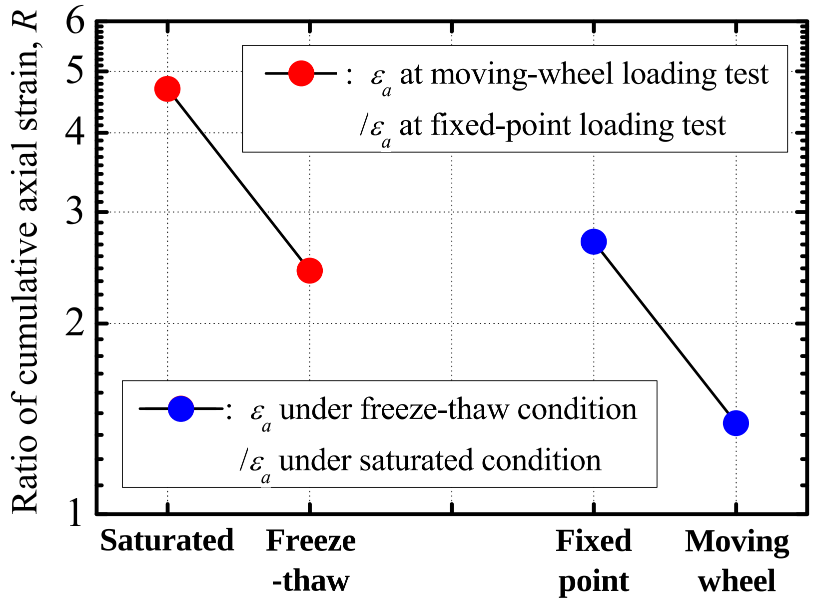
- CBR and M_r decrease with the increase in water content irrespective of the freeze-thaw history, and they drops with an increase in the freeze-thaw process cycles regardless of the water content.
- Considering the range of water content obtained from field measurement, it is expected that the freeze-thaw action seriously influences the bearing-capacity of unbound granular base course materials.

Results of cyclic loading tests

Influence of freeze-thaw & loading method



Cyclic plastic deformation under different freeze-thaw history



Effects of freeze-thaw on cyclic plastic deformation

- Freeze-thaw makes cumulative permanent strain during cyclic loading increase further in addition to the effect of water content.
- The influence of freeze-thaw on the cyclic plastic deformation should be considered even in a non-frost-susceptible material.

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Proposal of Experimental Formula (1)

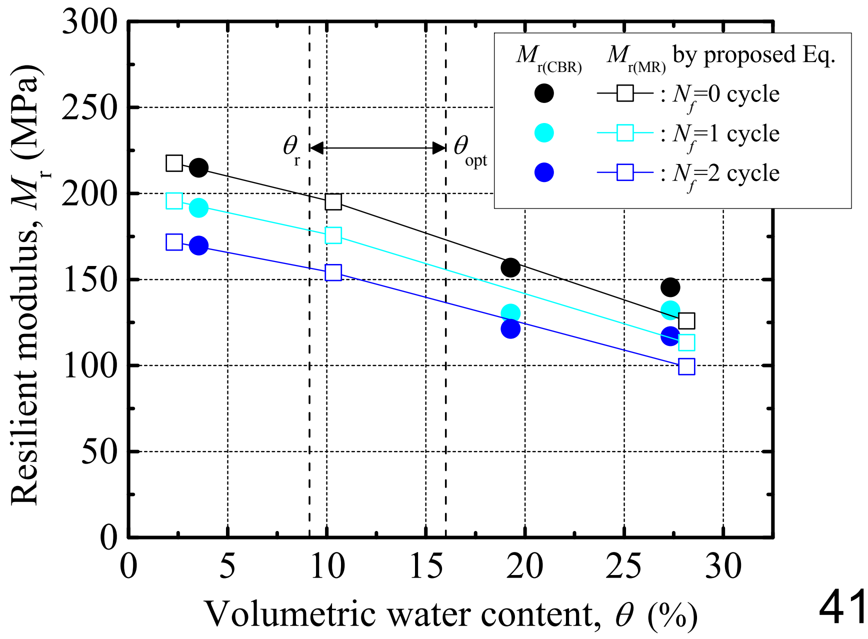
Assumptions

- Effects of freeze-thaw actions can be expressed by a compensation function $f(N_f, \theta)$, which uses number of freeze-thaw process cycles and volumetric water content as explanatory variables.
- M_r for C-40 subjected to repeated freeze-thaw actions can be estimated using the "modified universal model", which is the universal model multiplied by the compensation function.

Modefied Universal model : $$M_r = f\left(N_f, \theta\right) \cdot k_1 p_a \left(\frac{\sigma'_{ii}}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

Applicability of proposed formula

- Resilient modulus M_r estimated by proposed model seems to reproduce overall tendency for the M_r to decrease with the increase in the water content and the number of freeze-thaw process cycles.
- "Modified universal model" is sufficiently applicable to the quantitative evaluation of the M_r for unsaturated subbase course layer subjected to repeated freeze-thaw actions.



Proposal of Experimental Formula (2)

Assumptions

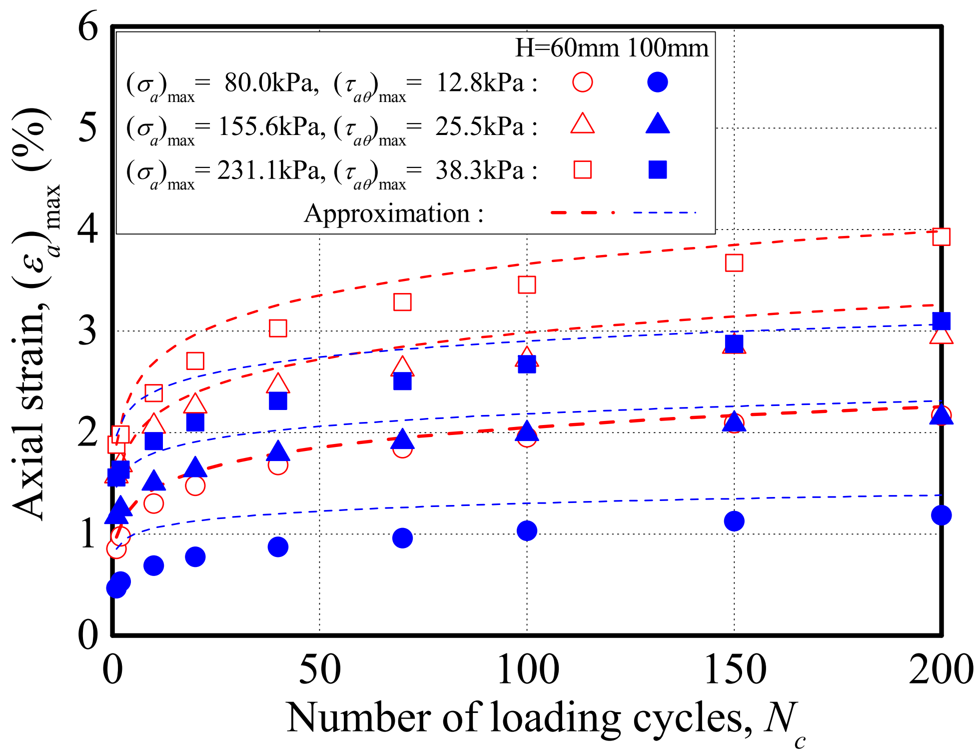
Under the same experimental conditions, cumulative axial strain in ML test can be estimated from cumulative axial strain of FL test by using average R_s as follows.

$$\varepsilon_a^{ML}(N_c) = R_{save} \cdot \varepsilon_a^{FL}(N_c) = \exp\left(a \frac{(\tau_{a\theta})_{\max}}{(\sigma_a)_{\max}} \right) \cdot \varepsilon_a^{FL}(N_c)$$

Note : a is a constant depending on water content.

Applicability of proposed formula

- Proposed simple experimental formula is effective in estimating the cumulative strain characteristics of coarse granular materials in the principal stress axis rotation field.



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Track condition of ballasted track

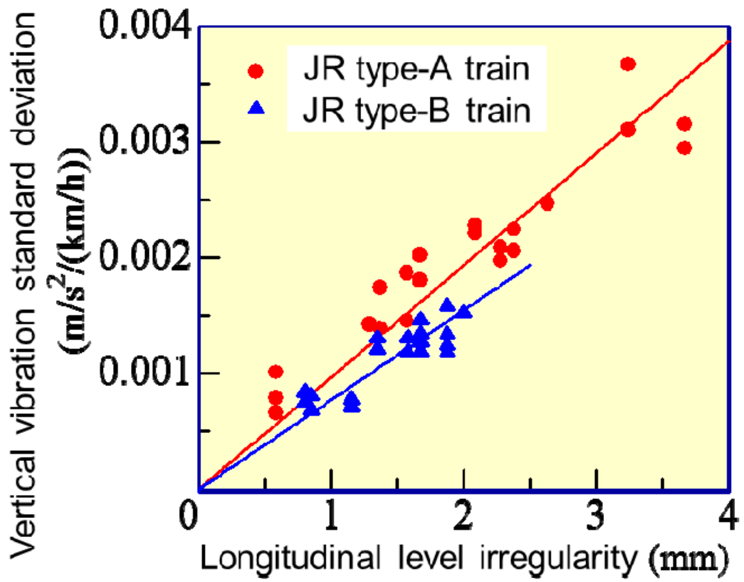
Design criteria of ballasted track

- Train vibration should be smaller than threshold limit value.
  - Traveling safety
  - Riding comfort
- Train vibration increases along with the increase in track irregularity.
- Train vibration can be estimated by

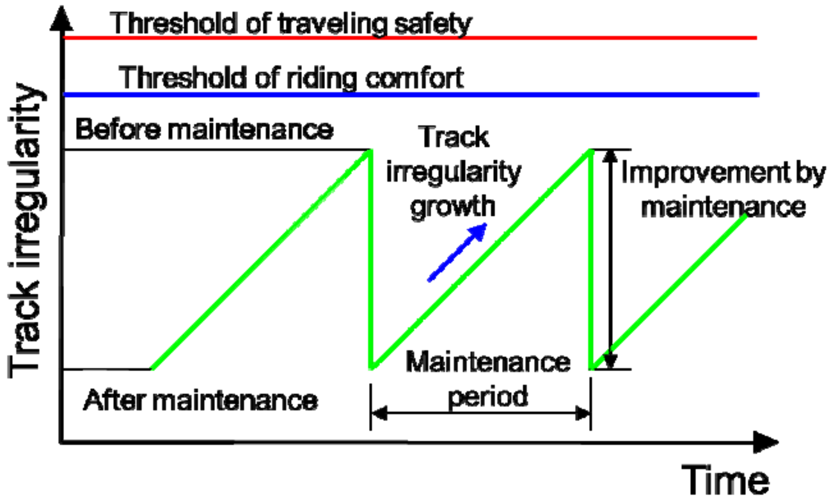
$$\alpha = a \cdot V \cdot \sigma$$

α: train vibration
V: train speed
σ: track irregularity

- Precise prediction of track irregularity growth is important for rational design & maintenance works of ballasted track.



Train vibration and track irregularity



Change in track irregularity with time

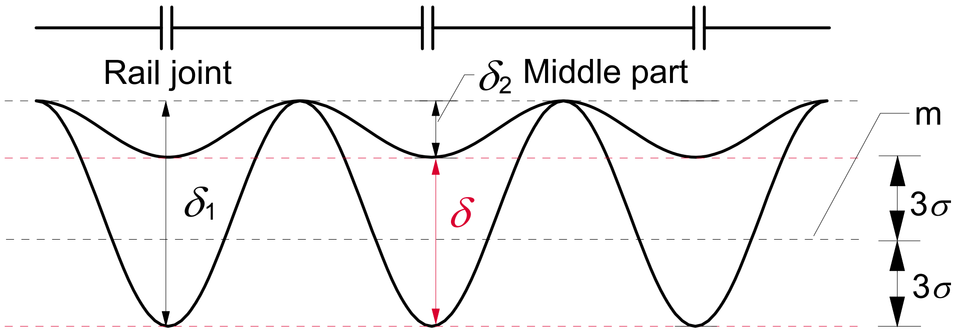
Design procedures of ballasted track

KEY POINTS : How do we calculate track irregularity using settlement?

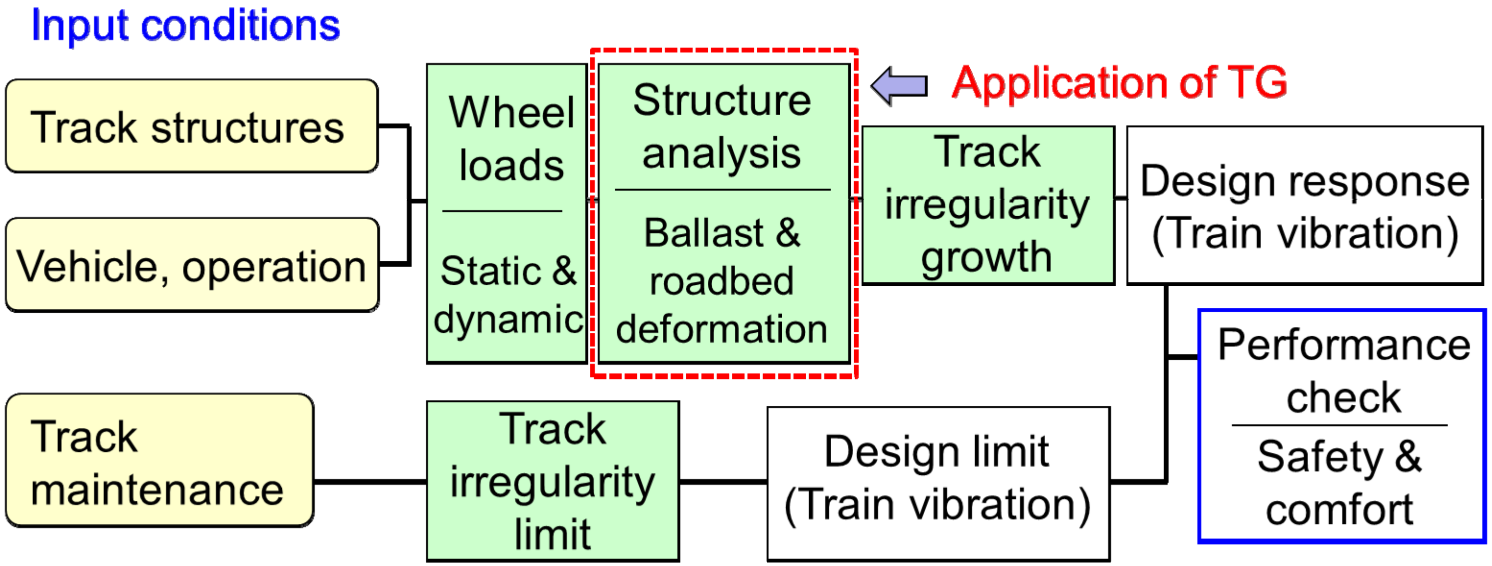
Assumption

- Track irregularity is defined by the difference between rail settlement at rail joint and that at middle part.
- Standard deviation of track irregularity can be estimated by

$$\delta = m + 3\sigma = 6\sigma$$

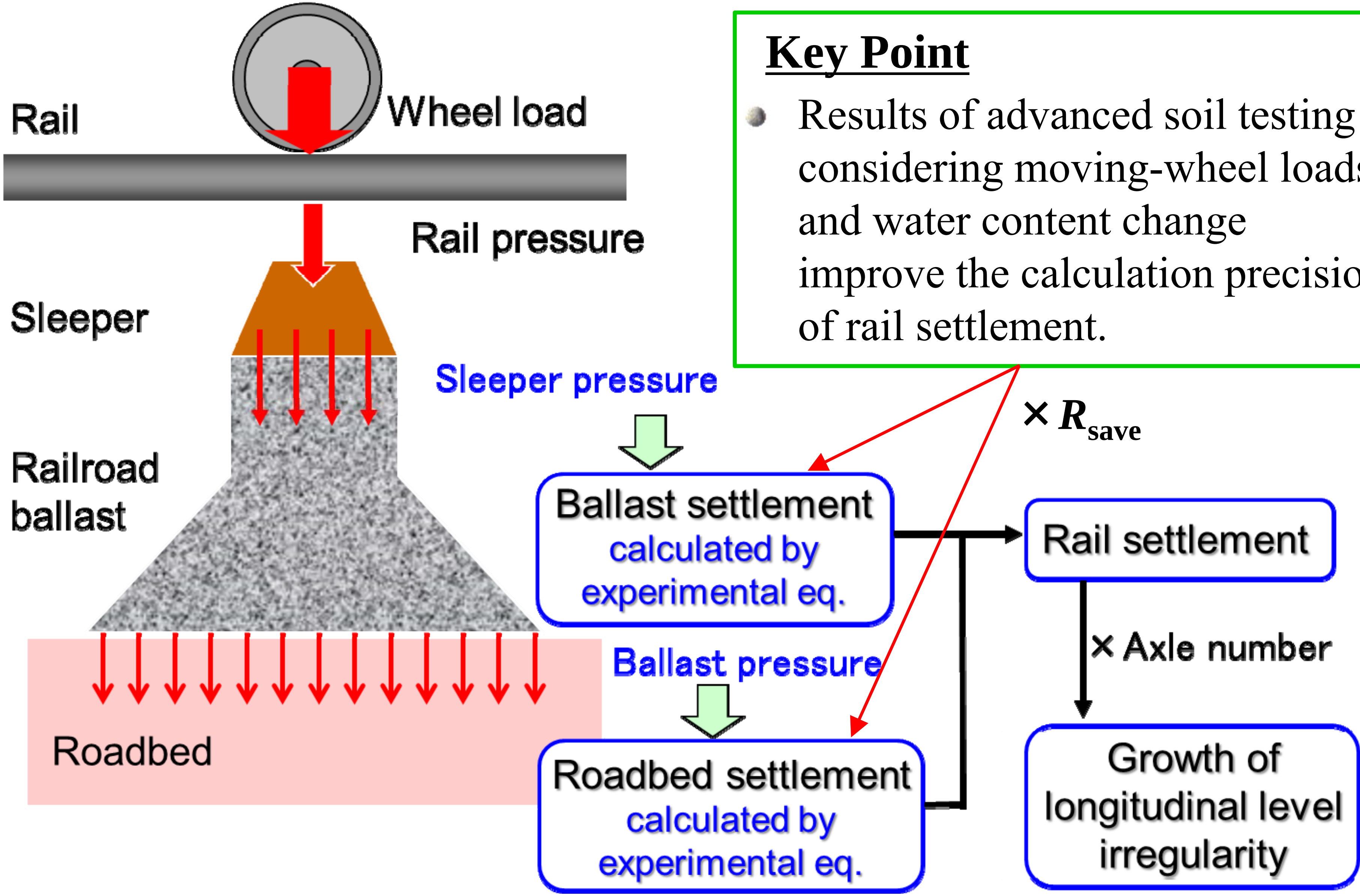


Rail settlement and track irregularity



Flow of design procedures for ballasted track

Application of advanced soil testing



Key Point

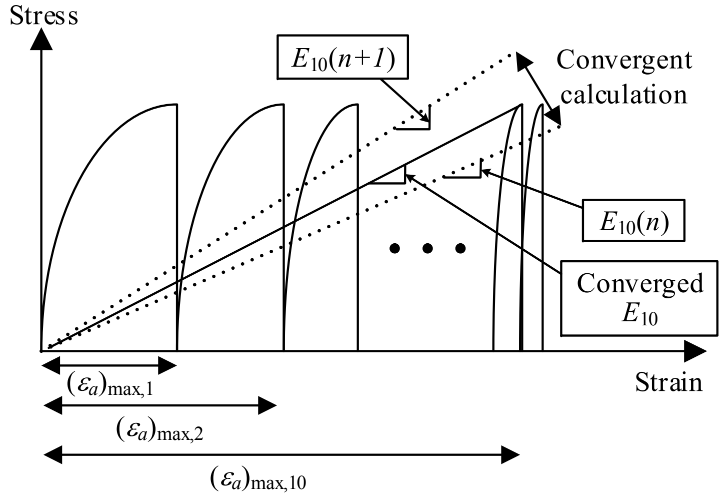
- Results of advanced soil testing considering moving-wheel loads and water content change improve the calculation precision of rail settlement.

Calculation of rail settlement in Japanese design standard

FE analysis based on cumulative damage model

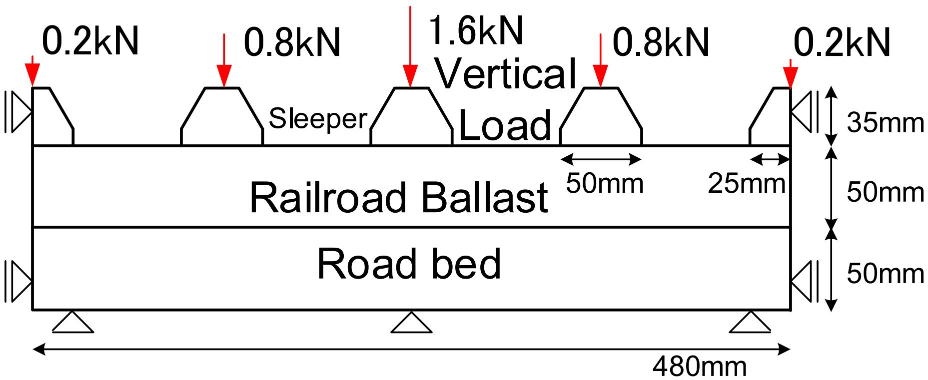
Cumulative damage model

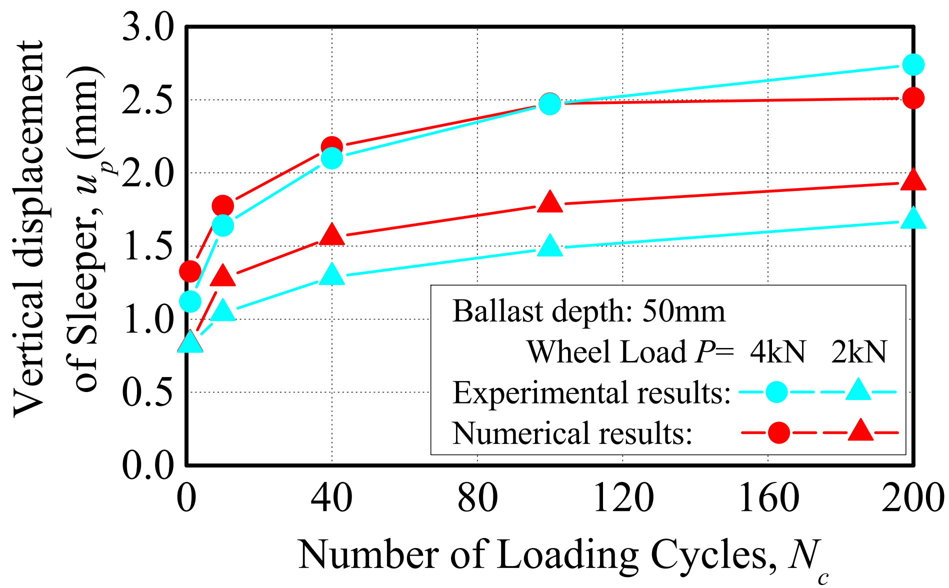
Deformation modulus of FE elements representing railroad ballast has been reduced in consideration of the cumulative strain characteristics of ballast, which is derived from advanced soil testing like multi-ring shear test.



FE analysis of ballasted track

FE analysis based on cumulative damage model was conducted to simulate small scale model tests of ballasted track.





- If element tests are conducted under the experimental conditions similar to actual phenomena, even simple linear elastic FE analysis can roughly estimate cyclic plastic deformation of railroad ballast under repeated moving-wheel loads.

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Concluding Remarks

- Change in water content as well as the effect of freeze-thawing seriously influences the bearing capacity of coarse granular materials.
- The synergistic effects of principal stress axis rotation and water content strongly influence cyclic plastic deformation of coarse granular materials and roadbed materials.
- The loading rate has a strong influence on the deformation-strength characteristics of coarse granular materials in unsaturated condition.

⇩

- When developing a rational design standard of ballasted track in cold regions for precisely predicting the mechanical behavior and evaluating the long-term performance, it is important to give a special consideration to the influence of water content, freeze-thaw history, loading rate, and principal stress axis rotation on the deformation-strength characteristics.

Thank You for Your Kind Attention