The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering (15ARC)

Model tests and numerical analysis on flow-outs of railway ballasts induced by flood inundation

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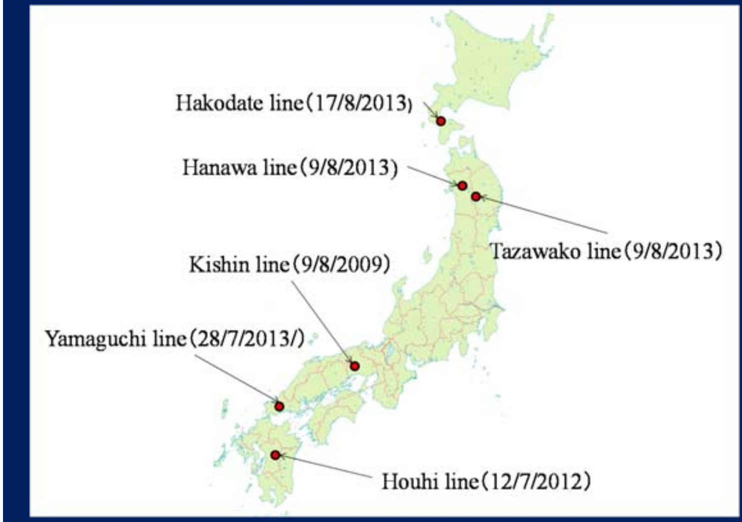
Background

Recently in Japan, railway ballasts have been flown out at several locations by heavy or intense rainfalls.



Locations flow-out of railway ballasts recently observed.

Kishin line, 2009

Yamaguchi line, 2013

Hakodate line, 2013

However, the flow-out mechanism has not yet been investigated in detail, so that the risk and the countermeasures cannot be reasonably proposed.

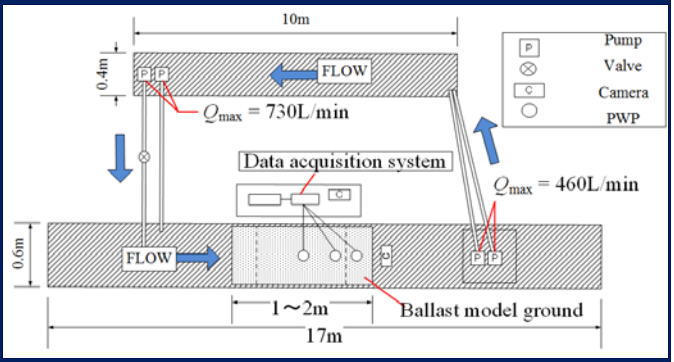
Objective

Therefore, in this research, **model tests and numerical analyses** were conducted to fundamentally investigate the flow-out mechanism.

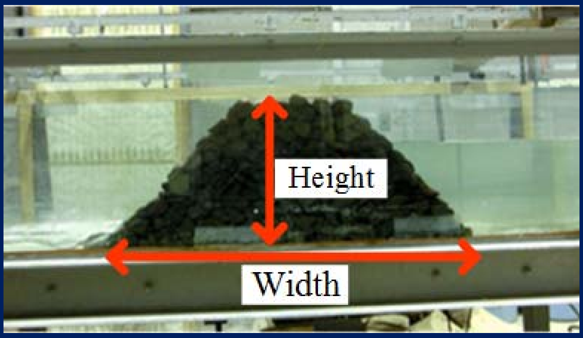
Model test apparatus

The apparatus was consisted of three components.

1. **Water flow circulation system** consisting of two water channels and several hydraulic pumps.
2. **Ballast beds** constructed in a water channel.
3. **Data acquisition system** by which water pressures and deformations of ballast beds were measured.



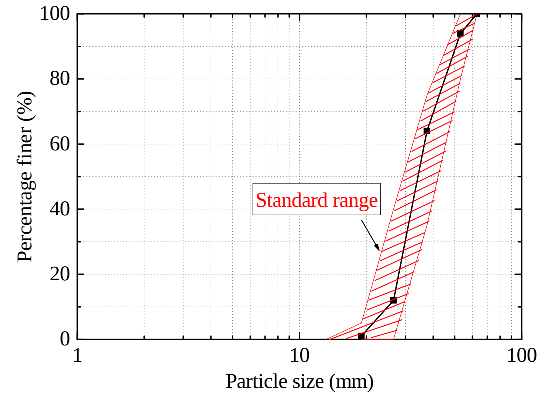
Plan view of hydraulic experiment apparatus



Ballast model ground

Model ground conditions and methodology

Railway ballasts which were crushed andesite were used for preparation of model grounds.
The model tests were conducted four times, which were named as case A through D. All the ballast beds were compacted to achieve the dry density 1.60g/cm³.

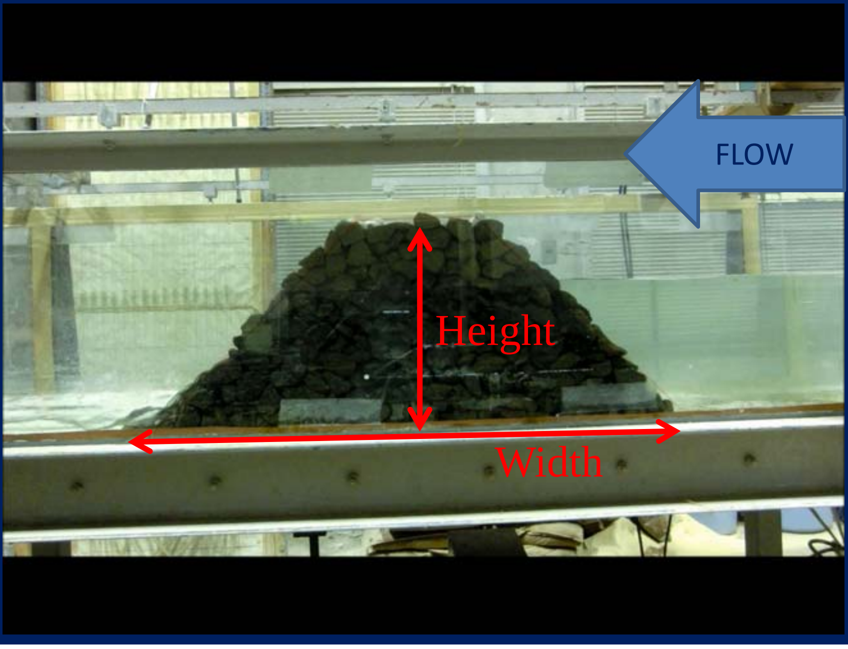


PSD of ballasts

Model ground conditions

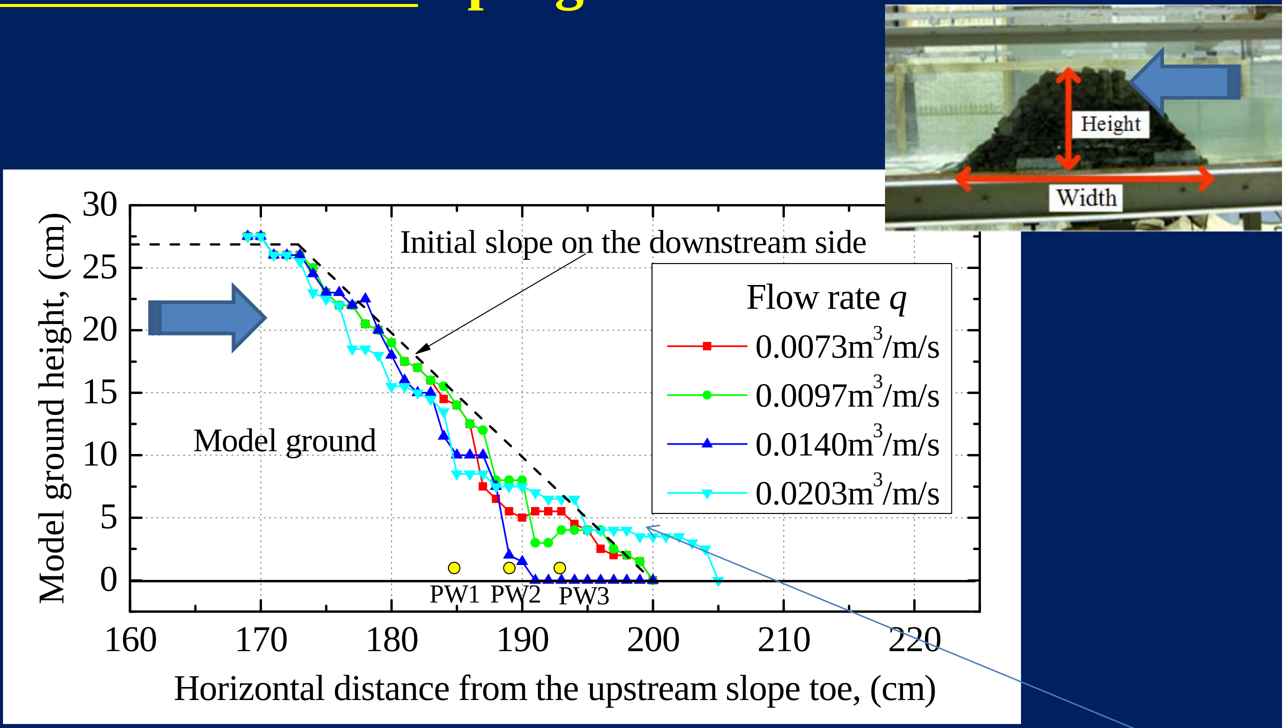
	Width	Height	Length	Dry density	Porosity	Slope angle
caseA	1.00m	0.39m	0.6m	$1.60 g/cm^3$	0.41	45° (1 : 1)
caseB	1.20m	0.25m				
caseC						
caseD	2.00m					

In each case, after the steady state flow was achieved, **upstream and downstream side water levels** of the ballast bed were measured as well as **pore water pressures** inside the bed. **Change of slope shape of the bed** was also measured at the downstream side. Then. the water flow rate was stepwise increased up to predetermined levels. At each flow rate level, the data acquirements were repeated.



Case A

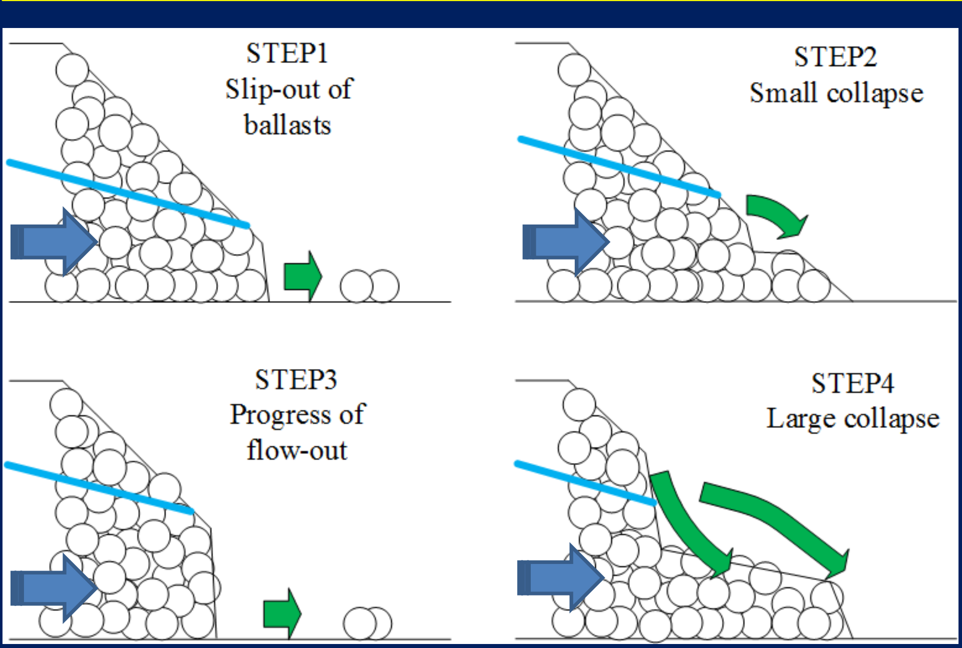
Model test results - progressive failure -



The slope shape was gradually changed with the increase of the flow rate *q*.

Change of slope surface profiles at the downstream side (Case D)

First, a few number of ballasts were slipped-out from the bed (STEP1). Then, a small slope collapse occurred (STEP2). The collapse deposited several ballasts near the slope toe. The deposited ballasts were washed out with the increase of the flow rate, resulting in appearance of a steep slope (STEP3). Subsequently, a large slope collapse occurred because of the lack of overall stability (STEP4).



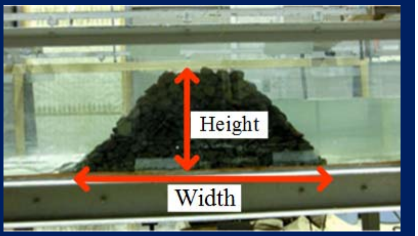
Schematic image of the progressive slope failure

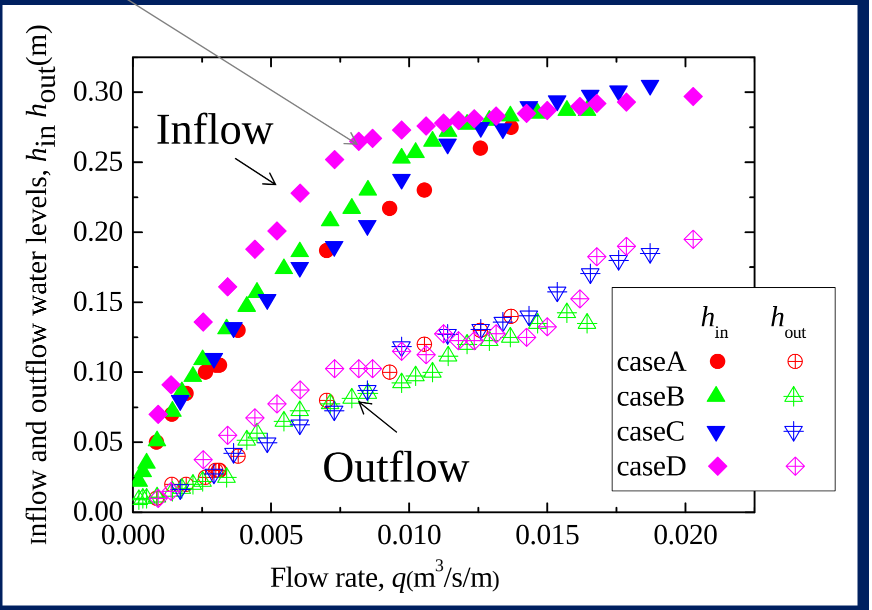
Seepage characteristics

Model ground conditions

	Width	Height	Length	Dry density	Porosity	Slope angle
caseA	1.00m	0.39m	0.6m	1.60g/cm^3	0.41	45° (1 : 1)
caseB	1.20m	0.25m				
caseC						
caseD	2.00m					

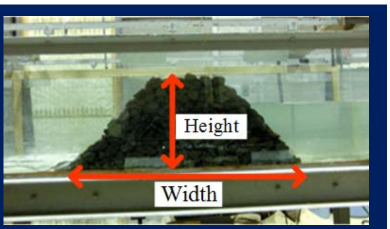
With the increase of q, h_{in} became higher. This trend was more significantly observed in case D, because the seepage distance was longer and the overall hydraulic gradient was lower owing to the wider bed.





Inflow and outflow water levels against flow rate

Relationships U_{ave} - i_{ave} were not linear so that they could not be represented by the Darcy’s law. The relationships were well represented by the Forchheimer’s law.

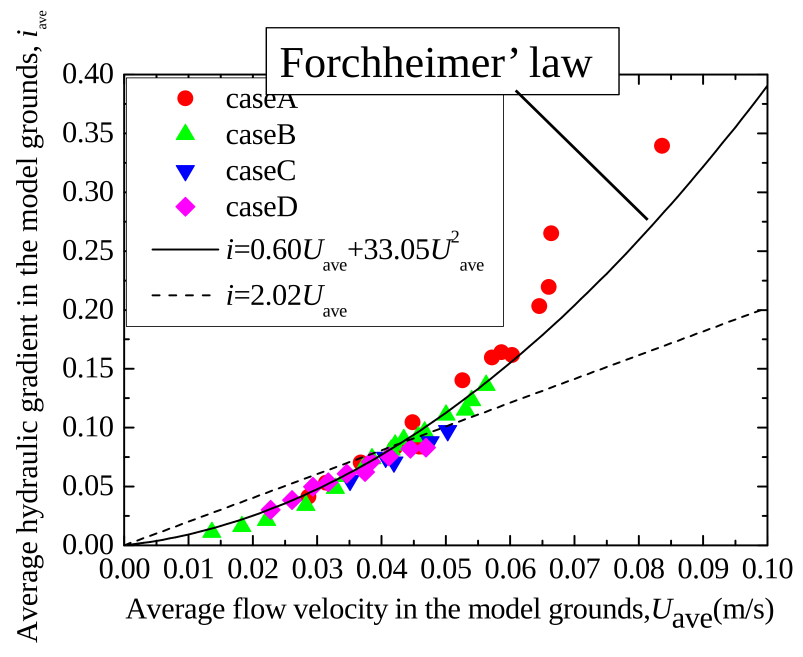


Average velocity

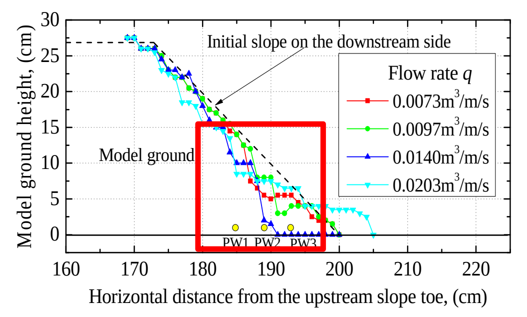
$$U_{ave} = \frac{2q}{h_{in} + h_{out}}$$

Average hydraulic gradient

$$i_{ave} = \frac{h_{in} - h_{out}}{L - 1/2\left(h_{in} + h_{out}\right)}$$

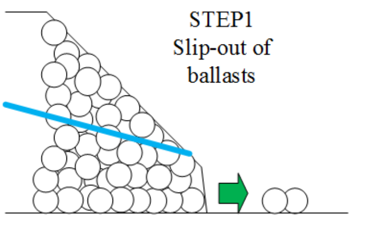


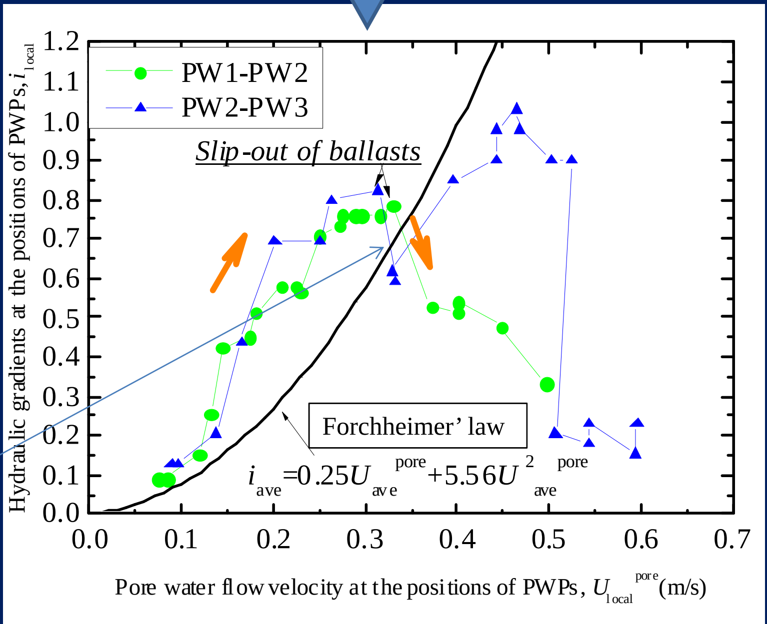
Average hydraulic gradient against average flow velocity till overflow was observed .



Based on measurements, pore fluid velocities U_{local}^{pore} and hydraulic gradients i_{local} near the slope toe were calculated.

The relationships between U_{local}^{pore} and i_{local} were also nonlinear. Rapid reduction of i_{local} observed represents that the permeability of the ballast bed suddenly became higher, indicating **the occurrence of the slip-out of ballasts**.





Local hydraulic gradient against pore water flow velocity near the downstream slope toe

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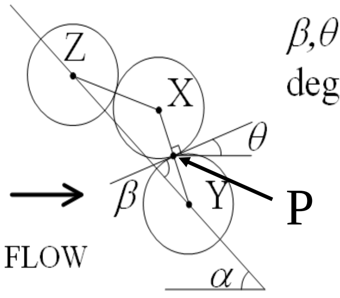
Micro mechanic model for prediction of slip-out of ballasts

Analyses were attempted to investigate the slip-out stability of ballasts with using a micro mechanic model..



β,θ : Parameters related to degree of interlocking of ballasts

Parameter values in this study

$\beta=(\beta_{max}+\beta_{min})/2=(90°+45°)/2=67.5°$

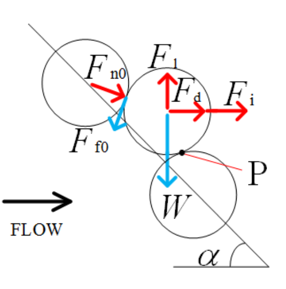
θ can be determined in consideration of $\alpha=45°$

Figure shows circular shape ballast particles X through Z along the downstream side slope. The slope angle α in the present study was 45 degrees . The safety factor F_s for the rotation of the particle X with respect to a point P was calculated.

Micro model to evaluate the stability of a ballast particle at the downstream slope surface

$$F_s = \frac{W\sin\theta + F_{f0}\left\{1+\sin\left(2\beta-90^\circ\right)\right\}}{F_d\cos\beta + F_l\sin\beta + F_i\cos\beta + F_{n0}\sin\left(90^\circ-\beta\right)}$$

(for rotation)



W: Self-weight F_l: Lift force
F_d: Drag force F_i: Seepage force
F_{n0}: Normal force induced by the upper part particle
F_{f0}: Tangential force induced by the upper part particle

$$F_d = {}^1\!/_2\,\varepsilon C_d A U_{ave}^{2\ pore}$$

$$F_l = {}^1\!/_2\,\varepsilon C_l A U_{ave}^{2\ pore}$$

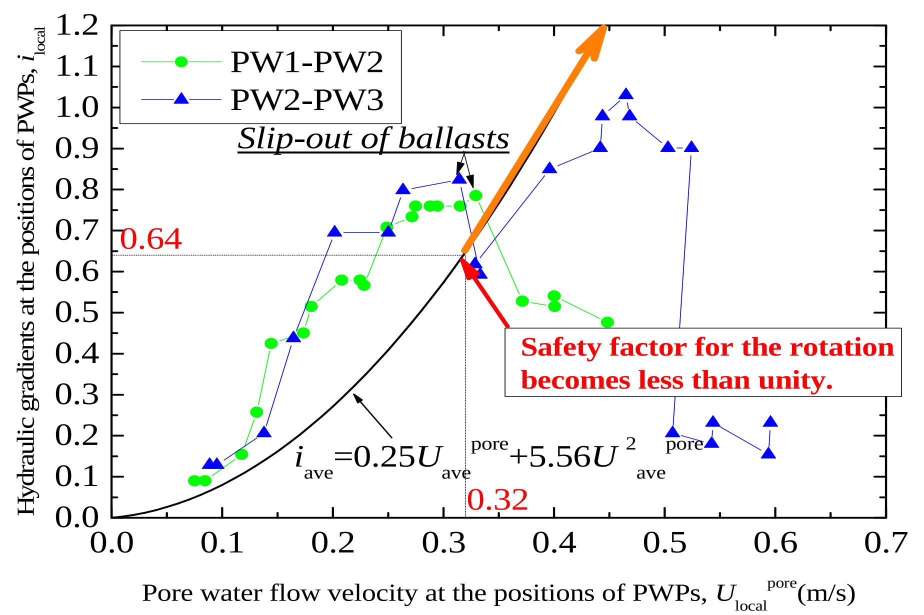
$$F_i = i_{ave}\rho_w g V = (aU_{ave}^{pore} + bU_{ave}^{2\ pore})\rho_w g V$$

$$F_{n0} = \rho_s g V\cos(180^\circ - \alpha - \beta)$$

$$F_{f0} = \mu F_{n0} \qquad V = \pi d^2/4$$

ε(=1.0), C_d(=0.5), C_l(=0.5), ρ_s(=2.71 g/cm^3), ρ_w=(1.00g/cm^3), μ(=0.5), d(=3.5cm)

Based on the micro mechanic model, the pore water flow velocities U_{ave}^{pore} where the safety factor F_s became less than 1.0 were estimated. The velocities when the slip-outs were observed in the experiments are close to *the calculated velocities*.



Hydraulic gradient and pore water flow velocity which gives the unstable state for the particle in the micro-mechanic model.

Conclusions

Model tests and numerical analyses were conducted to fundamentally investigate railway ballast flow-out mechanisms when heavy or intense rainfalls occur. As the results, the following findings were obtained.

- The ballast beds collapse progressively, which are triggered by the slip-out of a few numbers of ballasts at the downstream side slope.
- Permeability characteristics of the ballast beds are well understood by the Forchheimer’s law rather than Darcy’s law.
- The comparison between the model test results and the analytical results indicate that the flow velocity required for the slip-out can be reasonably explained by the proposed micro-mechanic approach.