PHYSICAL MODEL TESTS ON SLOPE DESTABILIZATION INDUCED BY INTERNAL EROSION

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Background

Suffusion

- Due to transport and migration, under the action of flow, of particles constituting the soil within the soil structure(***Bendahmane*** et al. 2008)

- Suffusion has implications with valley fill in catchment topography as well as hydraulic structure (i.e. clogging)

However

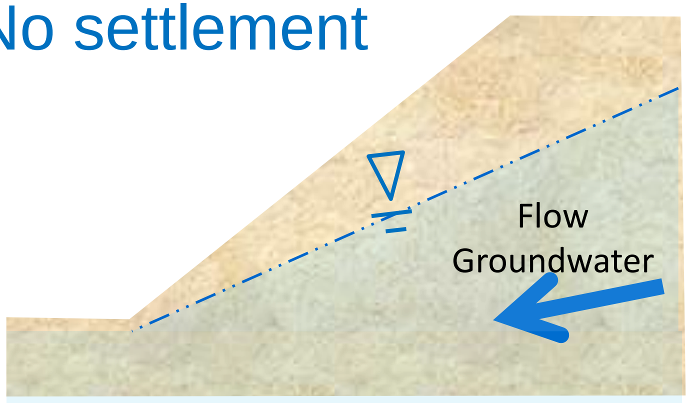
- observation report of phenomenon of suffusion is very rare because it is difficult to examine degradation of soils inside fill

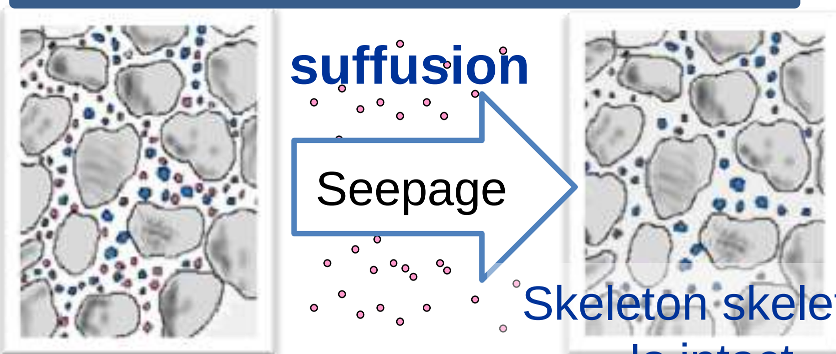
- the mechanisms of suffusion are not well understood

Objectives

Objectives

No settlement





Objectives of this study are

1. To reproduce suffusion phenomenon in physical model in the laboratory

2.To identify the key parameters governing suffusion

3.To demonstrate suffusion-induced deterioration in stability of soil structures

Method

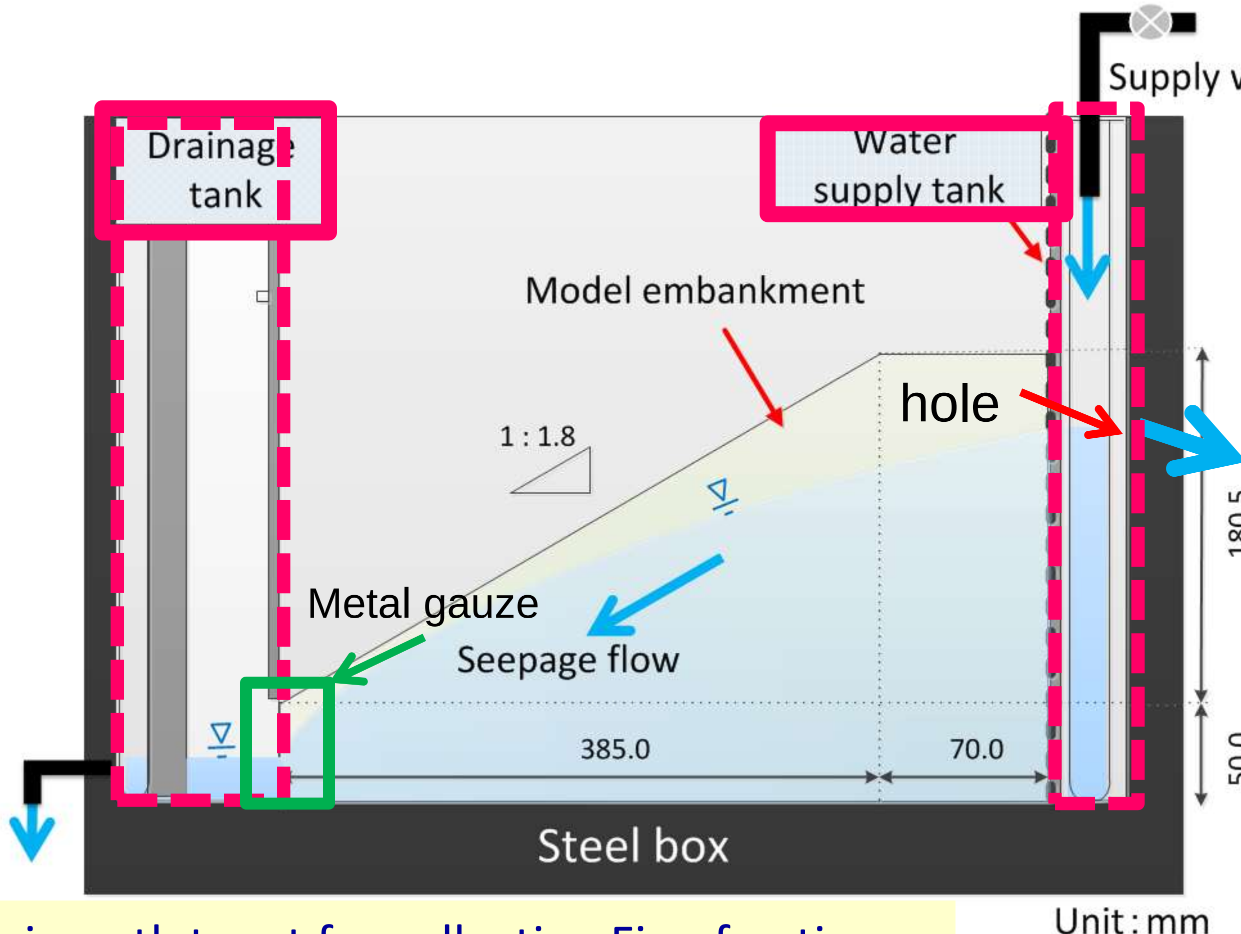
In this study, I performed a series of

- Seepage tests on the small-scaled levees
- Bearing capacity tests on levees

Test setup

Test setup

Experiment system (seepage test)



Vertical sidewalls between the tank and embankment model provide a metal gauze so that only water and fine fraction can flow through

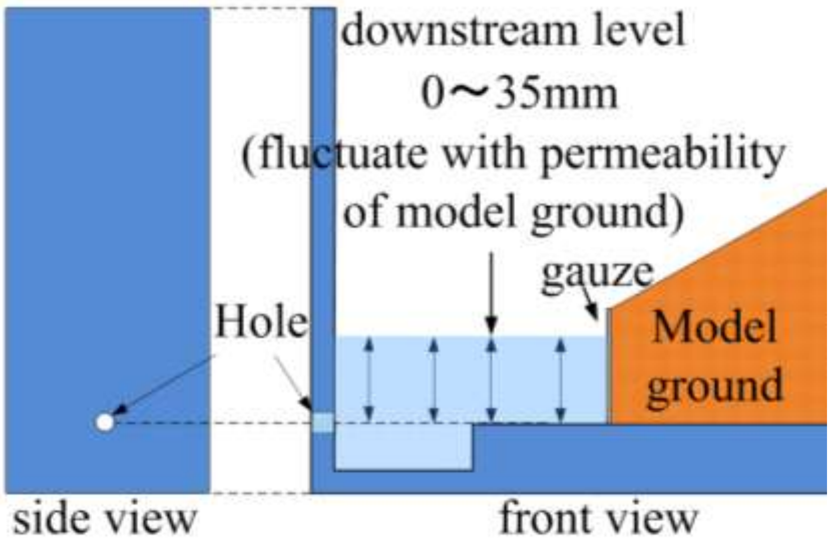
Drain outlet, net for collecting Fine fraction

By pouring the water in the water supply tank, seepage flow can be given to the model ground

Test setup

Experiment system (seepage test)

Boundary condition at the downstream

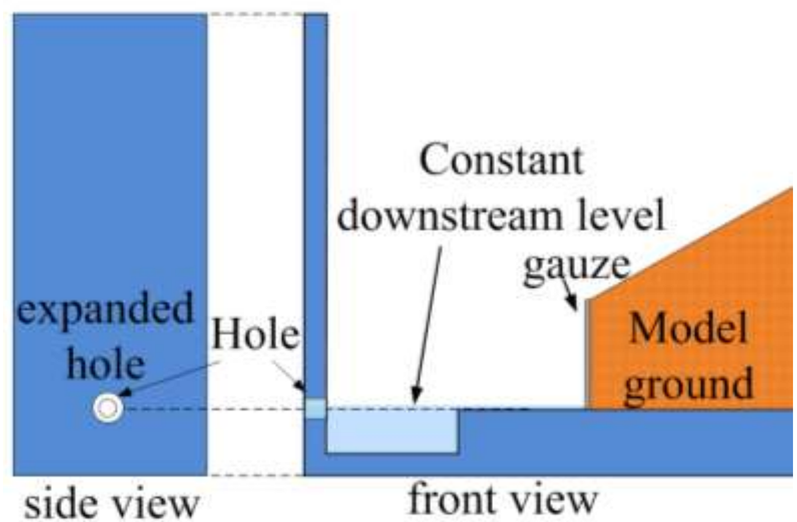


Type A

The water level is set at a height of 35mm from the bottom

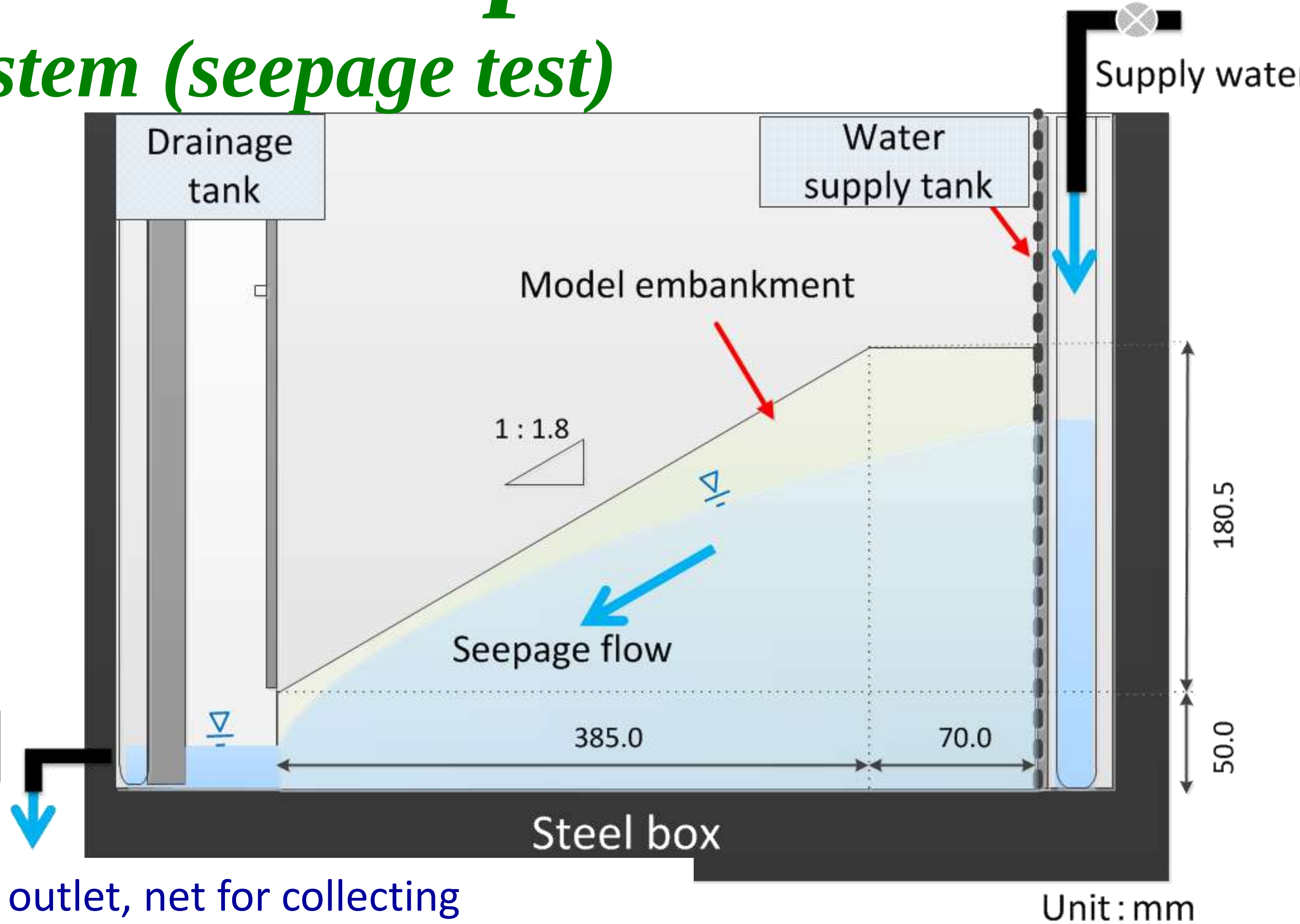
Type B

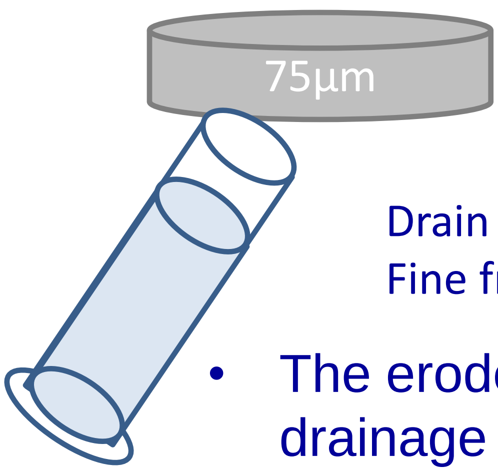
The water level is set at the bottom



Test setup

Experiment system (seepage test)



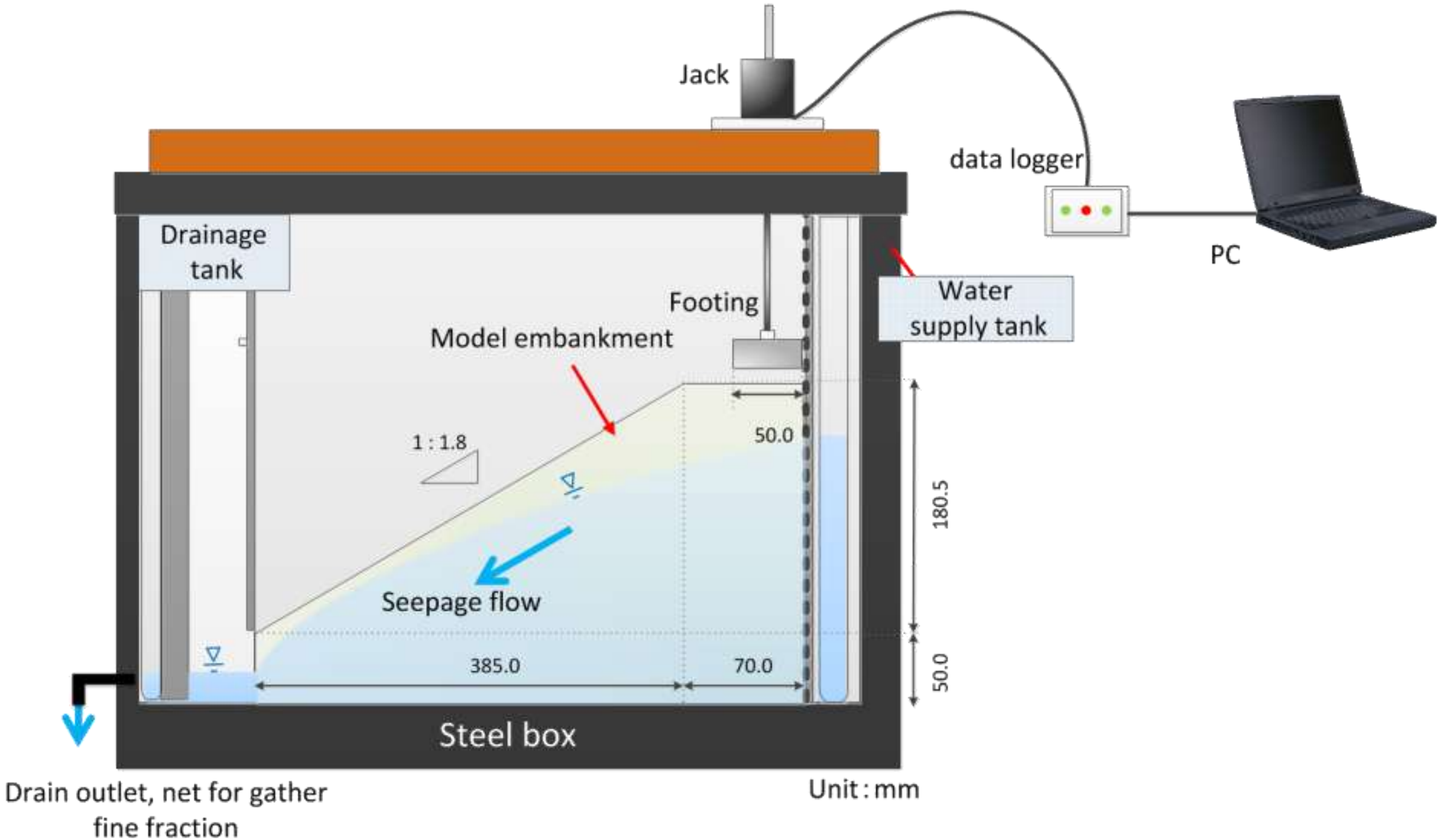


Drain outlet, net for collecting
Fine fraction

- The eroded fine fraction is collected at the outlet from the drainage tank by sieve whose opening is 0.075mm
- Flow rate and amount of eroded soil are regularly measured during the experiment.

Test setup

Experiment system (Bearing Capacity)



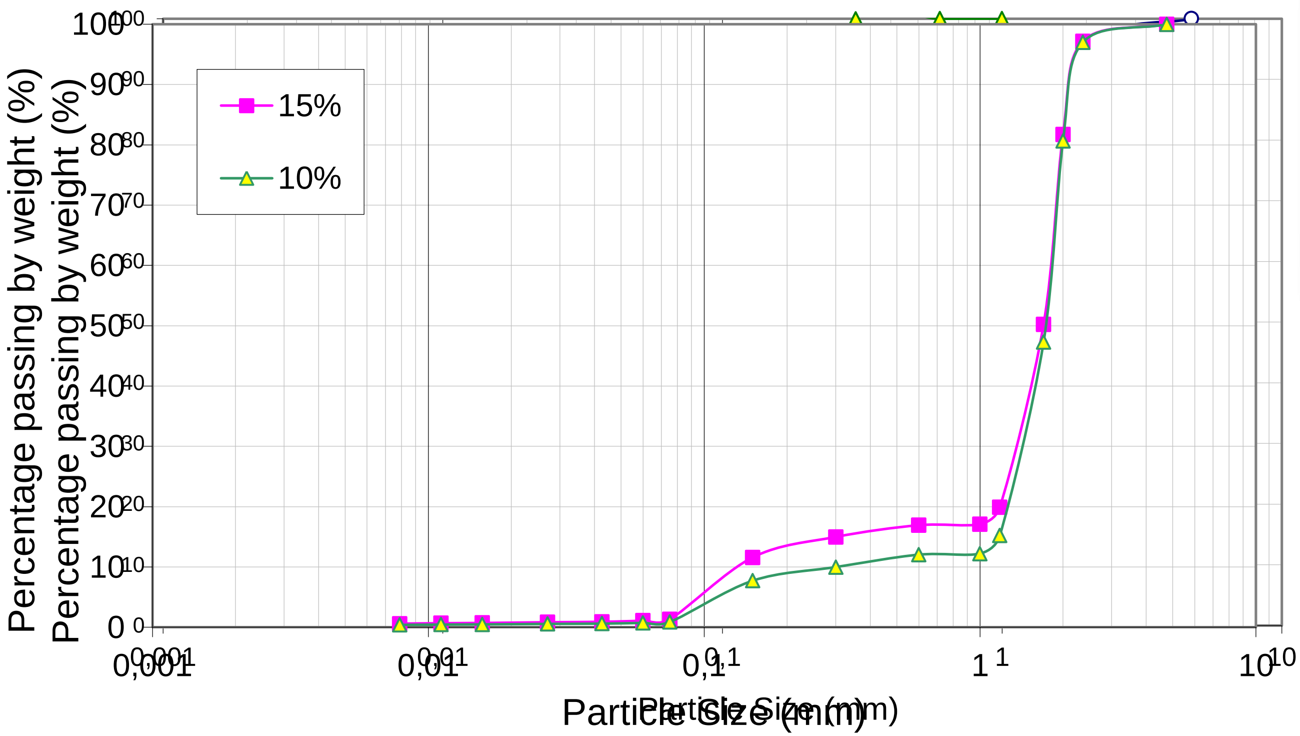
Test Conditions

Test setup

Soil materials

To cause suffusion easily, the mixture of the Silica No. 3 and Silica No. 8 are used as model materials

one contents10%, the other content 15% of silica No.8



Grain size distribution

Sample	Φ’	k
10	47.63	
15	44.31	1.844 mm/sec

Dr=30%

※Although Silica No. 8 sand is not categorized as fine fraction in the Japanese Industrial Standards, in this research it is considered as fine fraction due to the grain size of Silica No. 8 is relatively finer than Silica No. 3 sand that forms the soil skeleton.

Test case

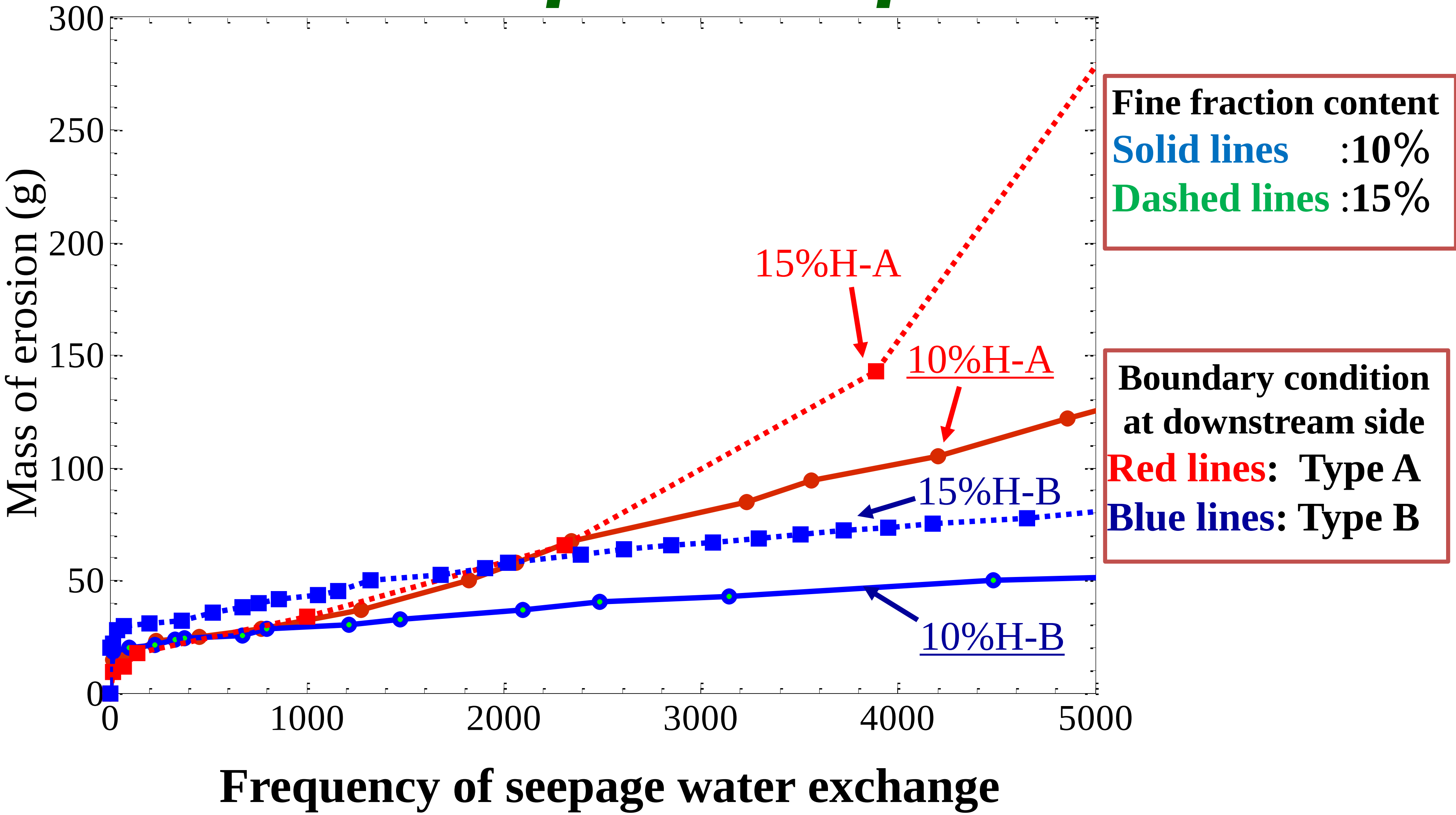
Four test cases are conducted with different fine content and the drainage condition at the downstream side

Case		Content of Silica sand No.8 (%)	Boundary condition of levee toe	Minimum density g/cm3	Dry density g/cm3	Seepage time (min)
10%-A	Initial	10	A	1.543	1.535	30
	10140	10	A	1.543	1.535	10140
10%-B	Initial	10	B	1.543	1.549	30
	5760	10	B	1.543	1.554	5760
	22850	10	B	1.543	1.544	22850
15%-A	Initial	15	A	1.567	1.588	30
	11710	15	A	1.567	1.603	11710
15%-B	Initial	15	B	1.567	1.551	30
	20670	15	B	1.567	1.558	20670

- The first part of the test code denotes the amount of fines
- The second part denotes the type of the boundary condition at the downstream

Test Results

Result of mass of erosion

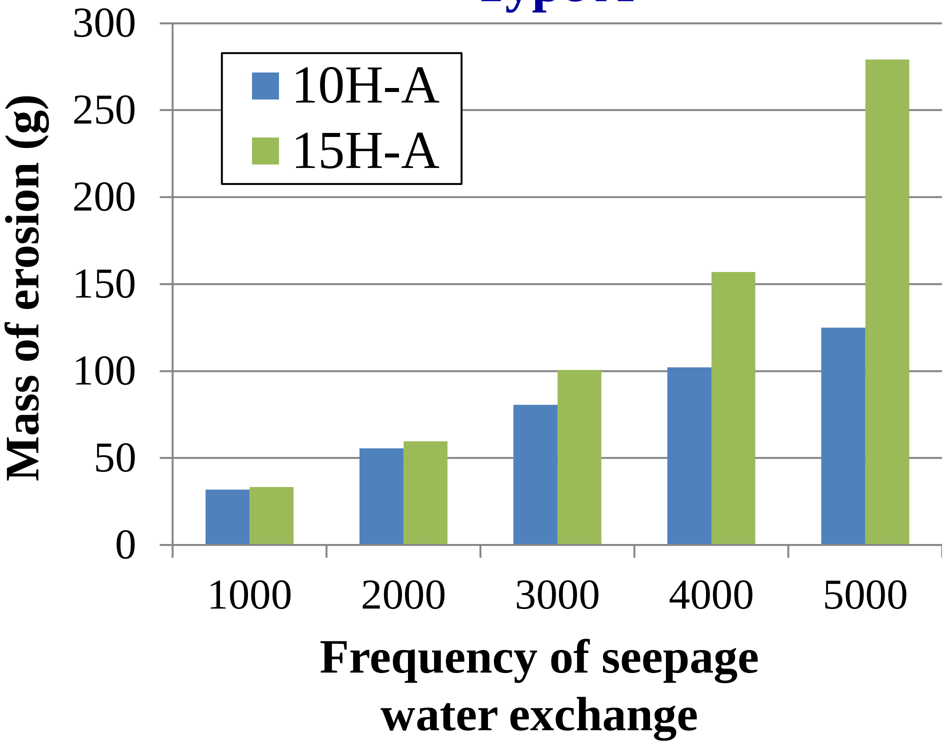


Seepage-induced suffusion in levee can be reproduced with the small-scaled models in the laboratory

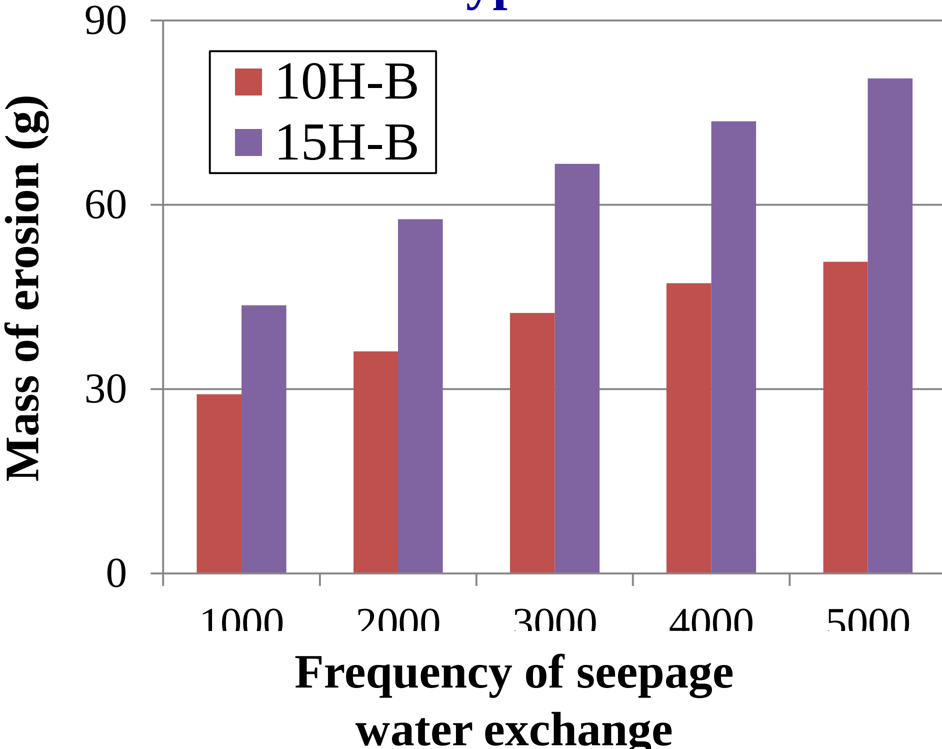
Result of mass of erosion

Effect of fine content

Boundary condition at downstream site Type A



Boundary condition at downstream site Type B



10%H-A < 15%H-A

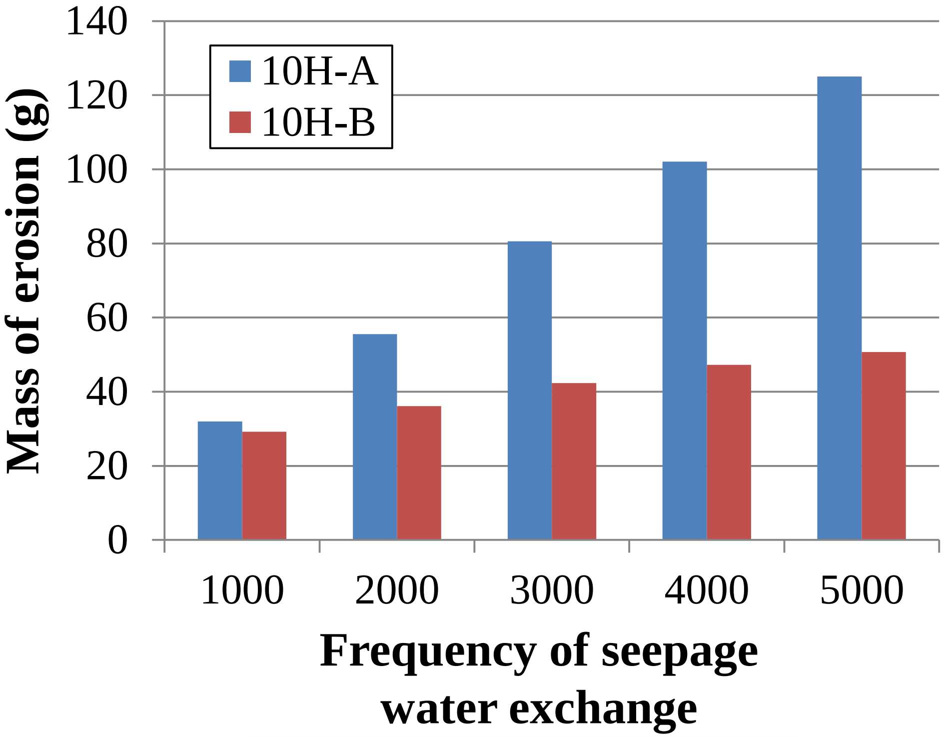
10%H-B < 15%H-B

If the volume of seepage water is the same, the tested soil with more fine content will show a higher tendency of erosion.

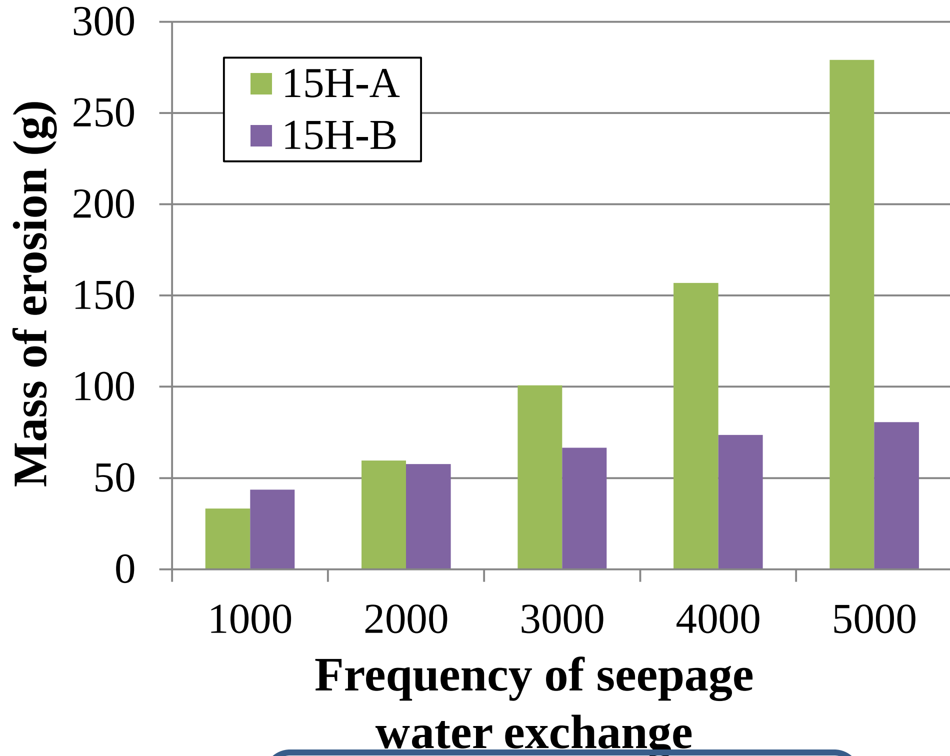
Result of mass of erosion

Effect of Boundary condition at the downstream

Fine fraction content：10%



Fine fraction content：15%

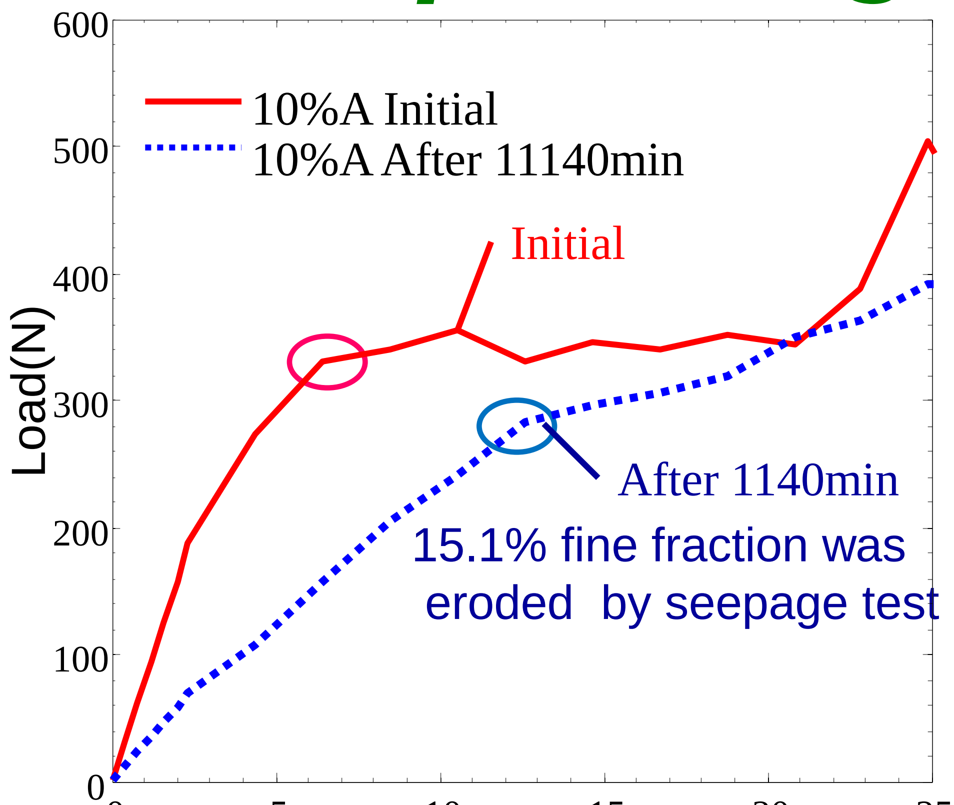


10%H-A ＞ 10%H-B

15%H-A ＞ 15%H-B

Hydraulic boundary condition at the downstream has a significant effect on amount of eroded fine fraction

Result of Bearing Capacity(Case 10%-A)



Loading speed： 62.5mm/min

Case	Ultimate Bearing capacity (N)	Settlement at Ultimate capacity (mm)
10%A Initial	**340**	6.0
10%A 10140min	270	11.0

The long term seepage causes deterioration of soil structure against loading

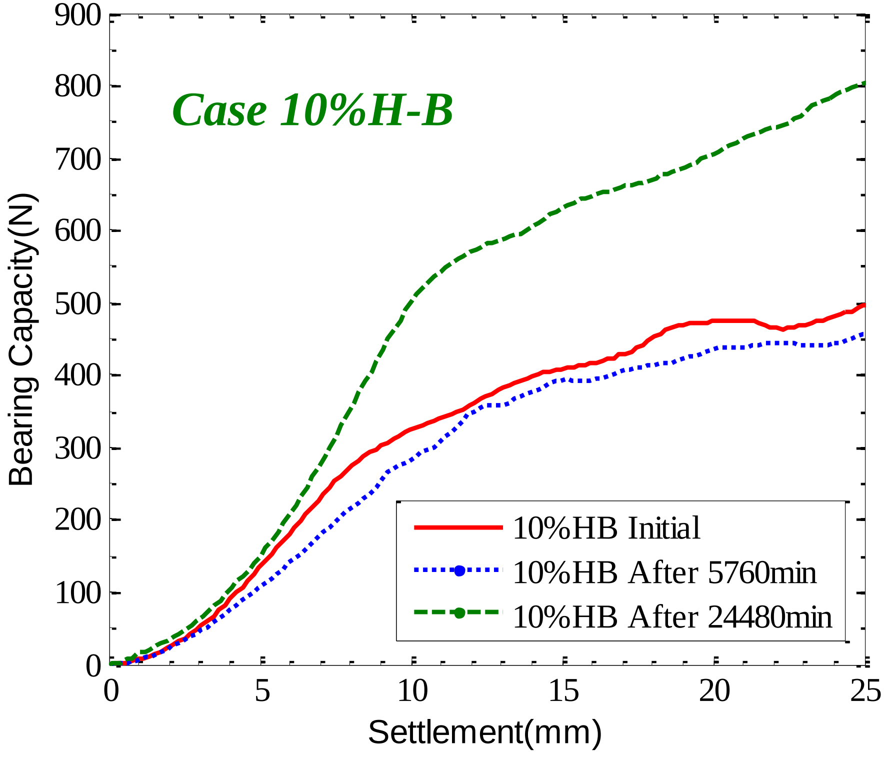
Degree of compaction 90.06 %

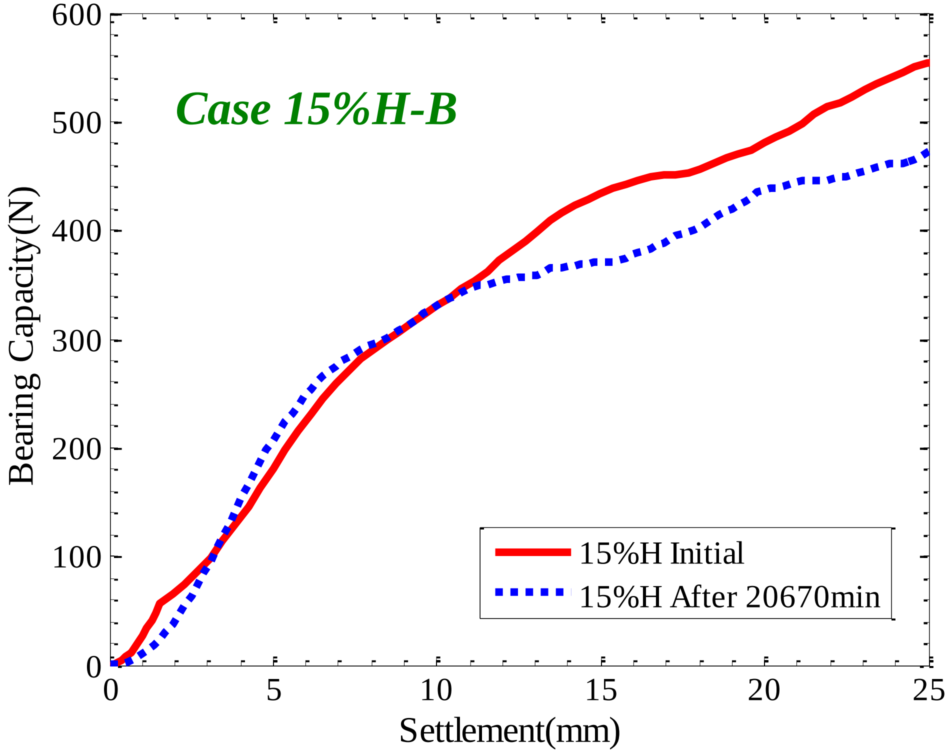
Conclusions

1. Seepage-induced suffusion in levee can be reproduced with the small-scaled models in the laboratory, provided that the model levee is loosely compacted.
2. If the volume of seepage water is the same, the tested soil with more fine content will show a higher tendency of erosion.
3. Hydraulic boundary condition at the downstream has a significant effect on amount of eroded fine fraction.
4. Suffusion can change the stability of soil structure depending on amount of eroded fine fraction and distribution of the fine fraction in the soil. When relatively large amount of fine fraction is eroded, the soil structure can be unstable.

Thank you for your kind attention!

Result of Bearing Capacity





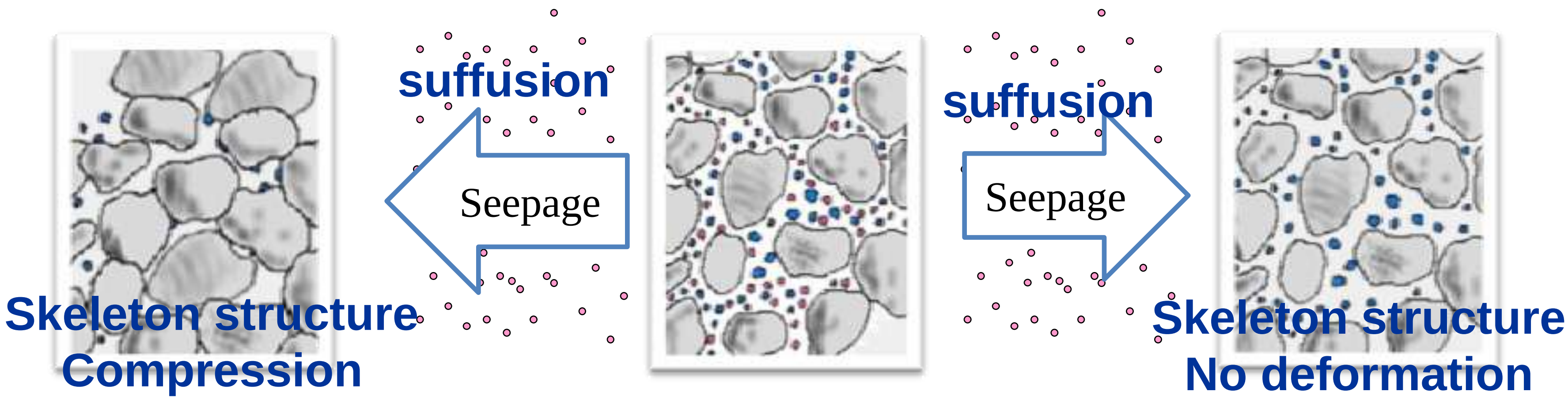
5.3% fine fraction was eroded by seepage test

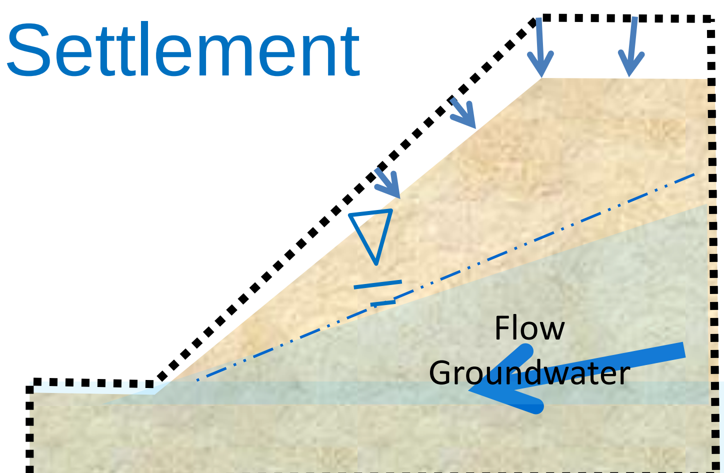
5.4% fine fraction was eroded by seepage test

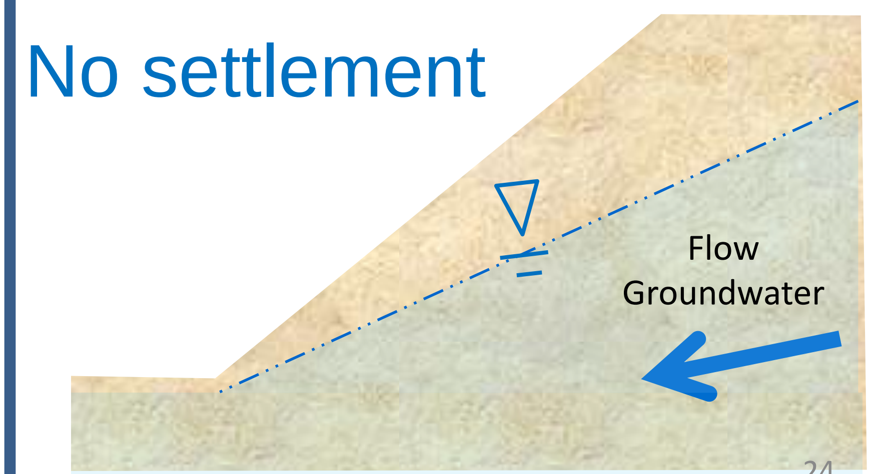
amount of fine fraction loss was small due to the difference in the hydraulic boundary condition around the toe as shown and no clear difference in the failure mode before and after suffusion.

Background

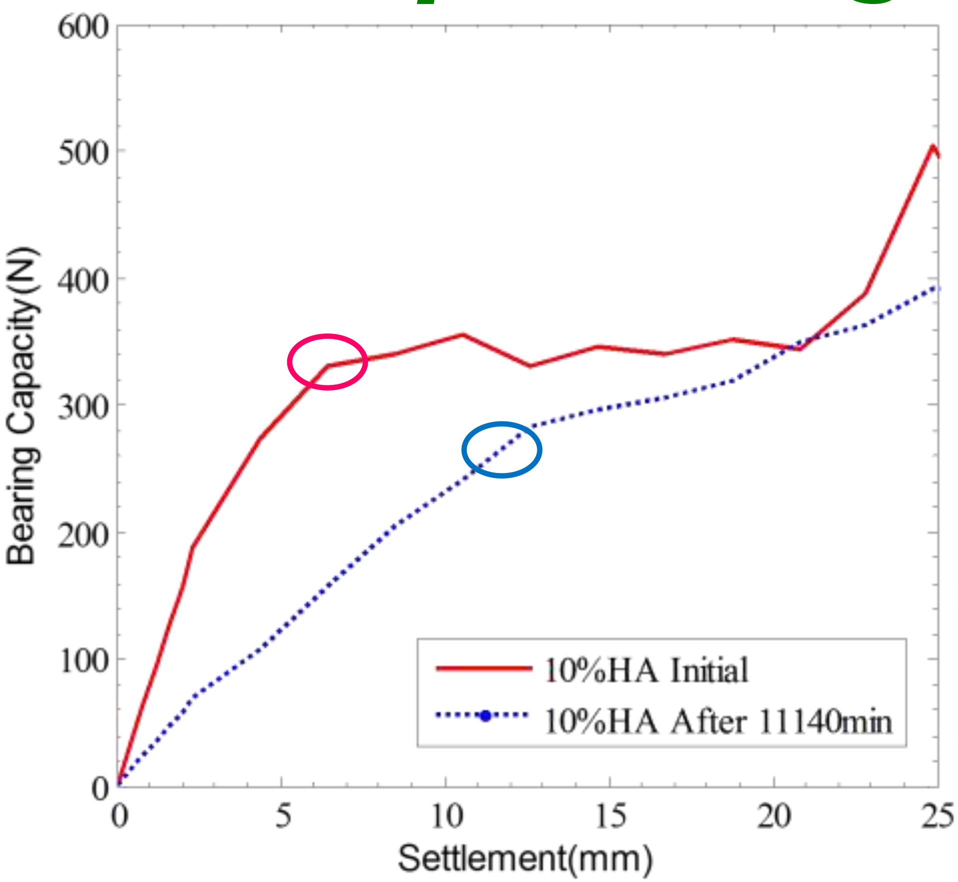
Discuss the performance shift of embankment by suffusion

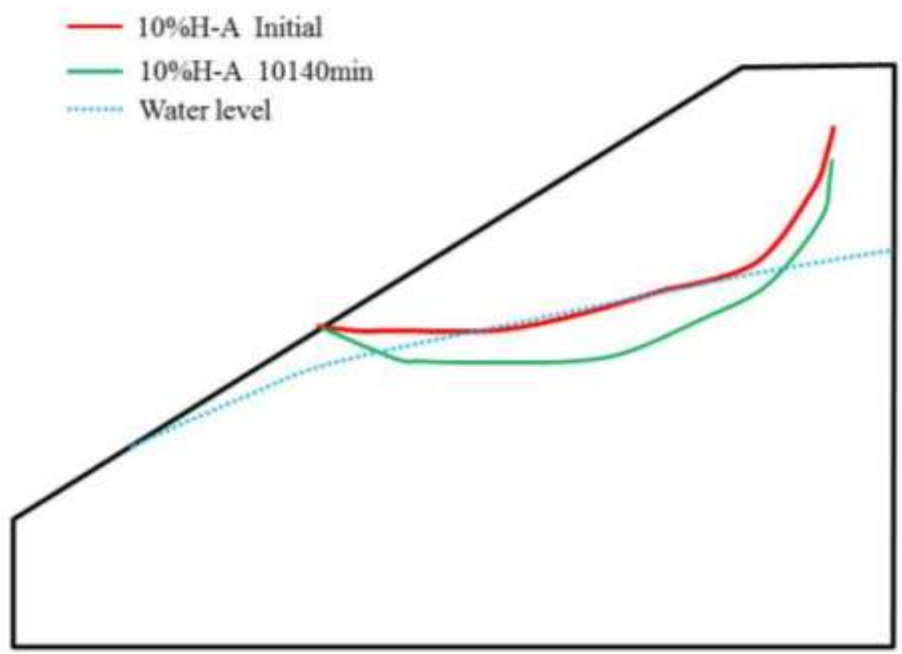






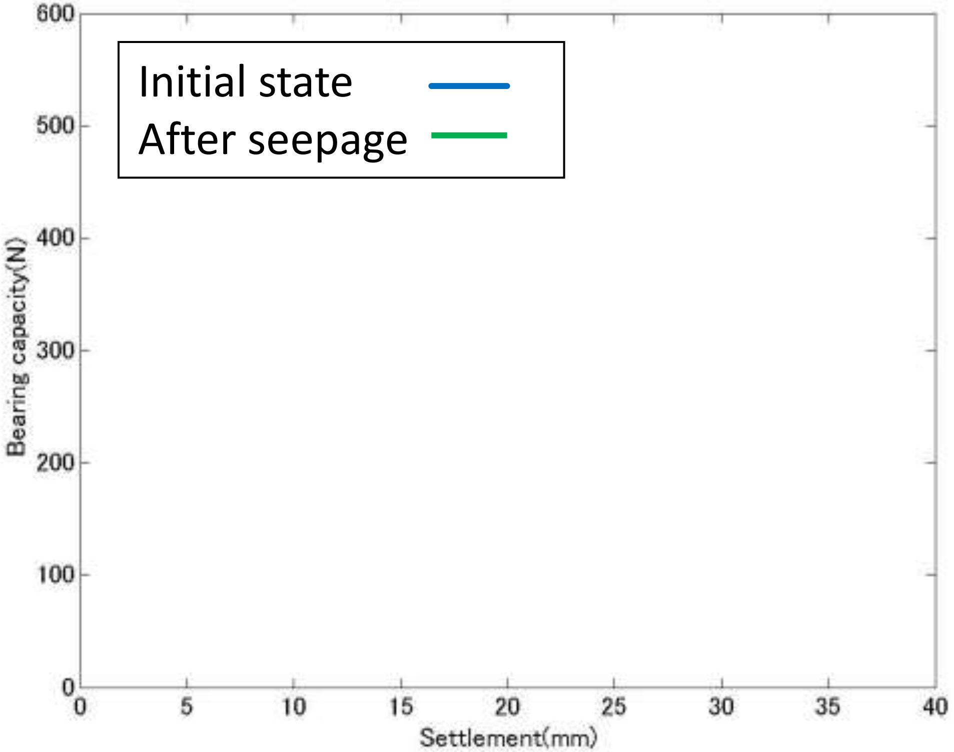
Result of Bearing Capacity (Case 10%-A)

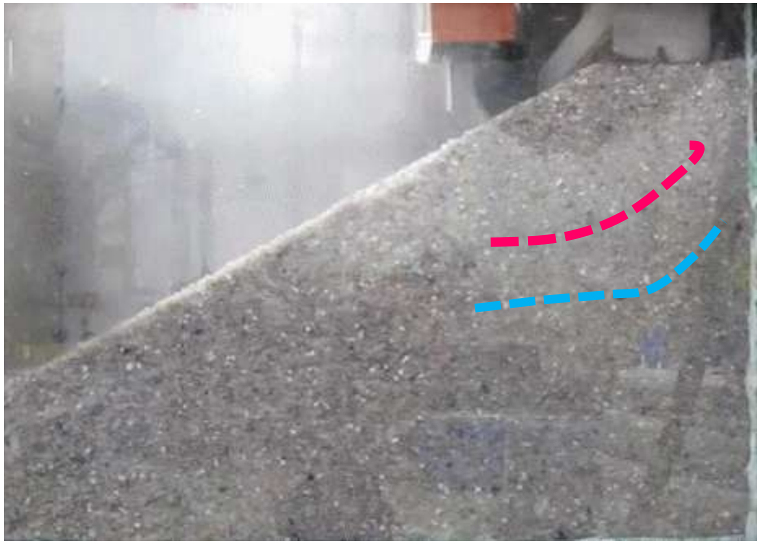




In initial state ,the slip surface appeared around the phreatic surface, like this while the large deformation zone was extended well below the phreatic surface due to the suffusion-induced strength reduction of the soil in the latter

Bearing capacity of top of slope(state of the experiment)





Initial state

The slip failure occurs along the

The long term seepage decreases the strength of the embankment and makes the position of slip surface deep

Result of evolutions of normalized eroded soil mass with time

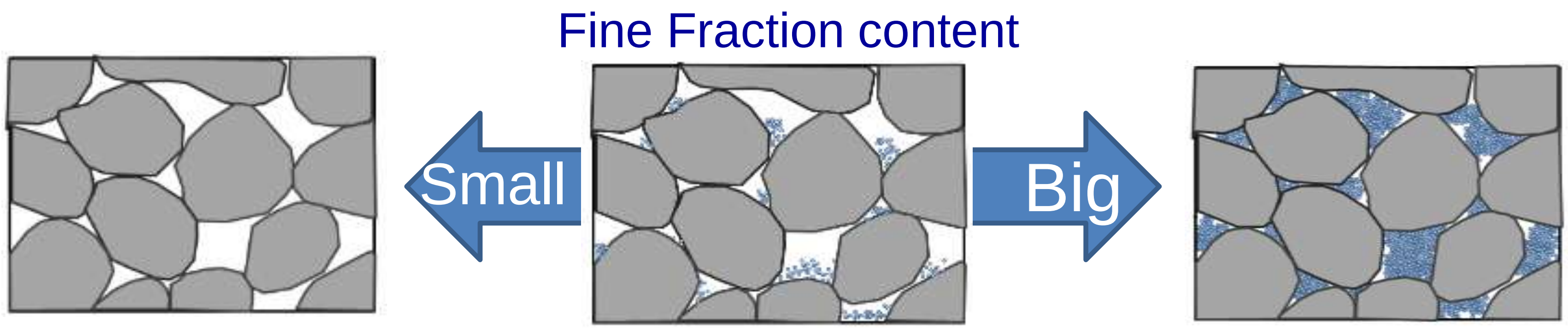
The ca

The amount of discharged fine fraction is normalized by total amount of the fine fraction under the phreatic surface before seepage test

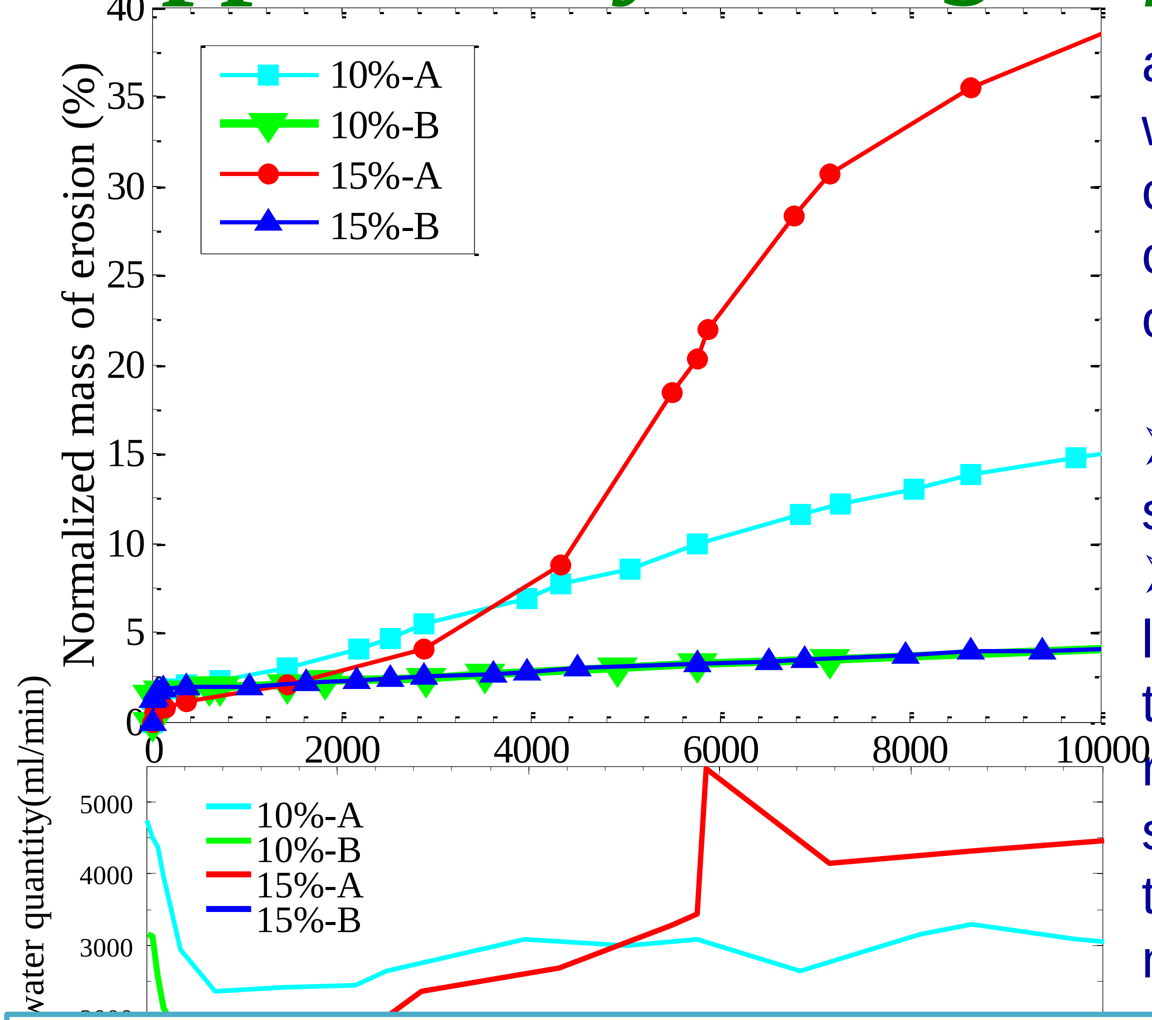
Result of Mass of Erosion

In this study, the larger the fine content, the larger the amount of fine fraction stored in the void formed by the coarse particles

- This tendency is to the narrower the flow channel for removing the fine fraction, and hence, the amount of eroded fines is less for the large fine content cases in the early stage of seepage tests



Supported by change of rate with time



amount of eroded soil increases with time. Especially in the cases with the Type A boundary condition, drastic increase is observed after some delay

- the larger the fine content, the smaller the flow rate
- in the cases where the water level is set at the middle of the toe of the slope, the flow rate increases with time after some delay and is coincide with the evolution of the eroded soil mass

It can be said that the flow rate and hydraulic boundary condition at the downstream have strong effects on initiation and progress of suffusion

Test setup

Soil materials

To **simplify** Suffusion, mixtures of **fine** and **coarse** fractions are used for the model slopes

Based on Kenney's(1985) approach, the fine particle content and grain size were decided, by considering the following three criteria:

- The size of the fine particles should be smaller than the size of the void between coarser particles which form the skeleton of the soil
- The amount of fine particles must less than enough to fill the void between coarser particles which form the skeleton of the soil
- The hydraulic gradient must be larger enough to move the fine soil particles through the "channel" between larger particles.

In addition, if we use the coarser soil than the prototype embankment material, phenomenon can be macroscopically observed and suffusion can occur in a short time

Result of Grain size analysis

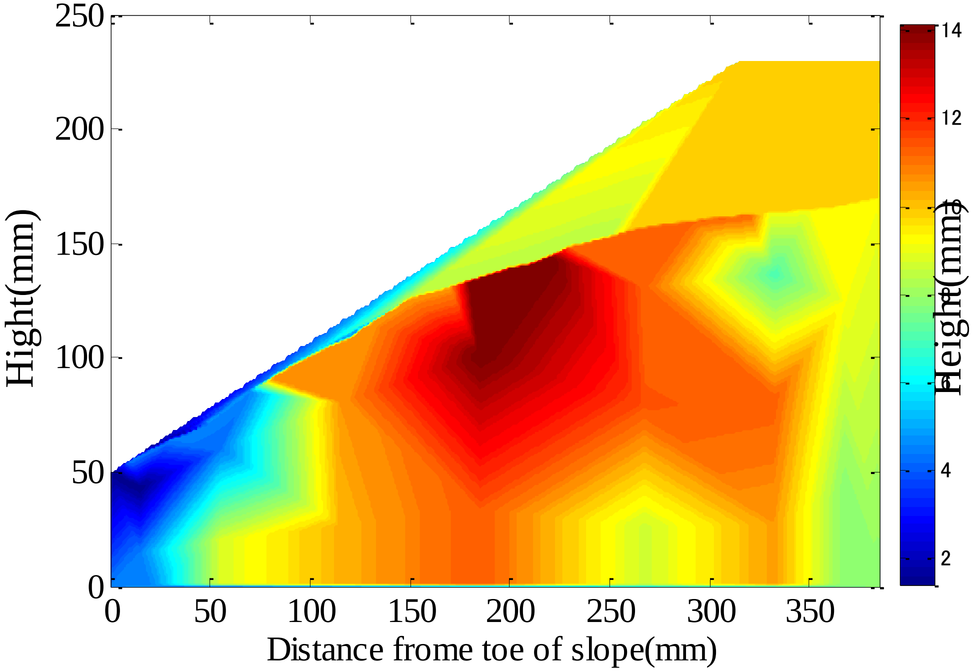
Type A

Unit(%)

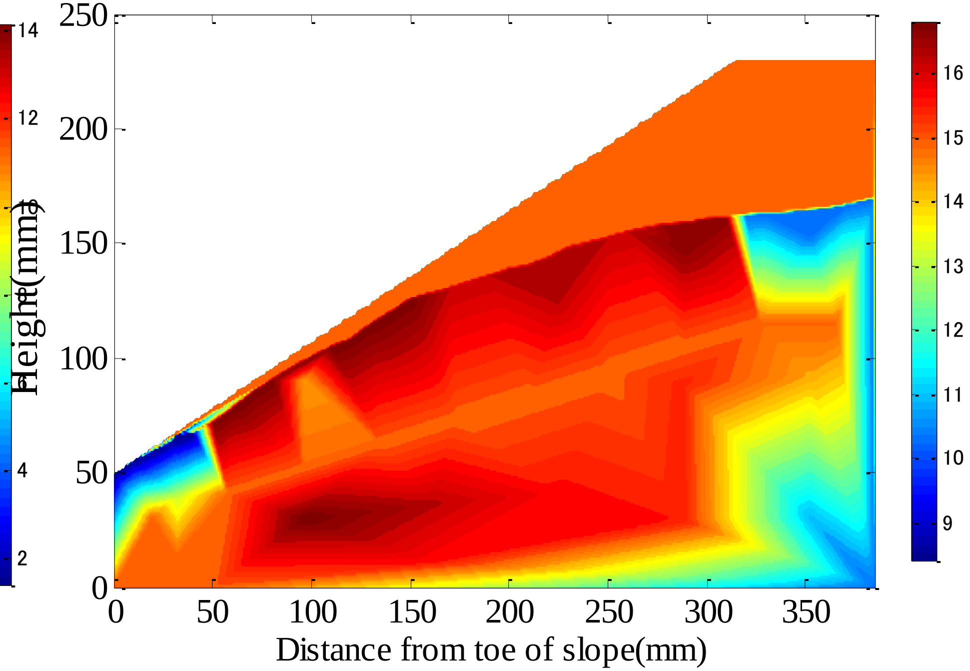
Case	Initial state	Distance from the slope toe			
		0-96.25mm	96.25-192.50mm	192.5-288.75mm	288.75-385.00mm
10%H-A	9.94	**7.69**	10.82	10.46	5.22
15%H-A	15.34	**8.44**	10.22	6.98	5.94

Result of Grain size analysis

Type B（10%H-A After 24480min）



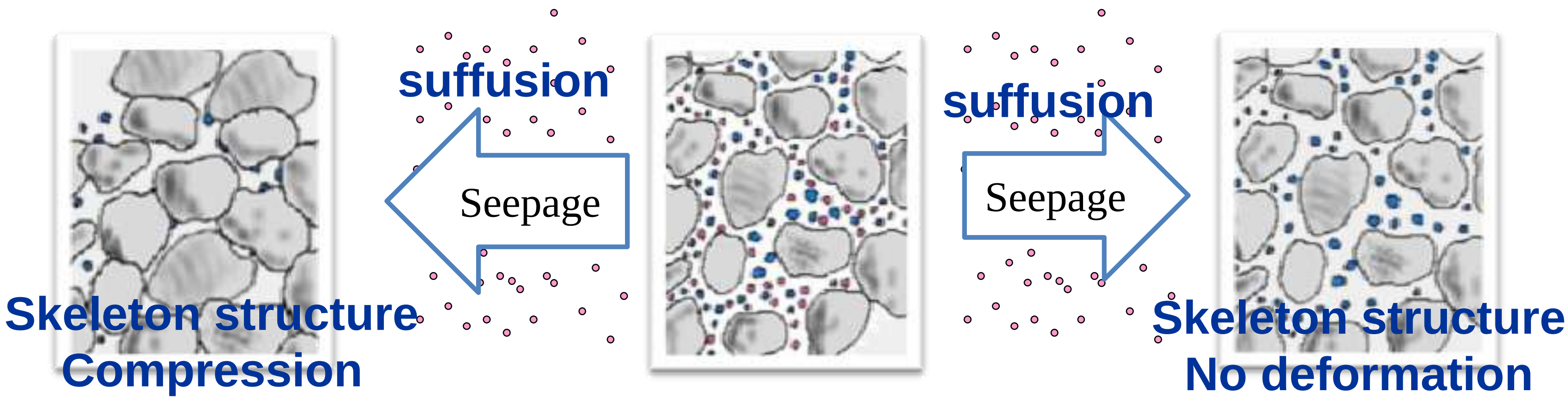
Type B（15%H-A After 20670min）

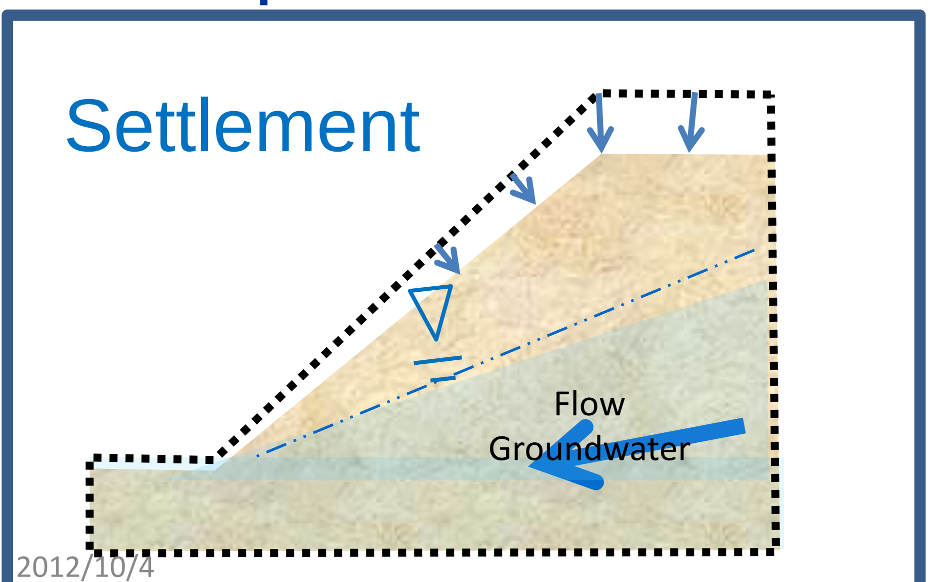


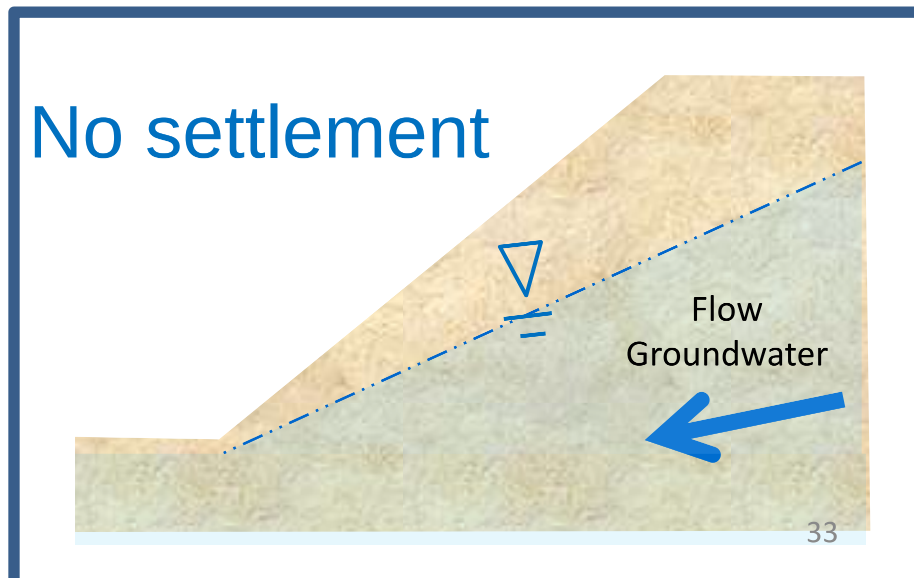
Unit (%)

Background

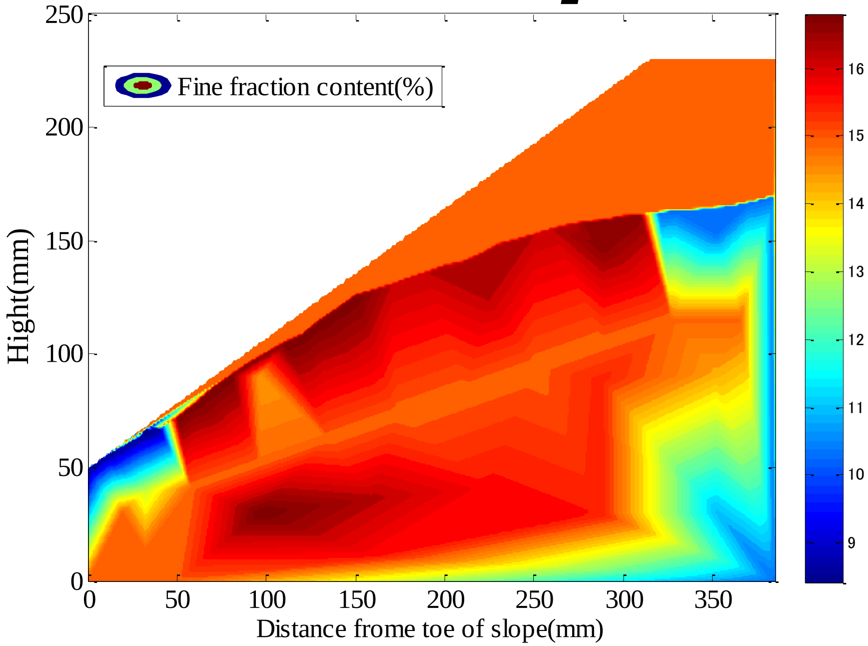
Discuss the performance shift of embankment by suffusion

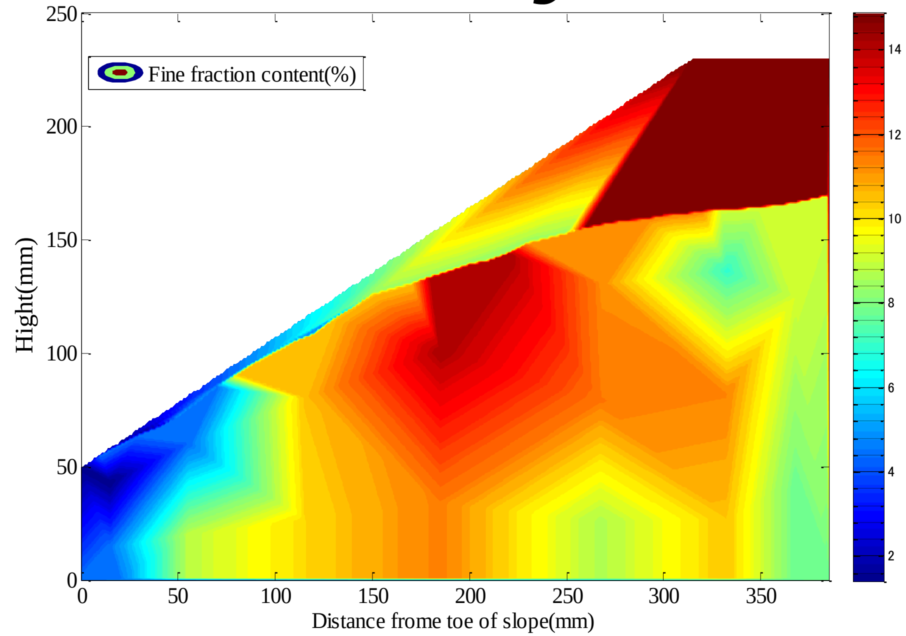


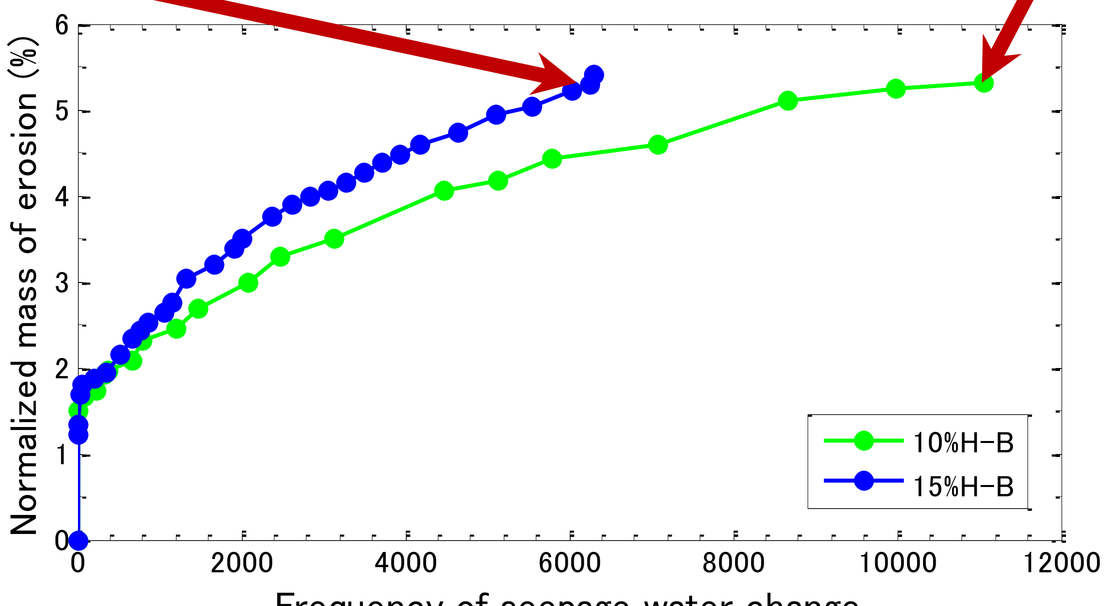




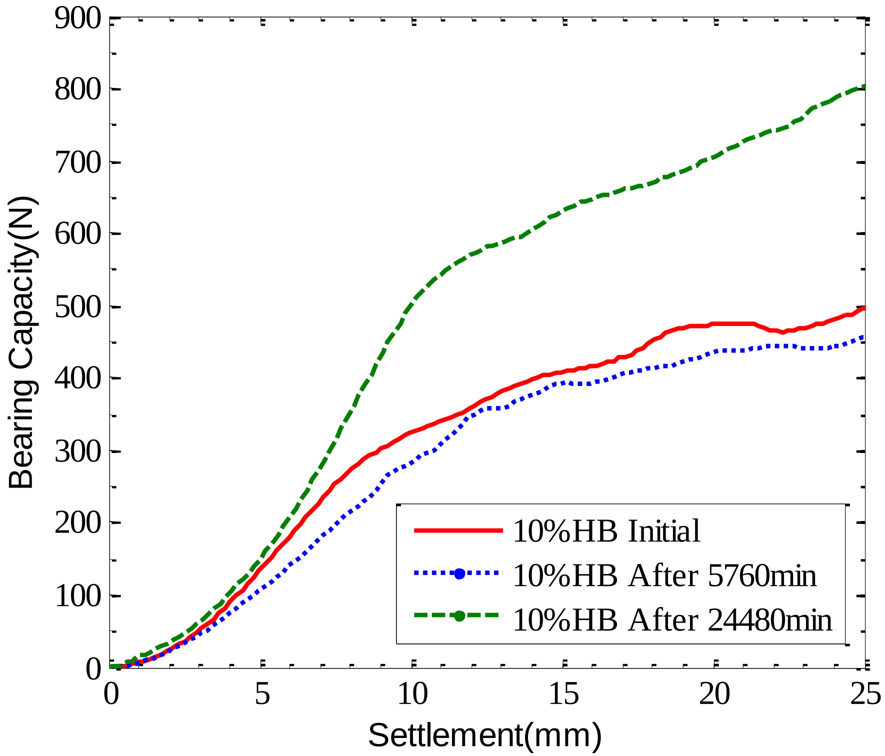
Result of Grain size analysis

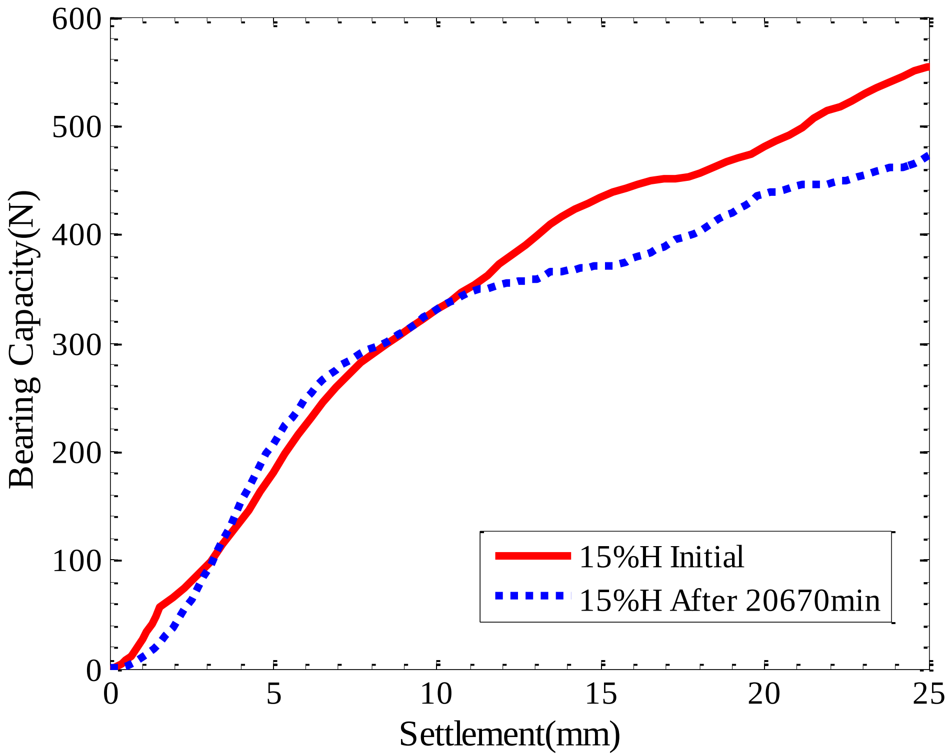






Result of Bearing Capacity(Case 10%-A)





5.3% fine fraction was eroded by seepage test

5.4% fine fraction was eroded by seepage test

Background

- Mid Niigata Prefecture Earthquake in 2004
- The Niigataken Chuetsu-oki Earthquake in 2007
- Noto Hanto Earthquake in 2007

Most of **damage** of **houses**, **road**s and **railways** was occurred in fills built on **catchment topography**

There EQ directed our eyes anew to the weakness of valley fills

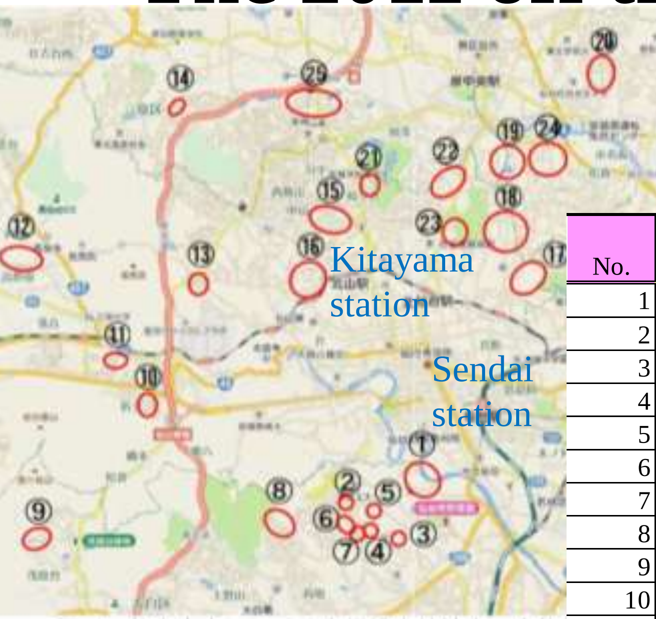
- Suruga Bay Earthquake in 2009

Inflicted social loss due to a valley fill collapse in Tomei Expressway, one of the busiest expressways in Japan

Valley fills built on catchment topography
are vulnerable to Large-scale EQ

Background

- **The 2011 off the Pacific coast of Tohoku**

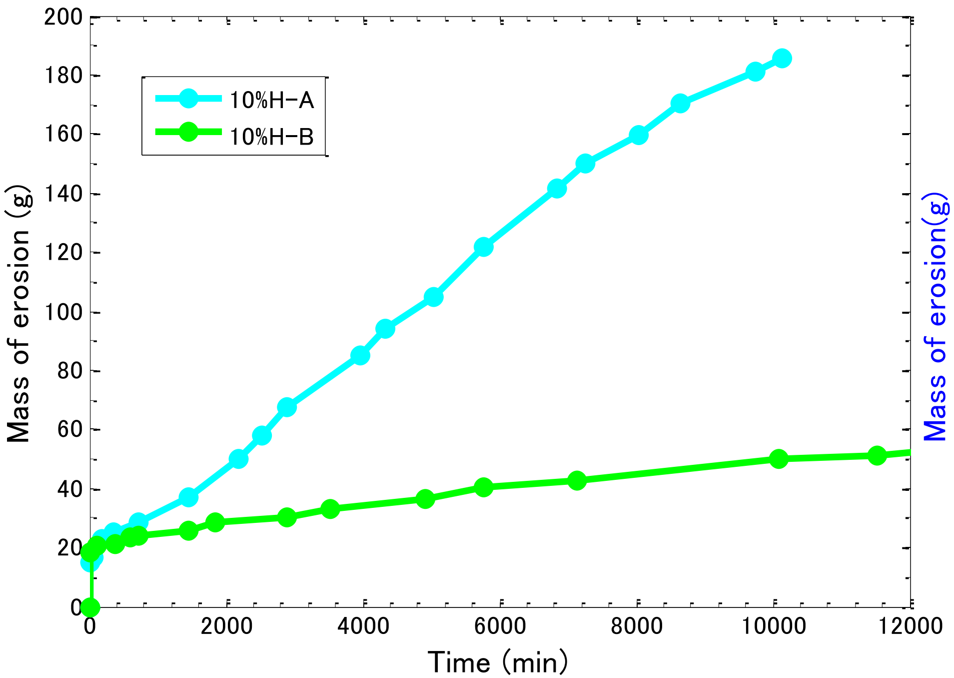


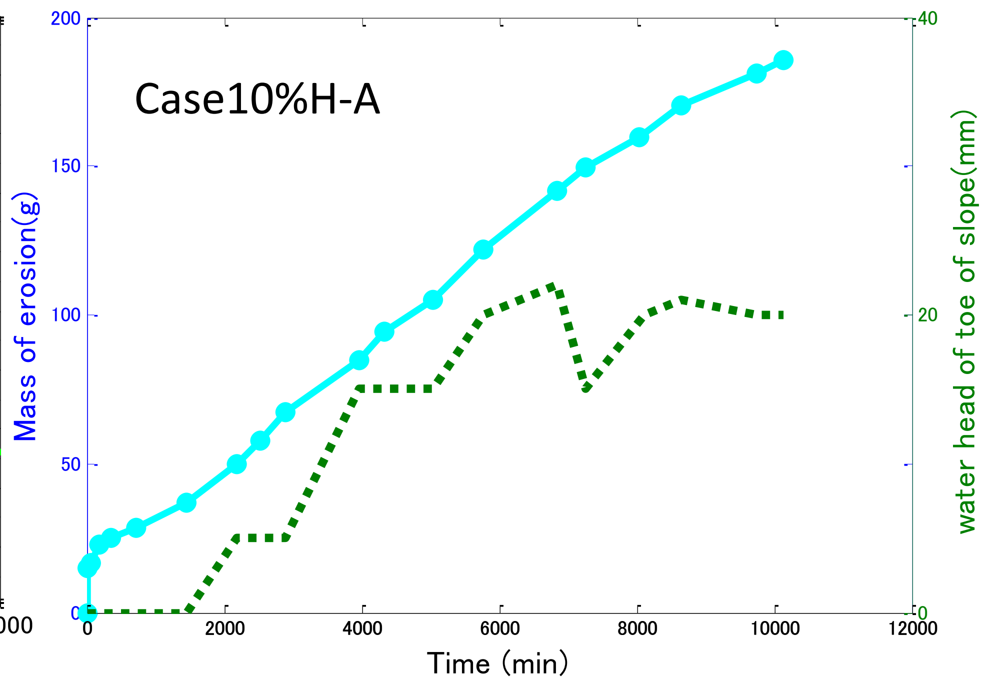
No.	District	Retainig Wall (collapse)	Residential Land	Slope Failure	Sliding of large fill: Valley fill	Sliding of large fill: Widened embankments	Sliding of large fill: large slope
1	1-chome,Mukaiyama	✓		✓			
2	Matsugaoka	✓					
3	3-chome,Midorigaoka	✓	✓		✓		
4	4-chome,Midorigaoka	✓	✓		✓	✓	
5	2-chome,Aoyama	✓	✓	✓	✓	✓	
6	Keiwamachi	✓					
7	Otoyamachi	✓					
8	1-chome,Yagiyaminam	✓					
9	5-chome,Moniwadai			✓			
10	5-chome,Oritate		✓				
11	1-chome,Seikaen	✓	✓	✓	✓		
12	2-chome,Takanohara	✓		✓			✓
13	7-chome,Minamiyoshi	✓	✓	✓			
14	3-chome,Kitanakayama	✓	✓	✓			✓
15	Takimichi	✓		✓		✓	
16	1-chome,Kaigamori	✓					
17	4-chome,Komatsushim	✓					
18	2-chome,Asahigaoka	✓					
19	Higashikuromatsu	✓	✓	✓			
20	Hosakacho	✓					
21	Sakuragaoka					✓	
22	Futabagaoka	✓			✓		
23	1-chome,Kitane	✓					
24	6-chome,Nankodai	✓	✓				✓
25	3-chome,Kamo	✓	✓				✓

Result of Mass of Erosion

In Case **15%H-A,10%H-A**, amount of eroded soil drastically increases after a certain elapsed time

- Due to increase flux, water head of toe of slope is rising
- **Boundary condition of downstream have a significant effect**

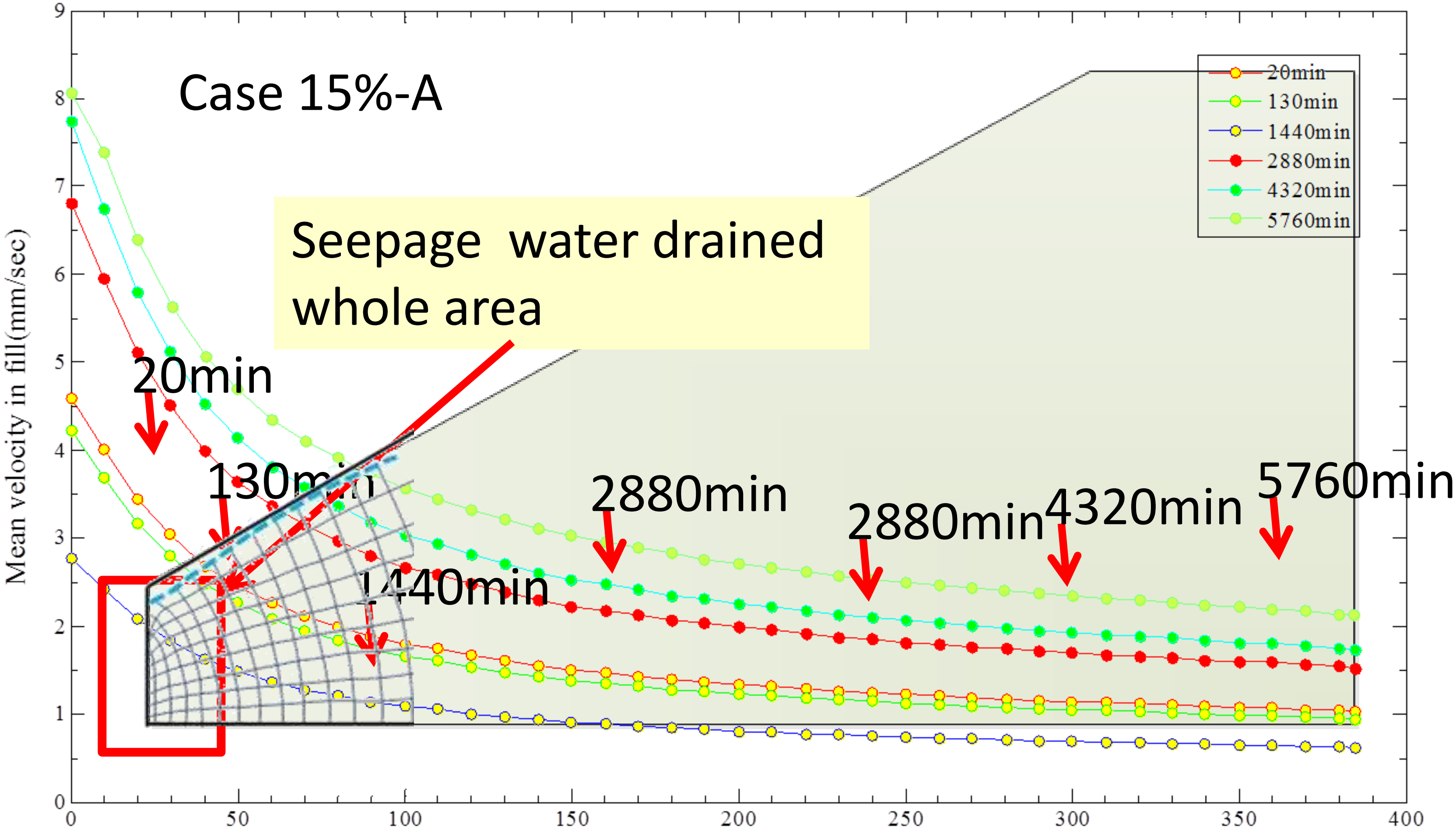




Result of Mean Flow Velocity (Type A)

These boundary condition of toe head affect velocity of seepage

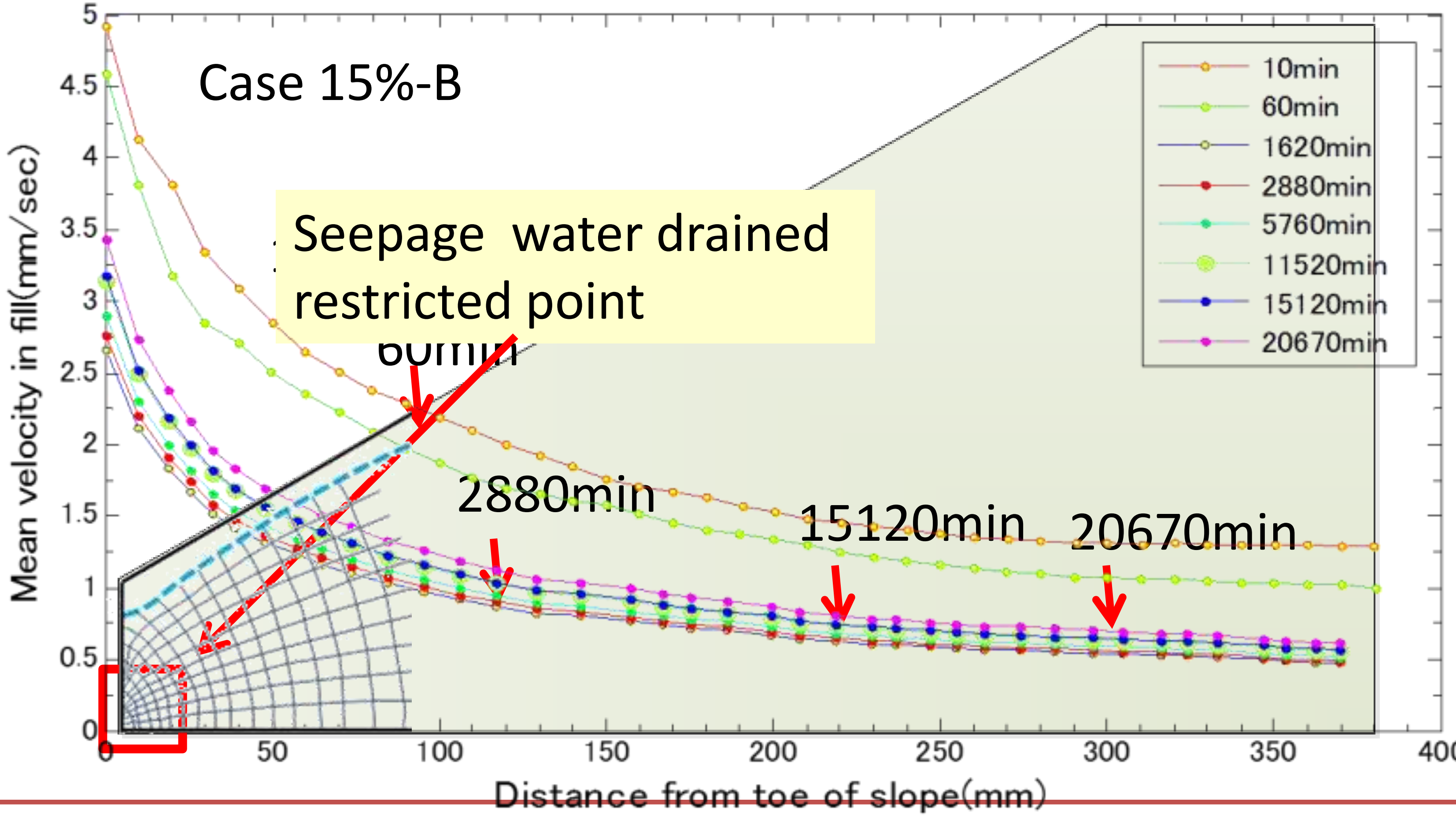
change of mean flow velocity with seepage time on case of variable head type



The mean flow velocity increases with time because fine fraction washed away by seepage

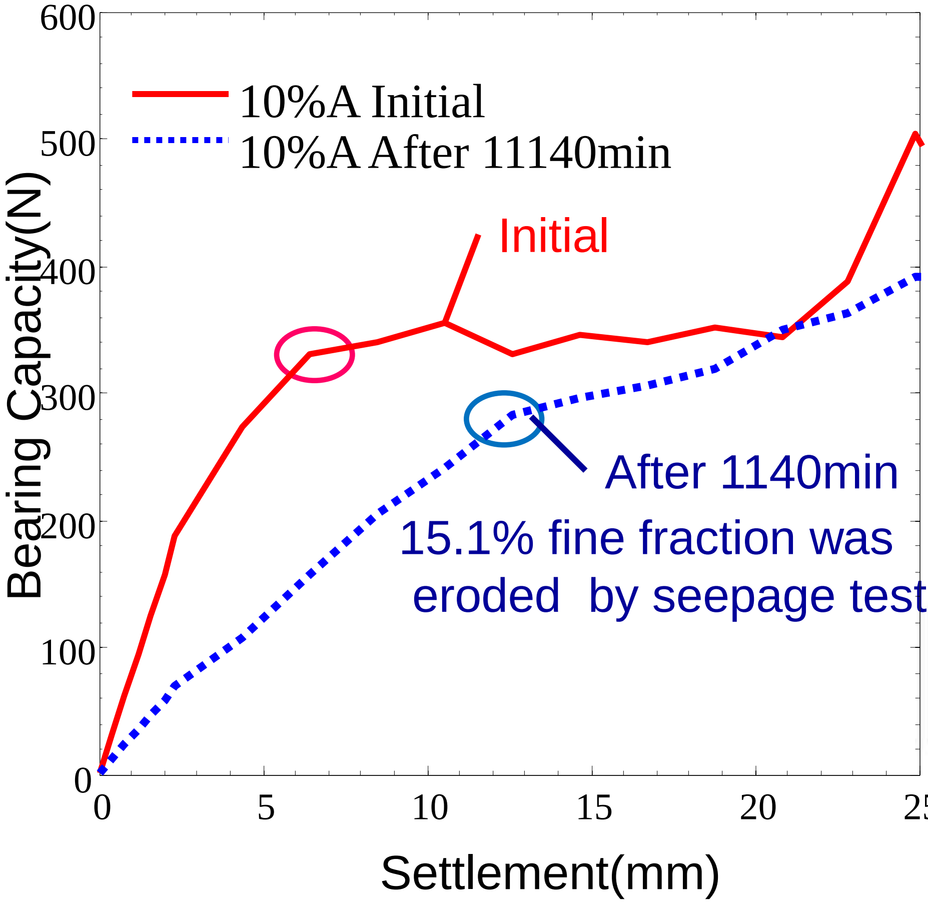
Result of Mean Flow Velocity(Type B)

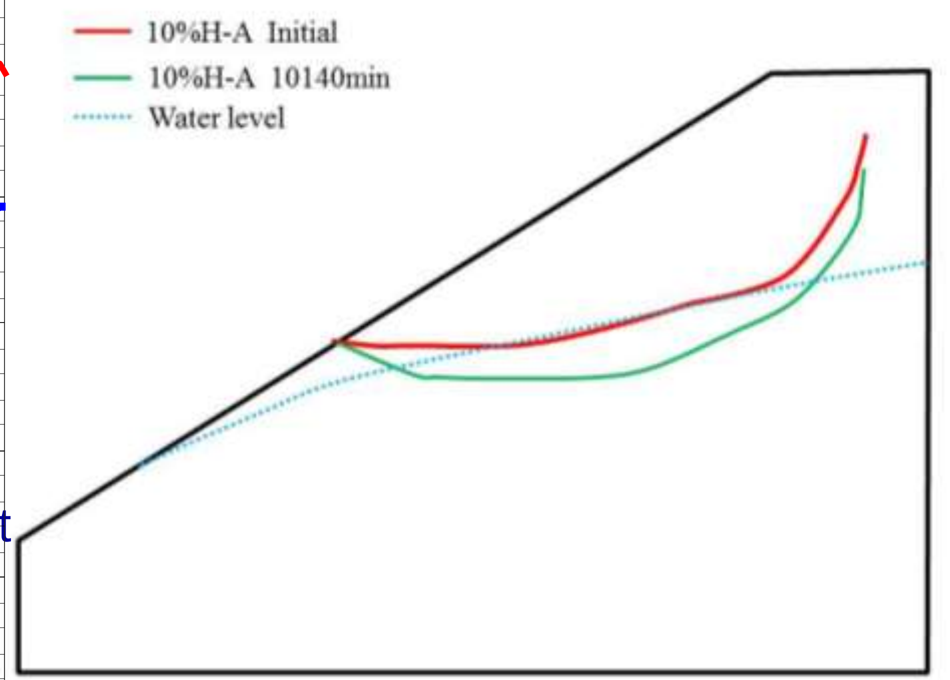
change of mean flow velocity with seepage time on case type of restricted drain point



The mean flow velocity decreases with time, because fine fraction is clogged in the middle of slope

Result of Bearing Capacity *(Case 10%-A)*

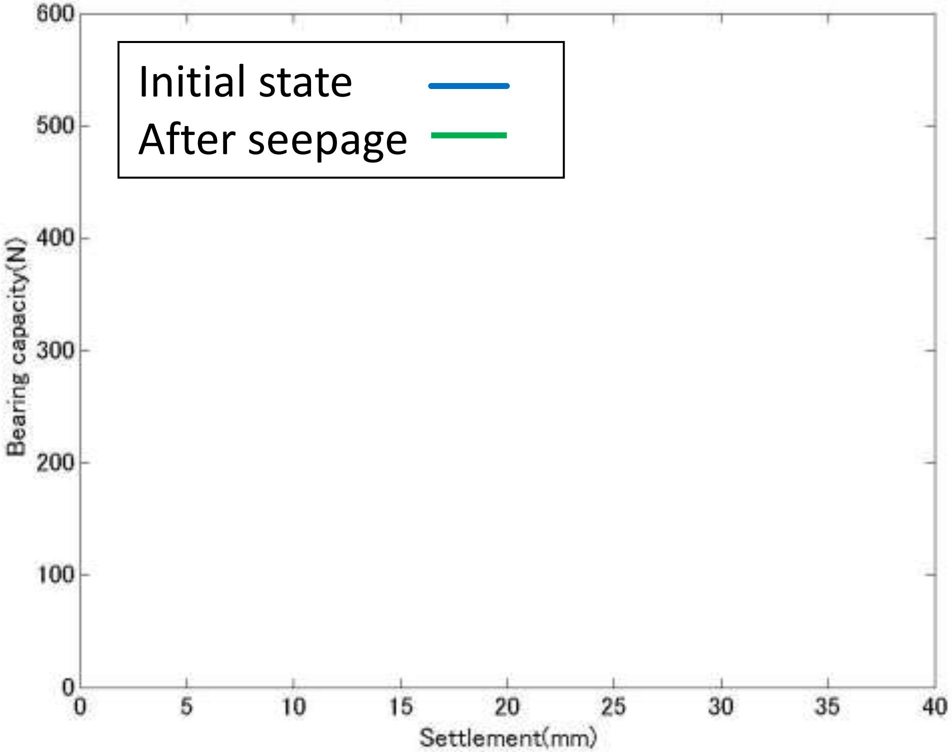


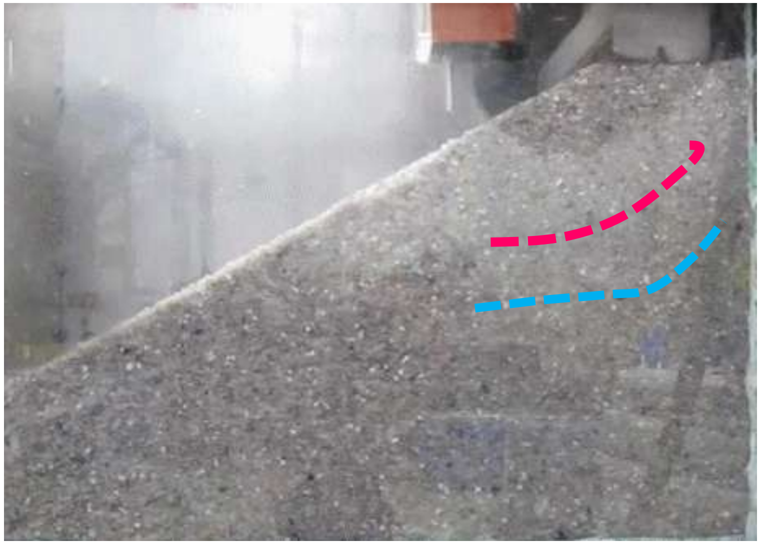


plots the slip surfaces in the loading tests

- Without suffusion, the slip surface appeared around the phreatic surface
- On the other hand, with suffusion, the deformation zone was extended well below the phreatic surface due to the suffusion-induced strength reduction of the soil

Bearing capacity of top of slope(state of the experiment)





Initial state

The slip failure occurs along the

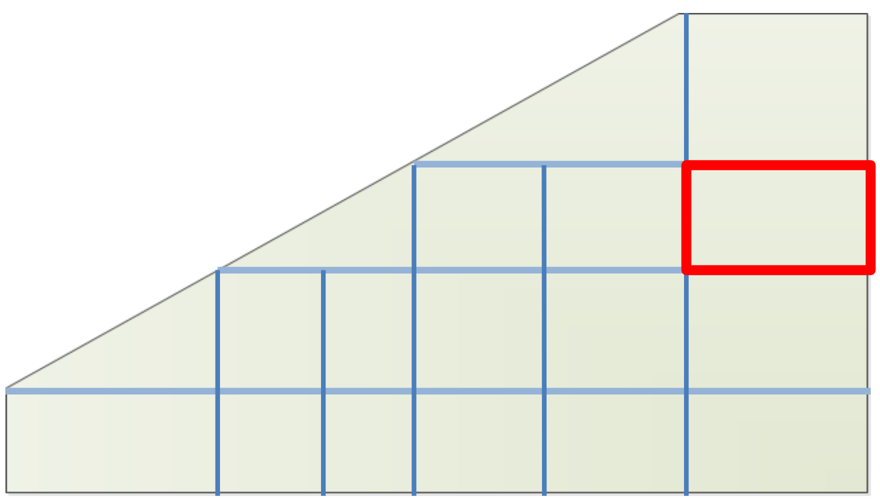
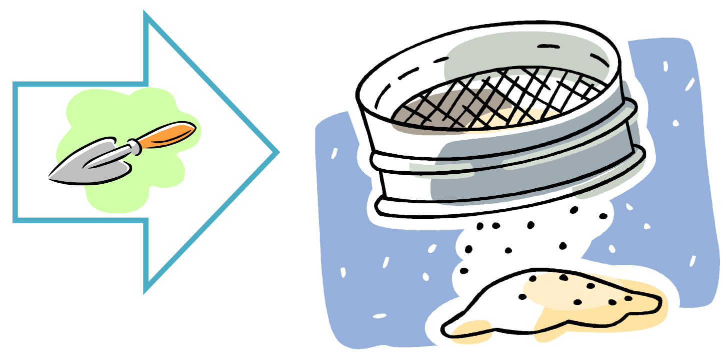
The long term seepage decreases the strength of the embankment and makes the position of slip surface deep

目的　どのように明らかにするか

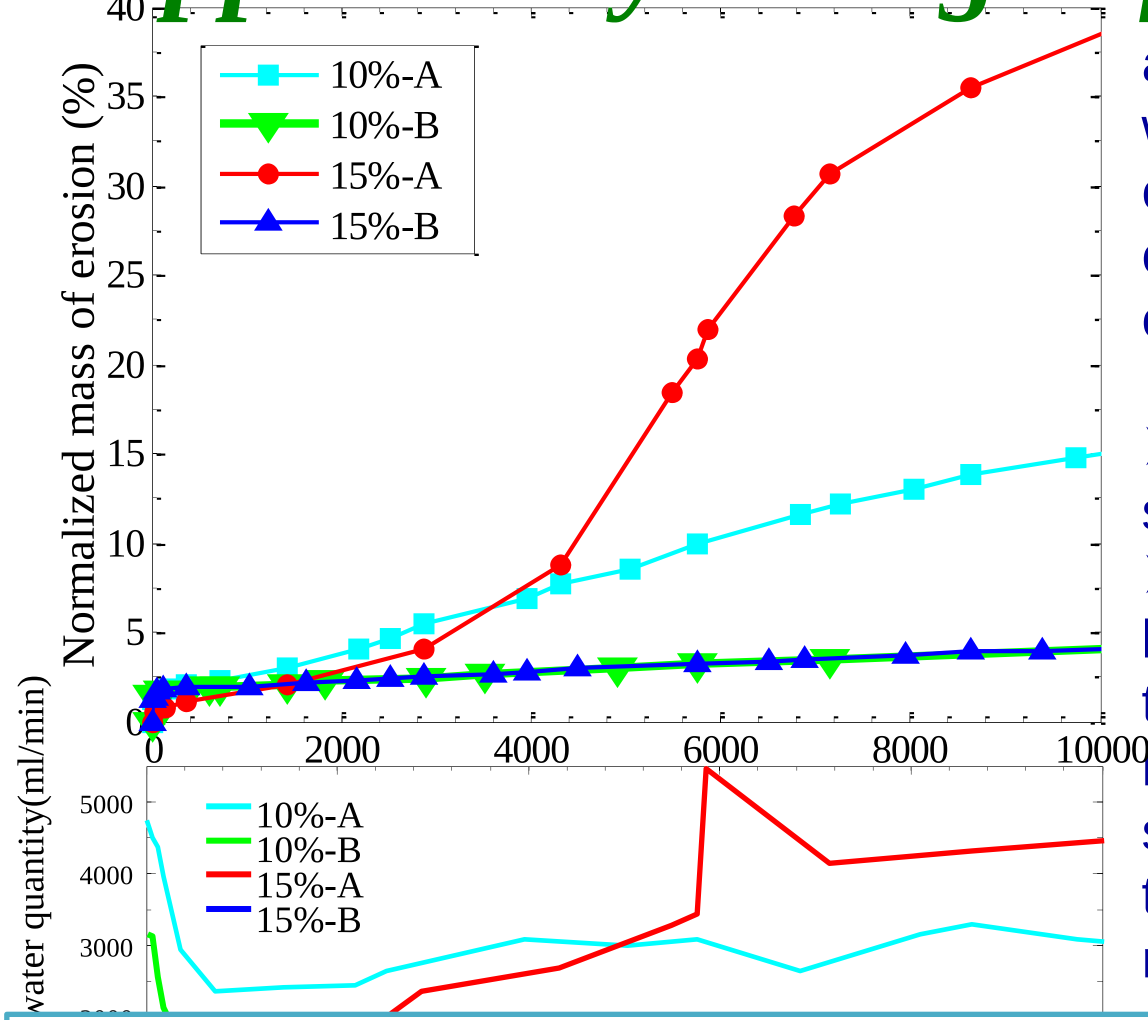
③ 2次元的な細粒分の移動傾向

これまでの多くの実験的研究は鉛直一次元的な浸透実験であり，実構造物を模擬した実験はない

- 堤体盛土を模擬した実験
- 部分ごとの粒度試験，色砂を用いた観察

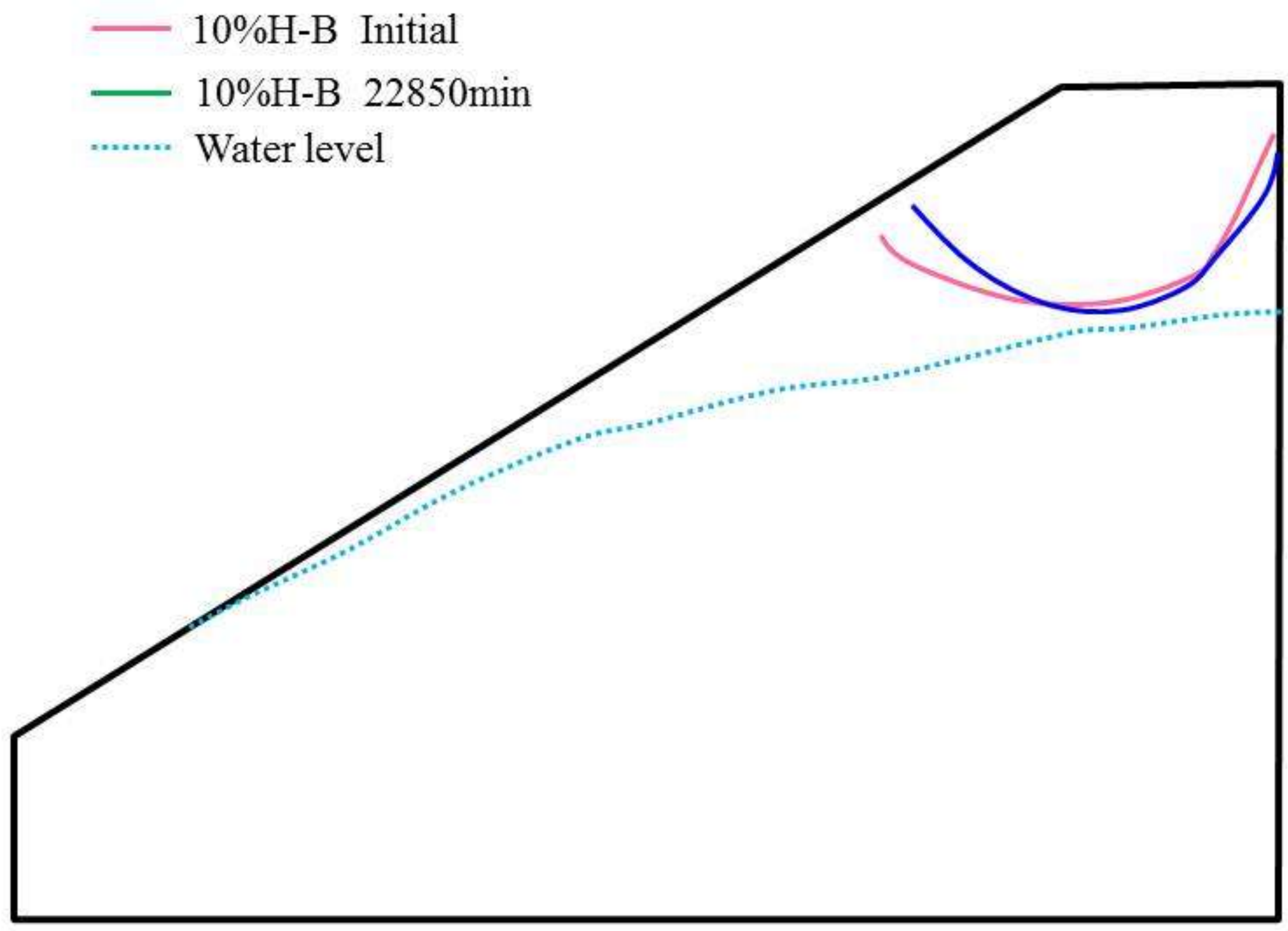
Supported by change of rate with time



amount of eroded soil increases with time. Especially in the cases with the Type A boundary condition, drastic increase is observed after some delay

- the larger the fine content, the smaller the flow rate
- in the cases where the water level is set at the middle of the toe of the slope, the flow rate increases with time after some delay and is coincide with the evolution of the eroded soil mass

It can be said that the flow rate and hydraulic boundary condition at the downstream have strong effects on initiation and progress of suffusion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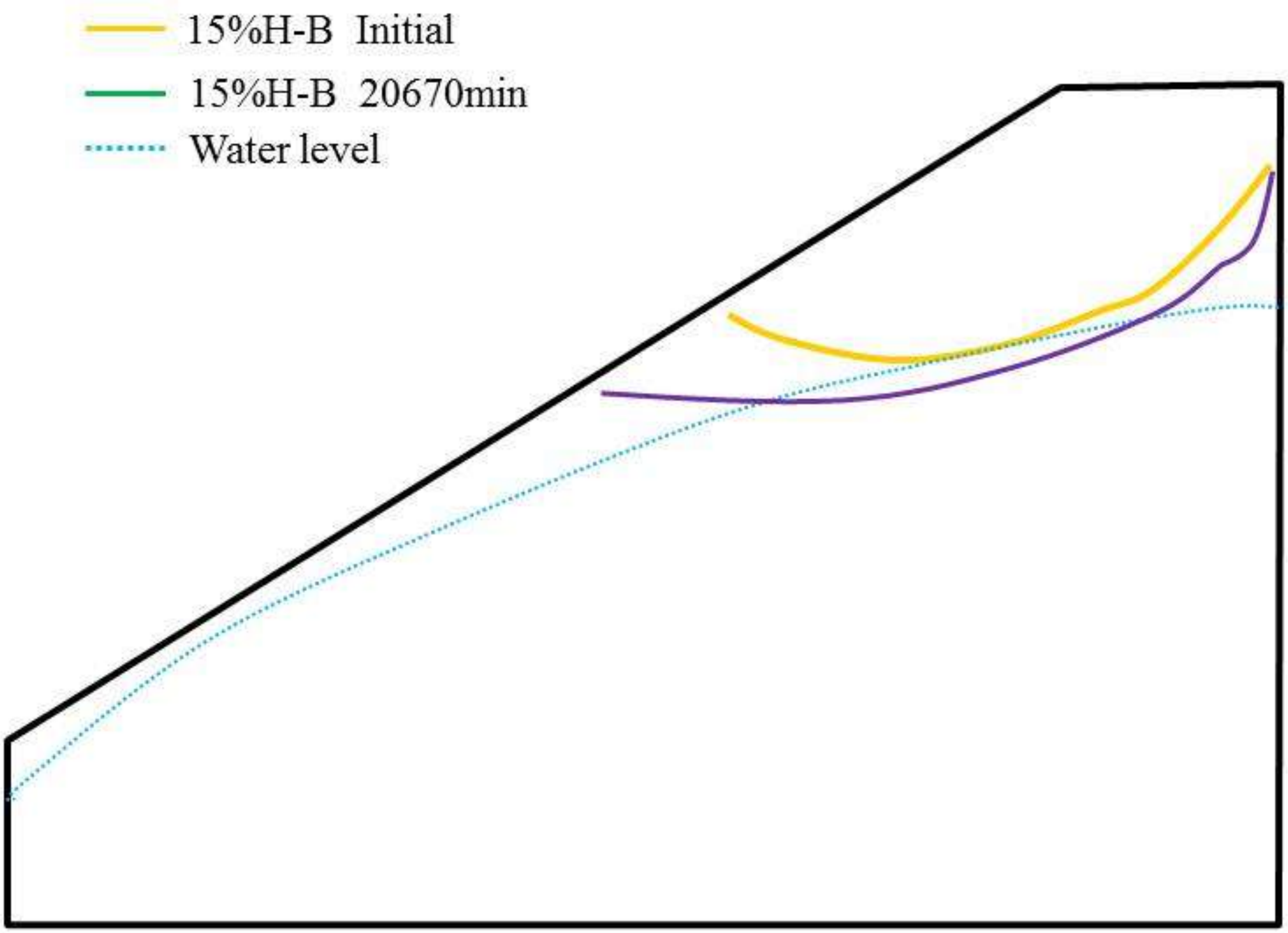
10%H-B 22850min
Water level


15%H-B Initial
15%H-B 20670min
Water level