Synergistic effects of moving wheel loads and water content change on mechanical behavior of substructures at ballasted track

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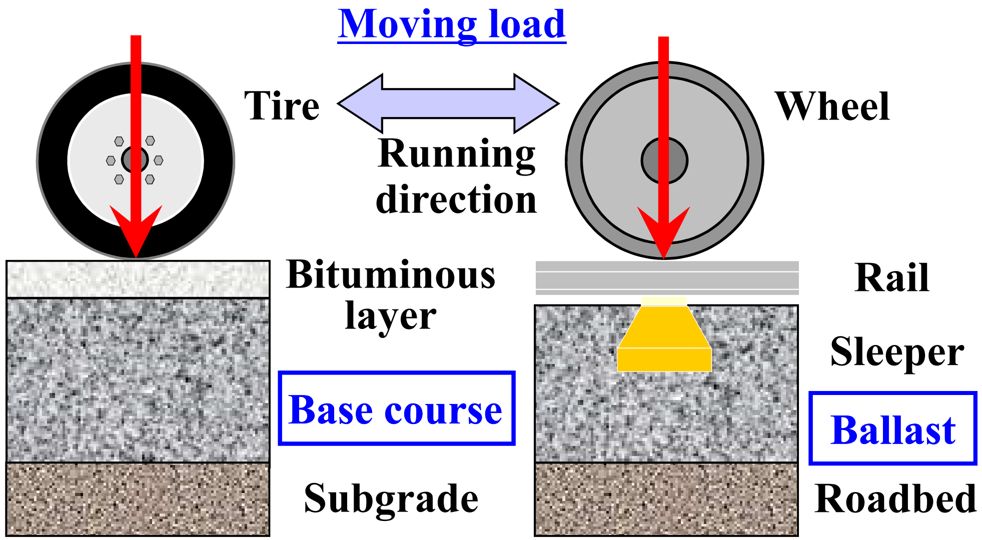
Background of research

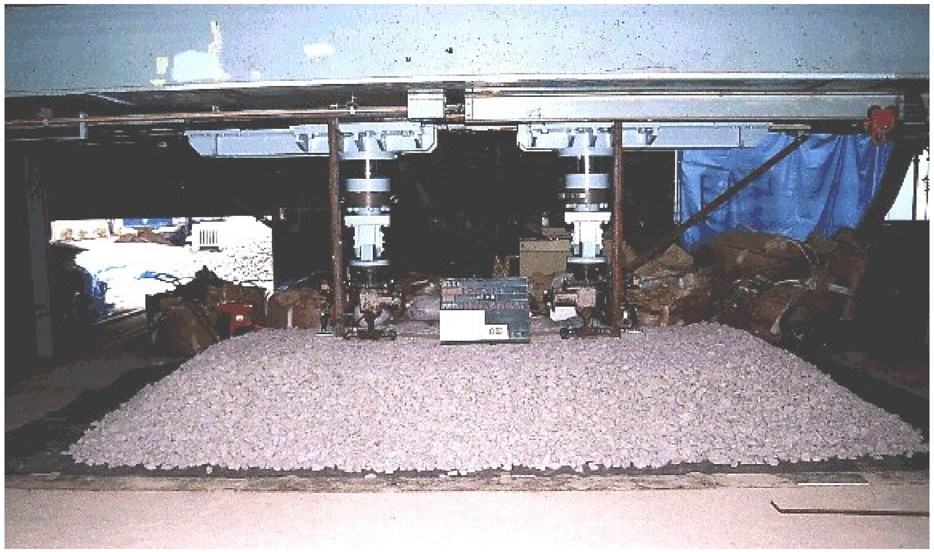
For saving maintenance costs of transportation facilities at road and railway, it is important to elucidate mechanical behavior of granular roadbed subjected to traffic loads.



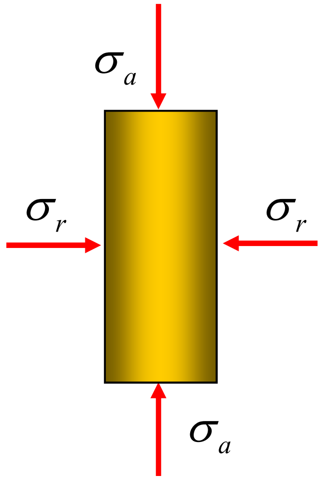
Conventional studies

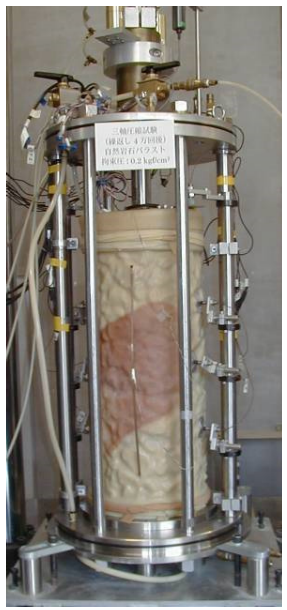
Following loading tests have been performed in Japan;

Model test : fixed-point loading test



Element test : Triaxial test





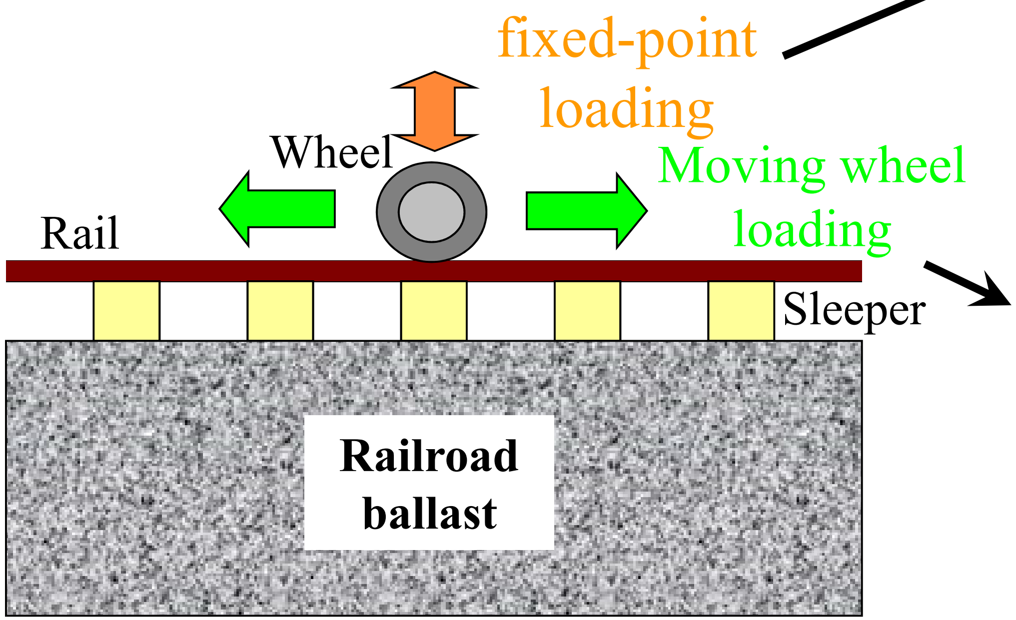
Effect of moving wheel loads

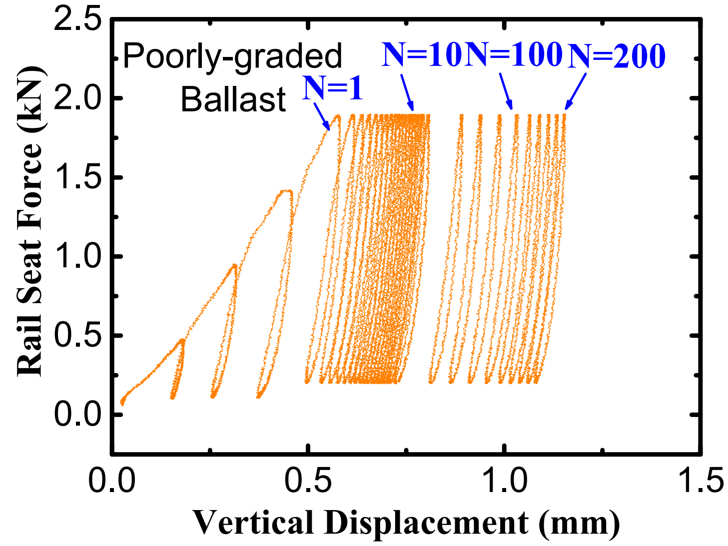
KEY POINTS

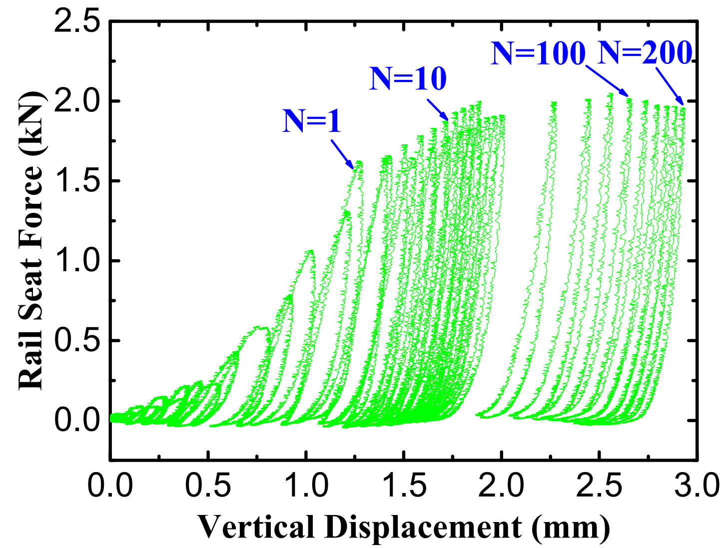
- **Can fixed-point loading tests simulate actual traffic loads ?**

Literature Review

Ishikawa & Sekine 2007



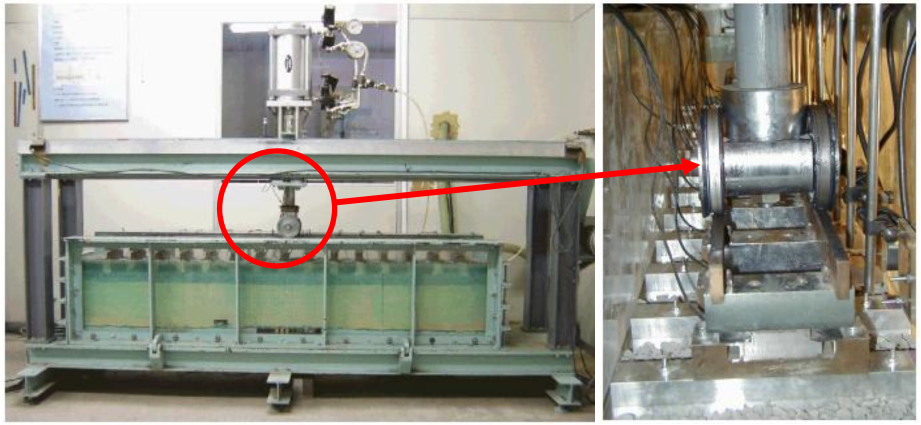


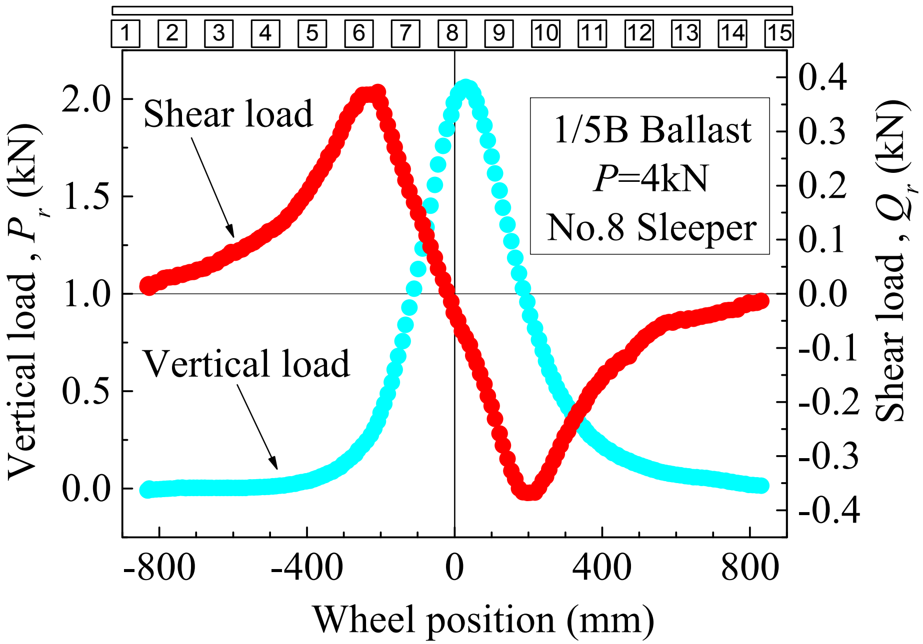


Moving wheel loads give a large residual settlement as compared with fixed-point cyclic loads.

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

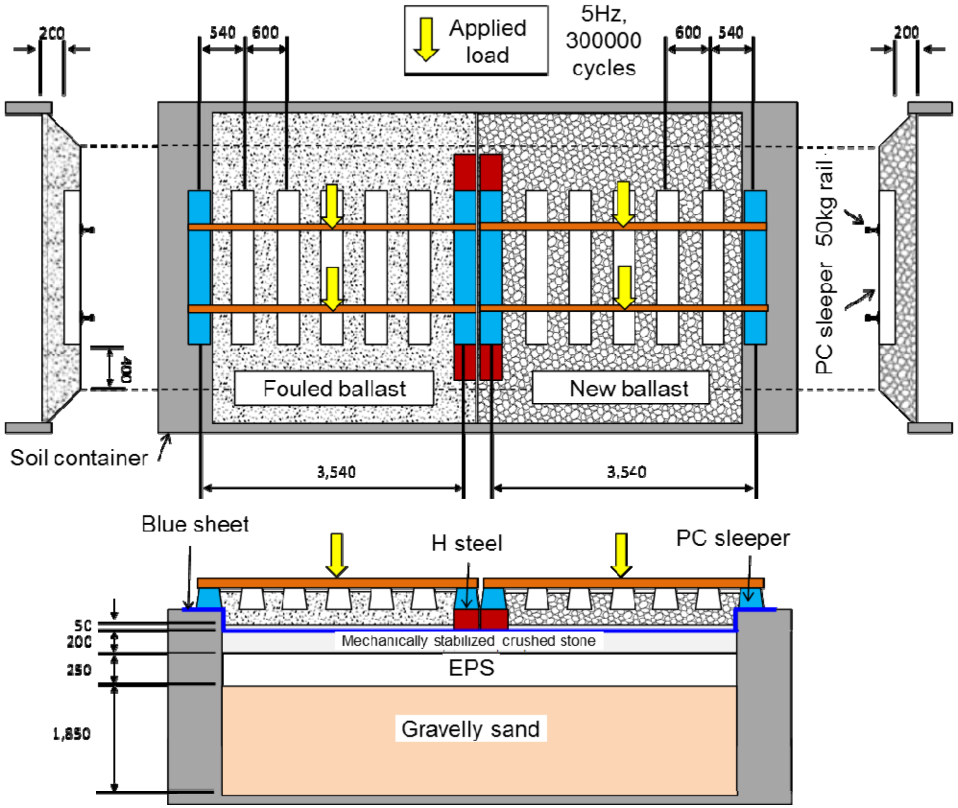
Literature Review

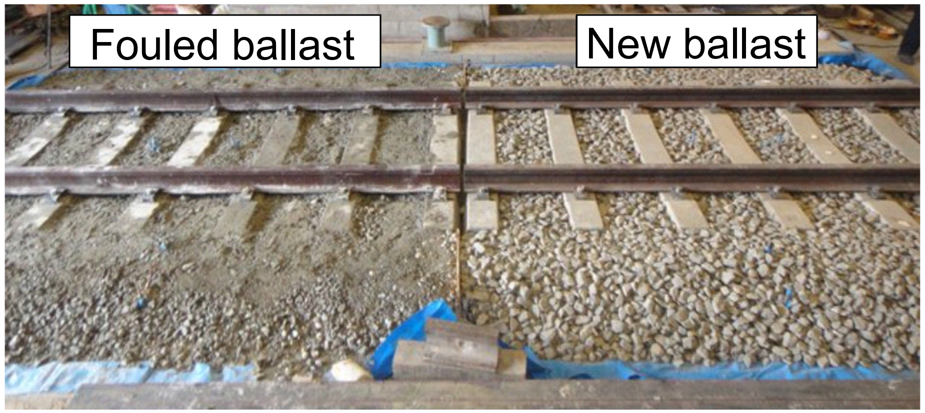
- In past studies, model and element tests have been performed mainly under air-dried condition.
- Deformation modulus of coarse granular materials decreases with the increase in water content. (Coronado et al. 2005, Ekblad & Isacsson 2006)

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).

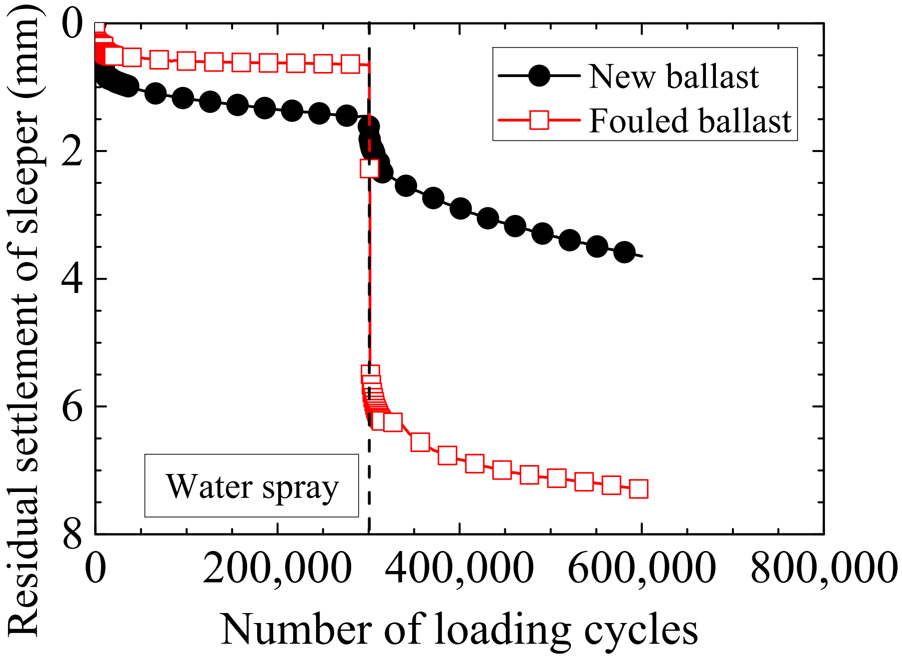




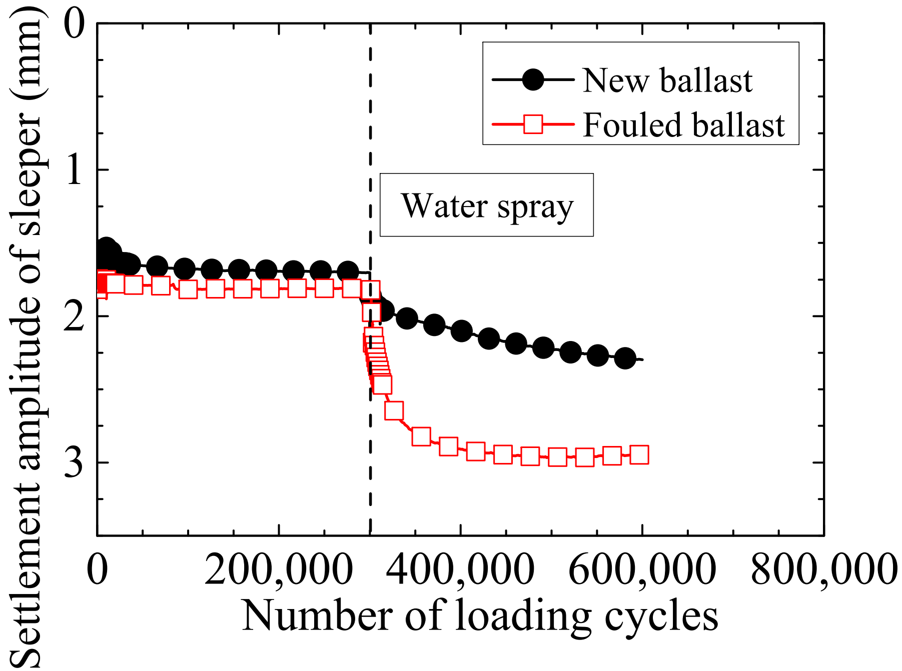
Full-scale model test

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.

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Objectives of Research

KEY POINTS

- **Are results obtained from conventional loading tests credible ?**
- **How about effects of water content in moving loading tests ?**

Research objective

- **To evaluate the effects of water content on the mechanical behavior of granular materials subjected to moving wheel loads in terms of the cyclic deformation characteristics.**

Research content

- Multi-ring shear tests of gravels and sand under various degrees of saturation.
  - Fixed-point loading without principal stress axis rotation (FL)
  - Moving wheel loading with principal stress axis rotation (ML)

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Multi-ring shear test apparatus

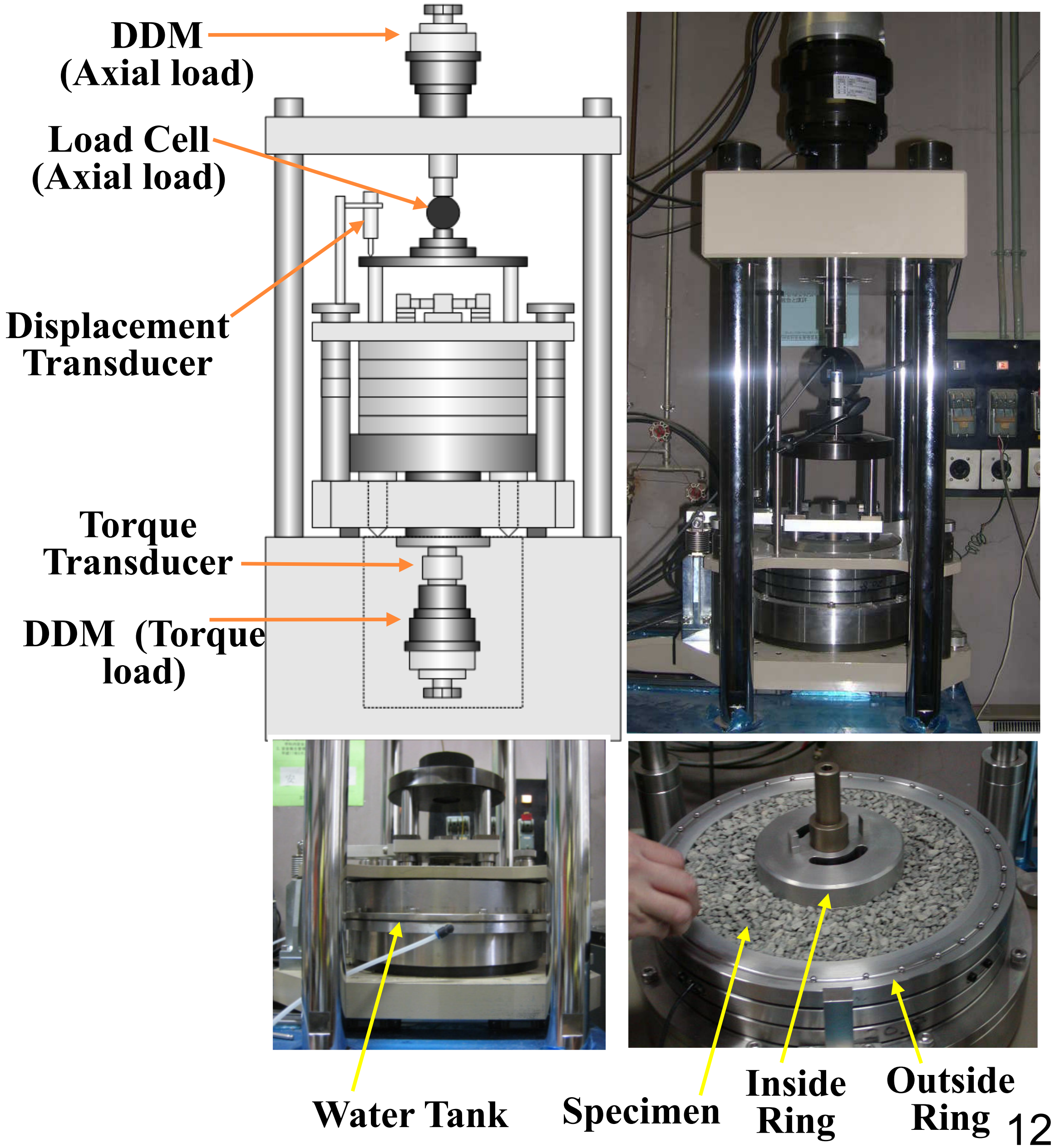
- Specimen size

  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.



Test Samples

1/5 ballast

C-9.5 gravel

Toyoura sand

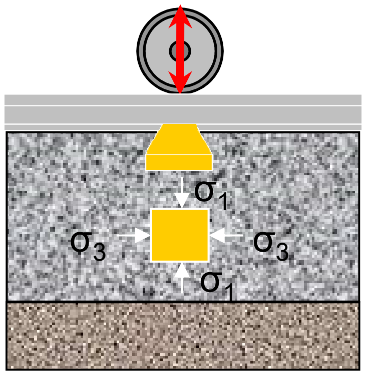
Sample	ρ_s (g/cm^3)	ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	D_{50}	U_c	$F_{cinitial}$ (%)
1/5 ballast	2.70	1.650	1.353	8.11	1.52	0.0
C-9.5 gravel	2.72	1.730	1.480	2.80	10.8	0.0
Toyoura sand	2.65	1.648	1.354	0.18	1.30	0.0

- Three 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, ballast and gravel have one-fifth and one-fourth similar grading of ballast and base course materials used in Japanese railway and road, respectively.

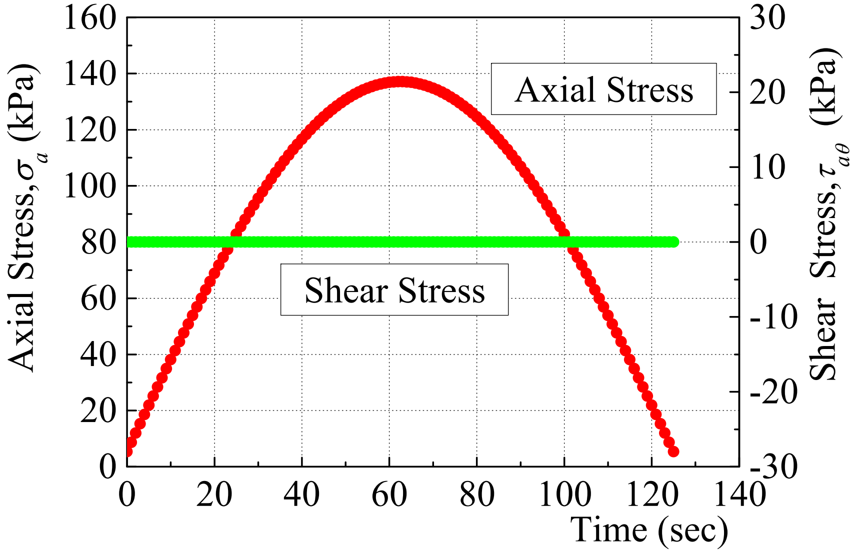
Testing Method

- 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.

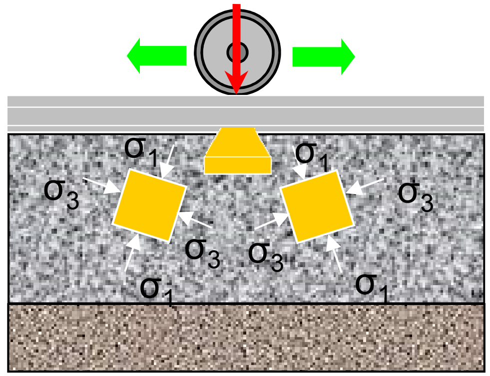
Fixed-point loading (FL)



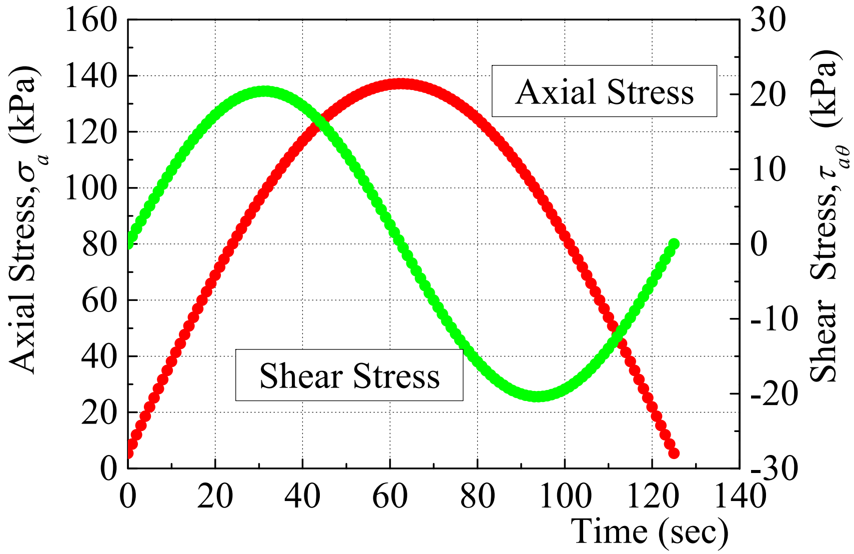
Increase & decrease of loads like triaxial compression test



Moving-wheel loading (ML)



Increase & decrease of loads with principal stress axis rotation



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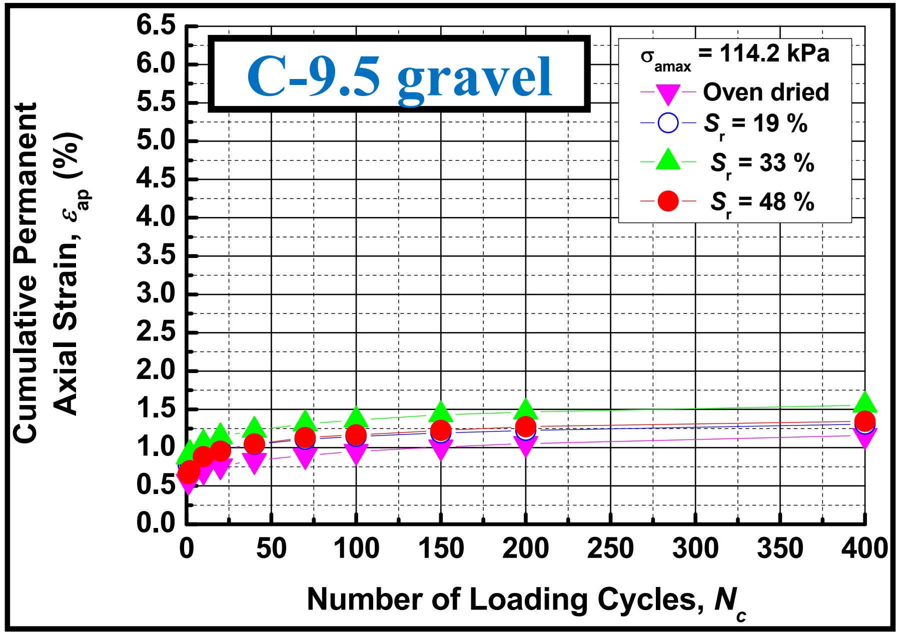
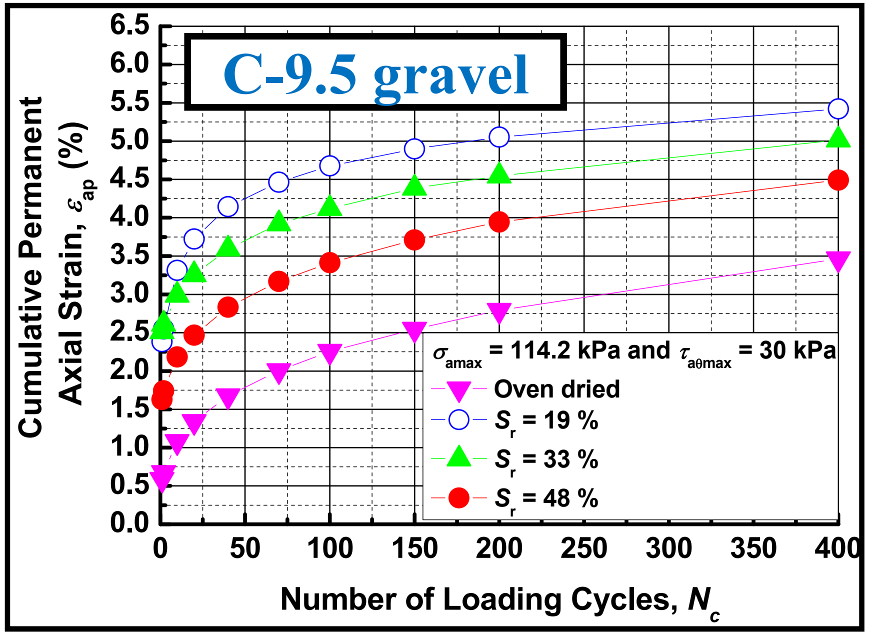
Results of cyclic loading tests (1)

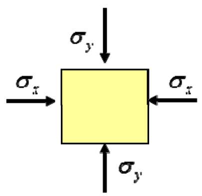
Influence of water content & loading method





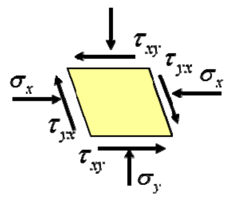
Fixed-point Loading

Increase & decrease of loads



Moving-wheel Loading

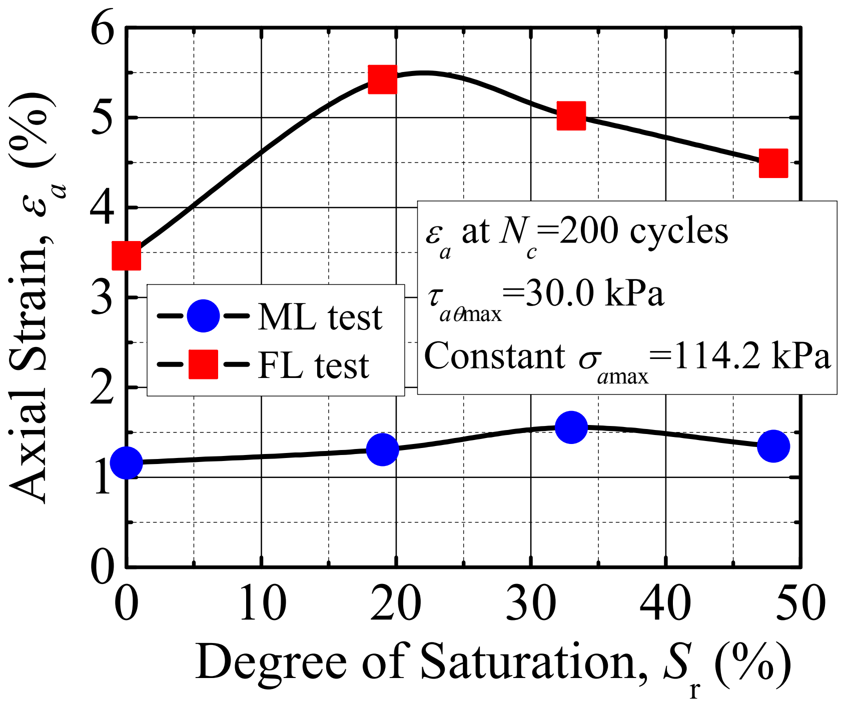
Increase & decrease of loads with principal stress axis rotation



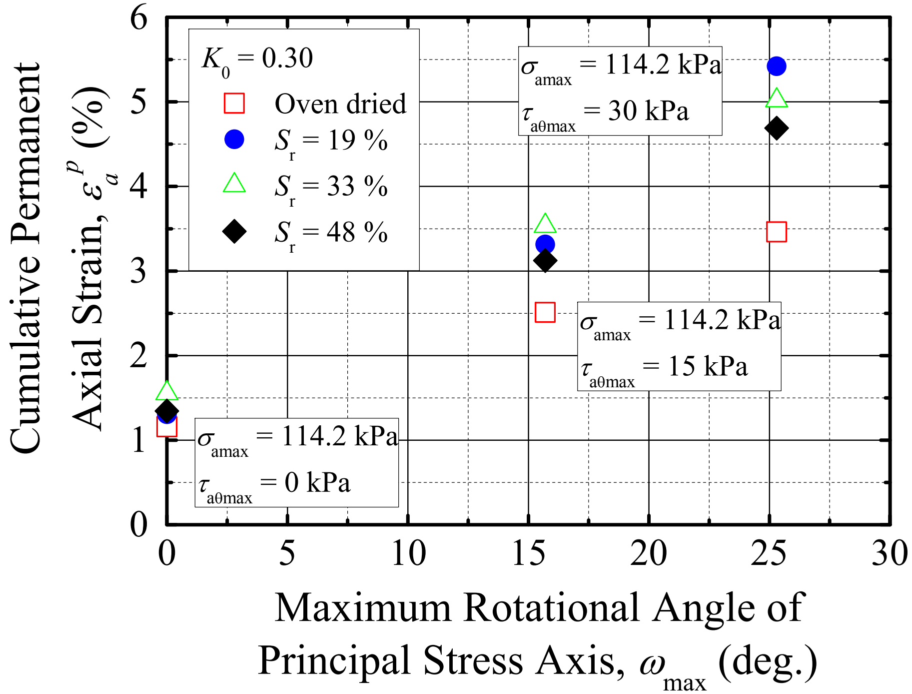
- Cyclic plastic deformation of wet gravel is more likely to increase with loading cycles than that of oven-dried gravel.
- The influence of water content on the cyclic plastic deformation for gravel appears more clearly in employing moving wheel loads.

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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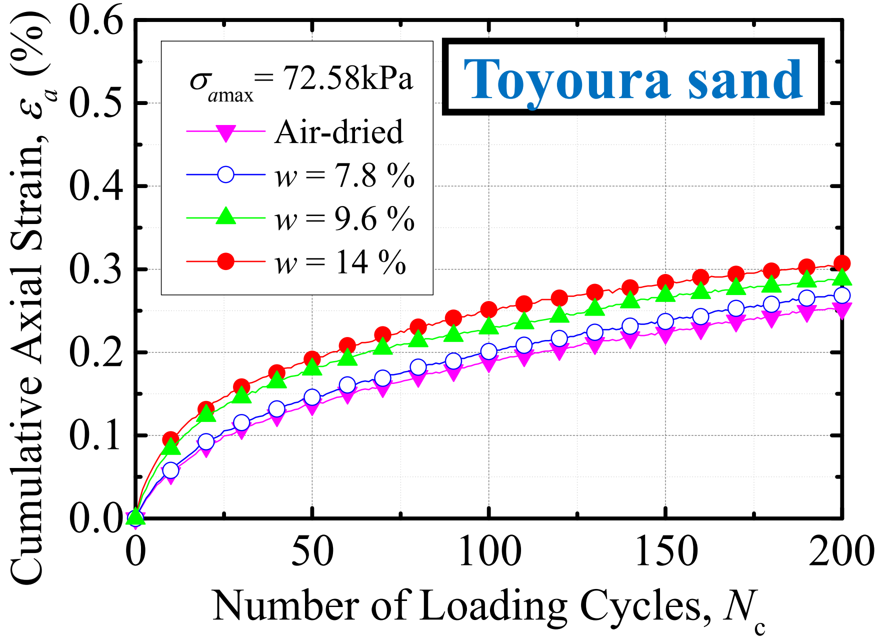
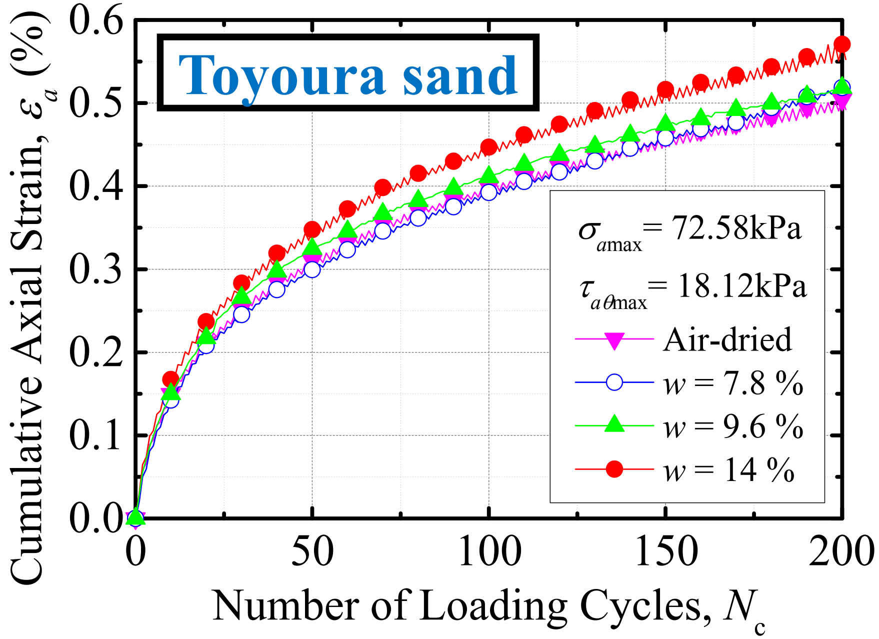
Results of cyclic loading tests (1)

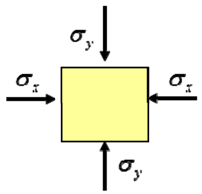
Influence of water content & loading method





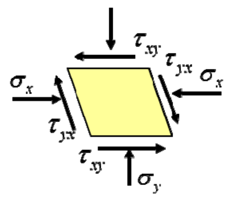
Fixed-point Loading

Increase & decrease of loads



Moving-wheel Loading

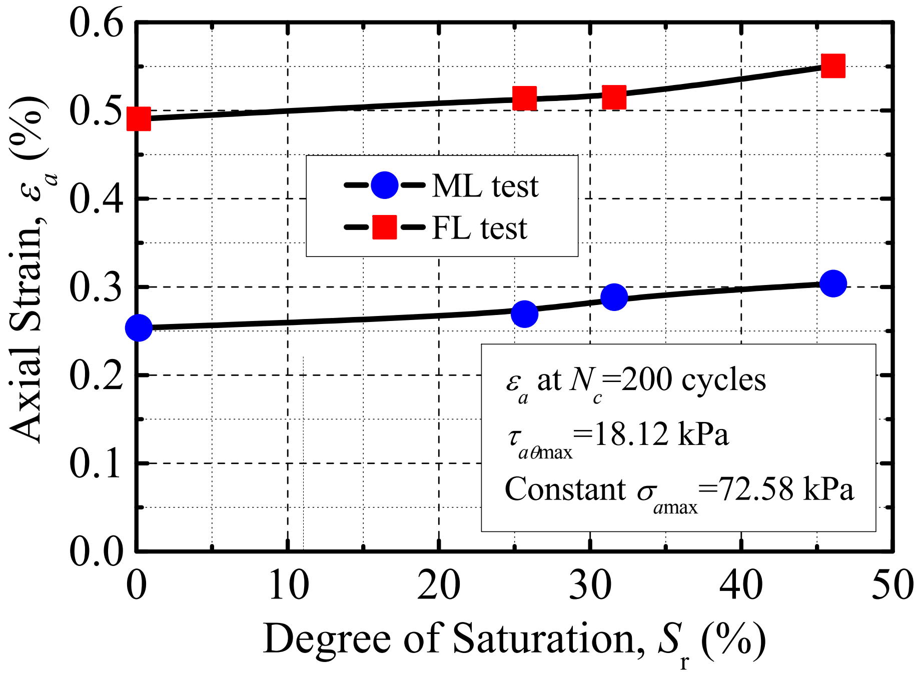
Increase & decrease of loads with principal stress axis rotation



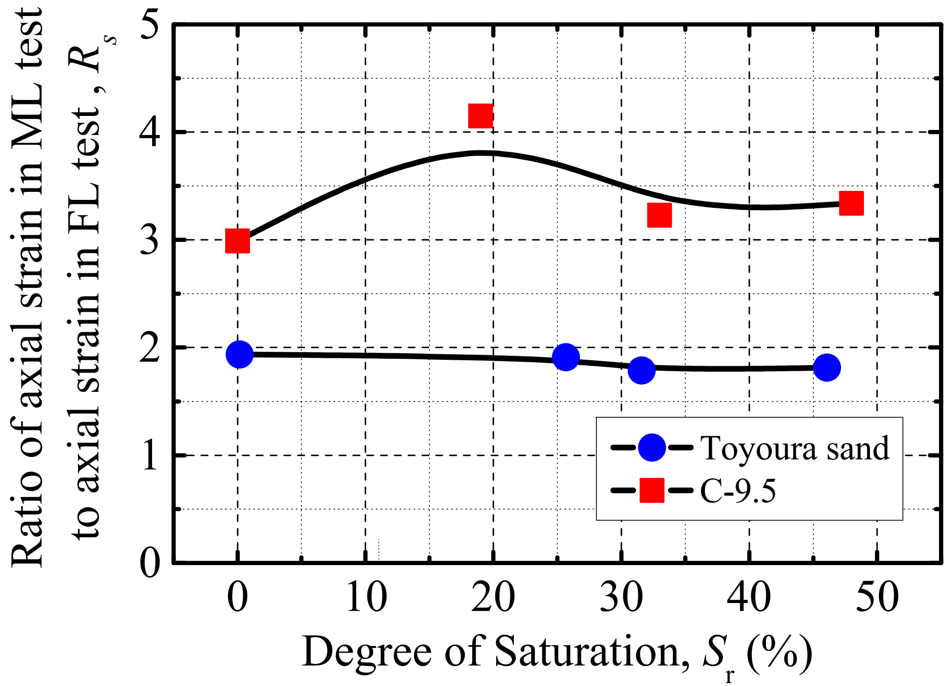
- As seen in the comparison for gravel, cyclic plastic deformation of sand in ML tests is larger than that in FL tests.
- Cyclic plastic deformation of wet sand is more likely to increase with loading cycles than that of air-dried sand.

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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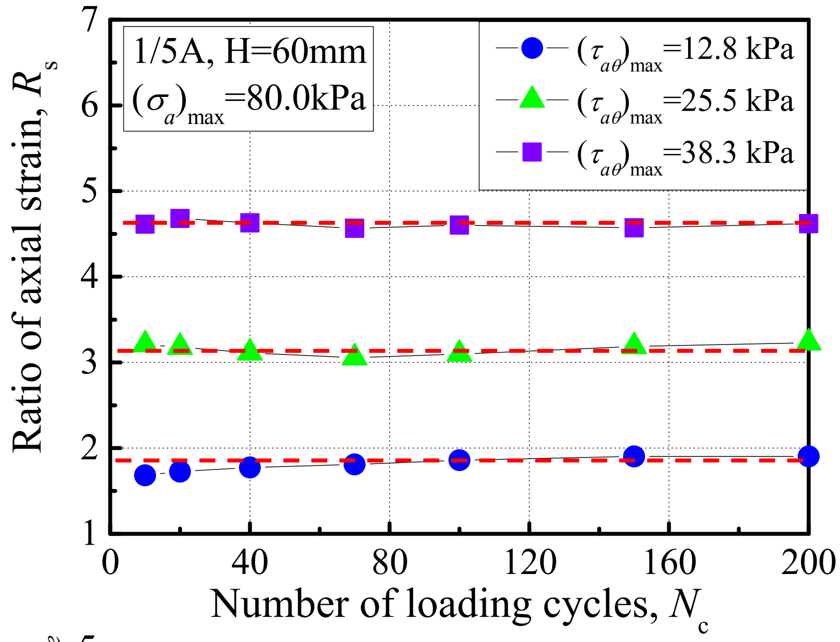
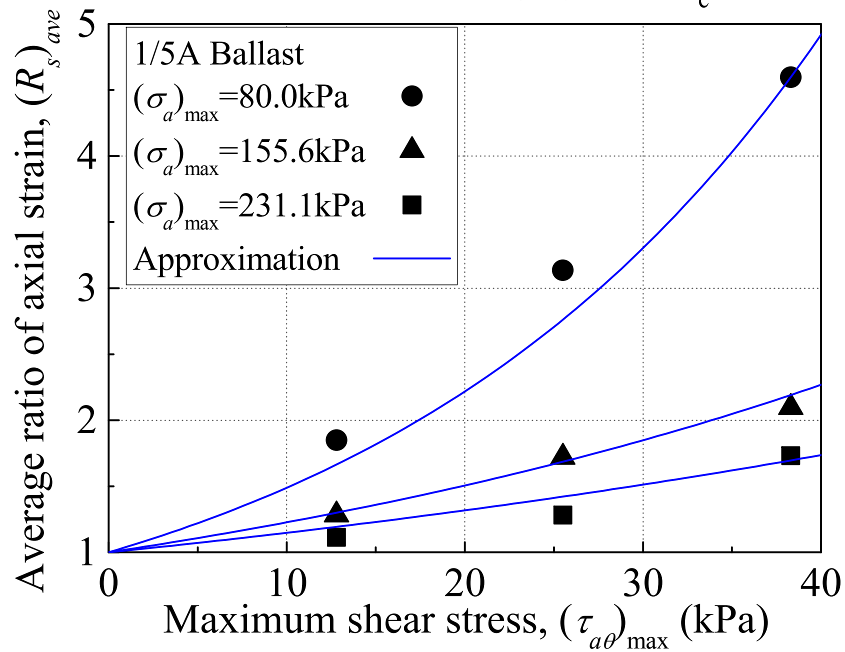
Effect of principal stress axis rotation





- Ratio of axial strain R_s is defined as a ratio of axial strain in ML test ε_a^{ML} to the one in FL test ε_a^{FL} as;

$$R_s = \frac{\varepsilon_a^{ML}(N_c)}{\varepsilon_a^{FL}(N_c)}$$

- R_s is almost constant throughout cyclic loading, regardless of loading conditions.
- Average R_s increases with the decrease in $(\sigma_a)_{max}$ or with the increase in $(\tau_{a\theta})_{max}$.
- Effects of principal stress axis rotation can be expressed by the ratio of axial strain R_{save} given by

$$\boxed{R_{s\,ave} = \exp\left(a \frac{(\tau_{a\theta})_{max}}{(\sigma_a)_{max}} \right)}$$

Proposal of Experimental Formula

Assumptions

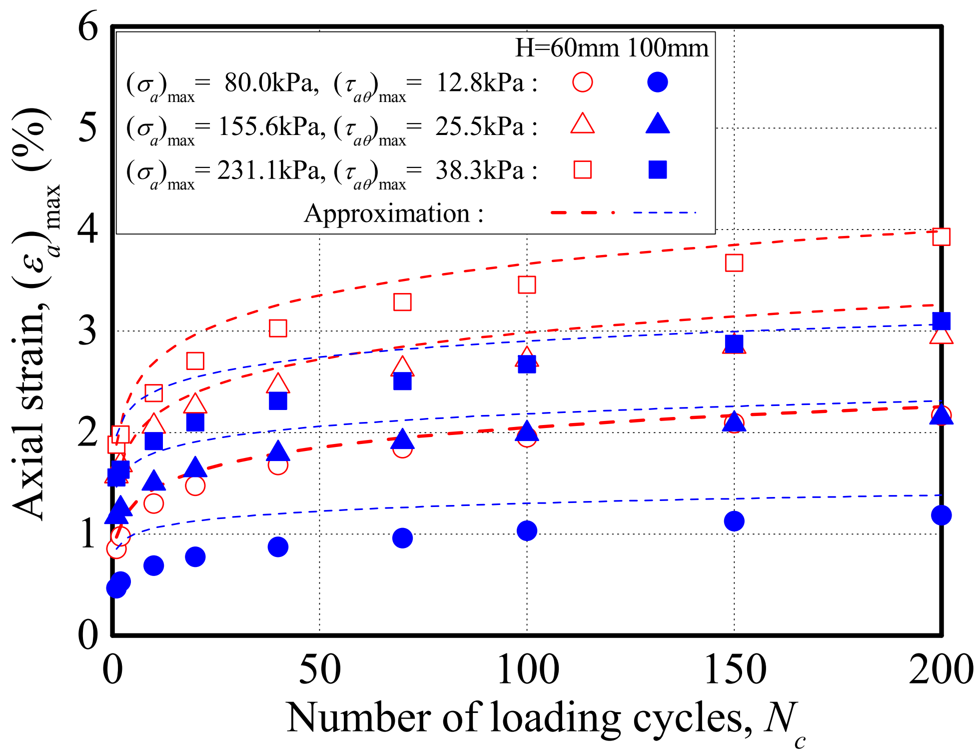
Under the same experimental conditions, cumulative axial strain in ML test can be estimated from cumulative axial strain of FL test by using average R_s as follows.

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

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

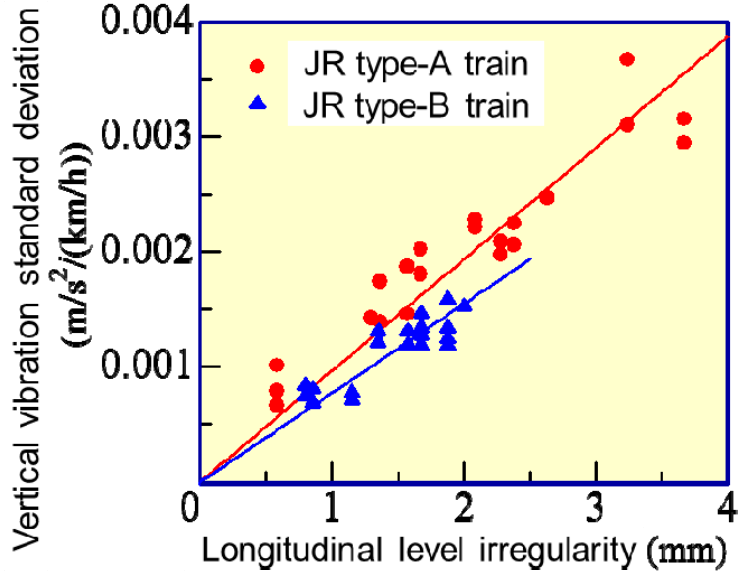
Design criteria of ballasted track

- 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

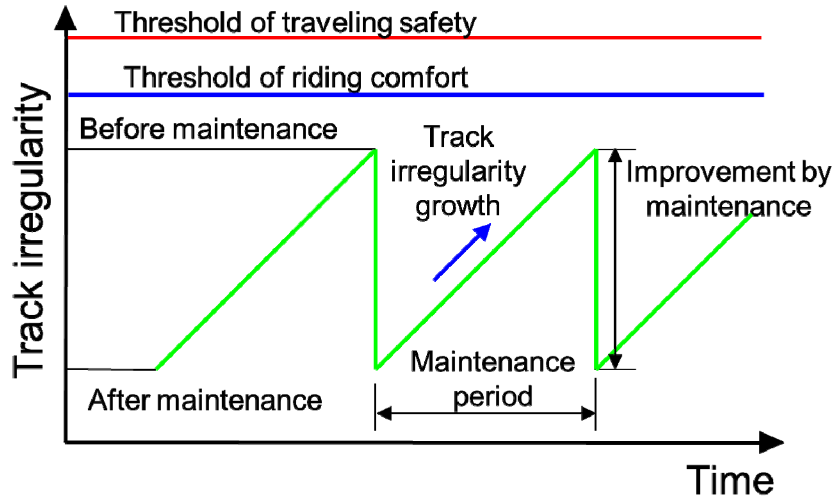
$$\alpha = a \cdot V \cdot \sigma$$

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

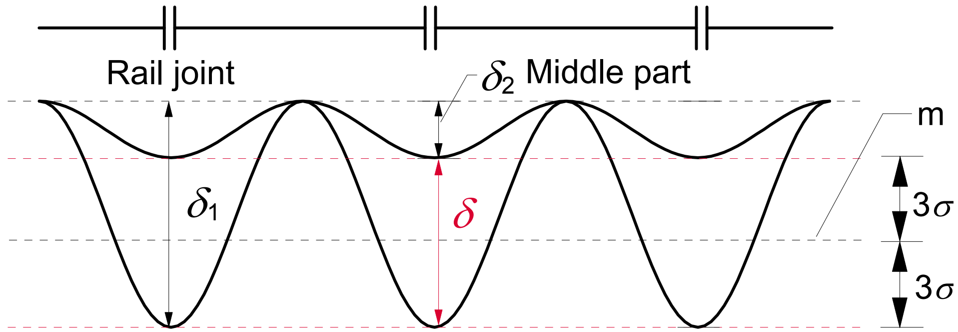
Design procedures of ballasted track

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

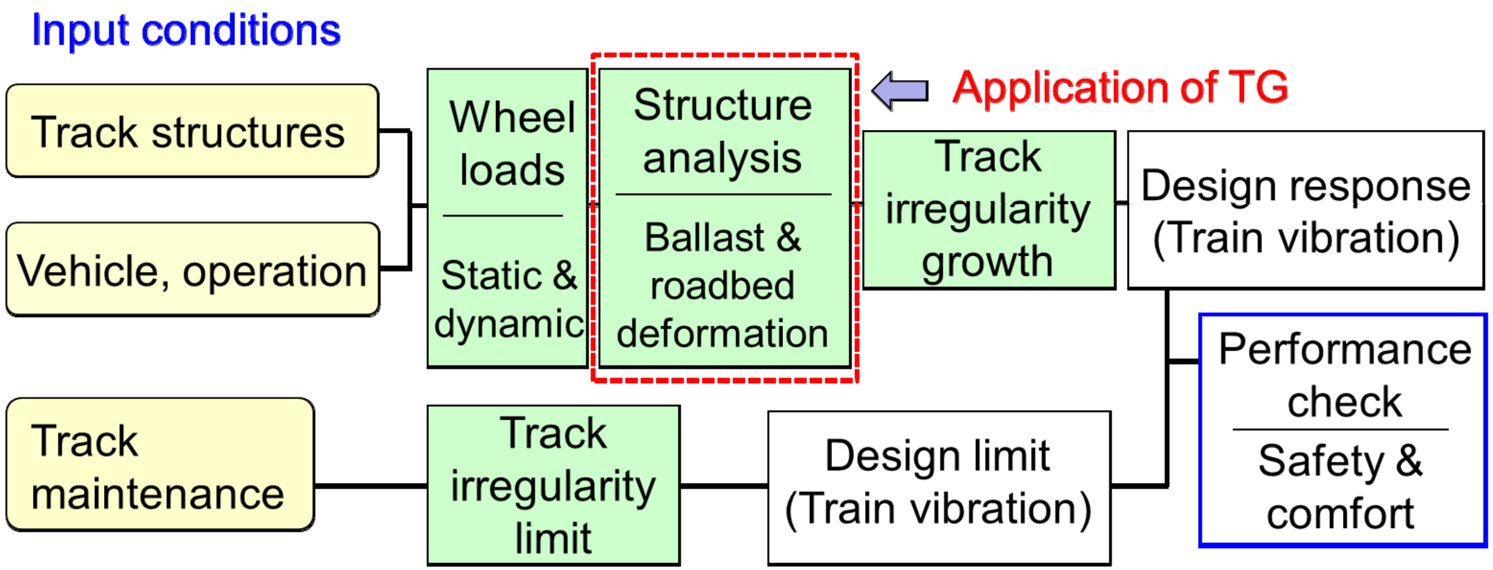
Assumption

- 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

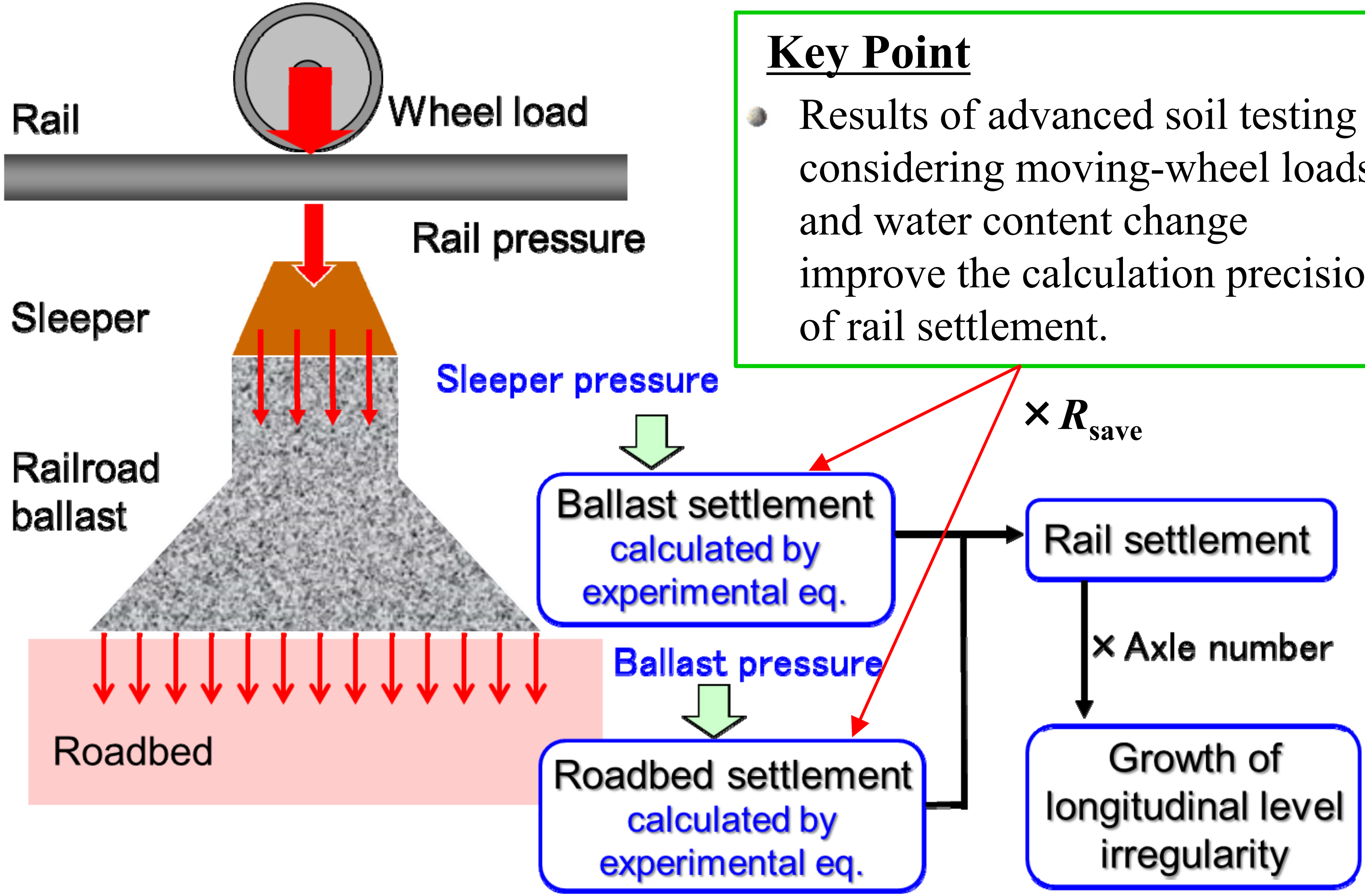


Flow of design procedures for ballasted track

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

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Concluding Remarks

- The synergistic effects of principal stress axis rotation and water content strongly influence cyclic plastic deformation of coarse granular materials.
- Under the same experimental conditions, cumulative axial strain obtained from moving-wheel loading test can be estimated from that of fixed-point loading test by considering the effects of principal stress axis rotation and water content.

⇩

- When developing a rational design standard of ballasted track 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, and principal stress axis rotation on the deformation-strength characteristics of granular materials.

Thank You for Your Kind Attention