Experimental research on internal erosion and its mechanical consequences for gap-graded soil

Tokyo Institute of Technology

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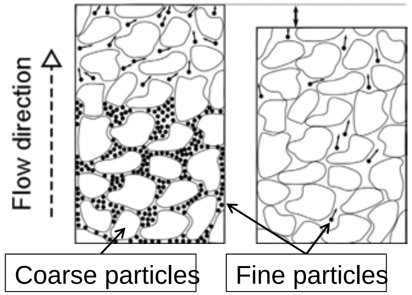
Workshop exploring recent developments considering seepage and instability in cohesionless soil, Imperial College London, UK, 31 Aug. - 1 Sept., 2017

Introduction

Seepage-induced internal erosion (suffusion)

- Migration of fine particles through matrix formed by coarse particles under seepage flow.



Top view of sample in upward seepage test

Similar to Skempton & Brogan (1994)
on Gap-graded soil (25% fines content; 60% relative density)

Summary of experimental findings

Expected consequence of internal erosion

- If volume change due to erosion is not so large, internal erosion results in <u>increase of void ratio</u>.
  - <u>Reduction in strength</u> and <u>increase in permeability</u> are expected.
  - Leading to instability and/or malfunction of hydraulic structures.

Through tests on gap-graded soils, we found / confirmed that

- Internal erosion makes <u>drained strength smaller</u>, while <u>undrained strength larger</u>.
- <u>Stiffness of eroded soil is larger</u> than that without erosion.
  - We try to explain mechanism through optical observation.
  - Attempt made by Higo and coworkers is also introduced; Observation made by micro X-ray CT by Higo *et al*. (2017).

Acknowledgements

Experimental research at Tokyo Tech

- Conducted by the former PhD students:
  - Dr KE, Lin
  - Dr OUYANG, Mao
- Supported by JSPS KAKENHI Grants (23760440 and 25420498).

Experimental research at Kyoto Univ

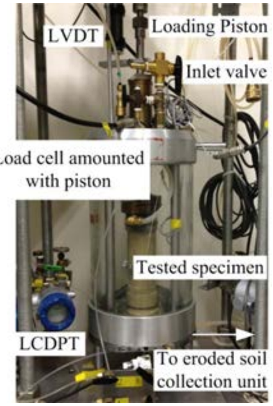
- Dr Yusuke HIGO allows me to share their experimental results with you in this workshop.
  - Y Higo, Y Hamada, S Iwanaga, Y Hisaizumi & R Kido: Imaging fine soil particles transportation through soil skeleton caused by seepage flow, *3rd Int'l Conf. Tomography of Materials and Structures, Lund, Sweden*, June 2017

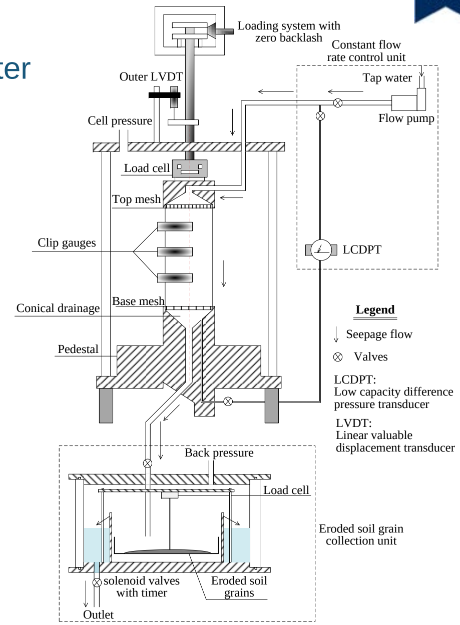
Since the work by Higo et al. (2017) contains unpublished test results, some slides were removed from the slide set used in the presentation.

Equipment

Triaxial seepage permeameter

- Back pressure is applied through sedimentation tank.
- Erosion test and shear test can be done continuously.

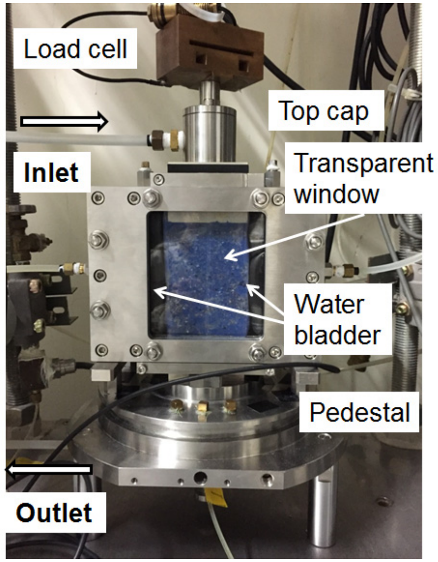




Equipment (cont'd)

Plane strain erosion apparatus

- Observation of particle movement can be made through transparent window / membrane.

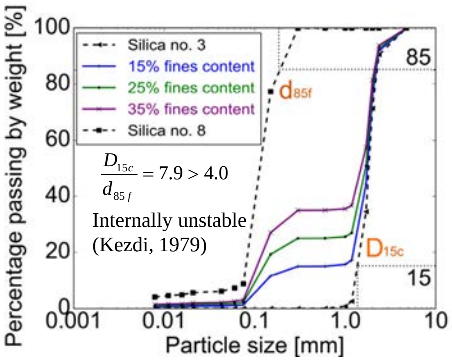


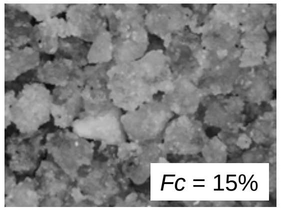
Materials

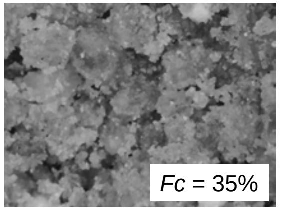
Mixtures of Silica #3 (coarse) and Silica #8 (fine)

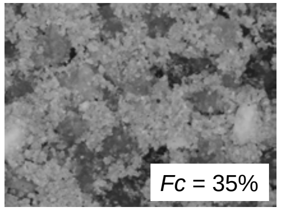
- Fines content: 35%, 25%, 15%
- Relative density: 30%, 40%
- Confining pressure:

  50kPa, 100kPa, 200kPa





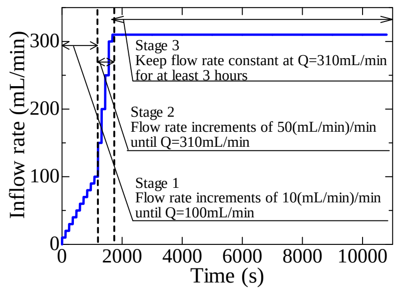


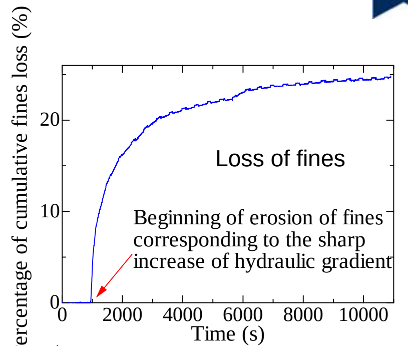


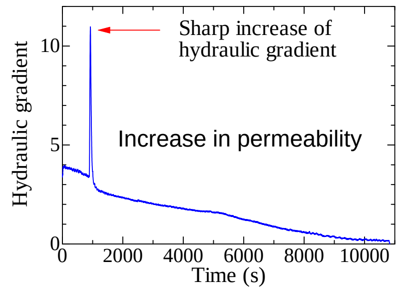
16 x 12 mm

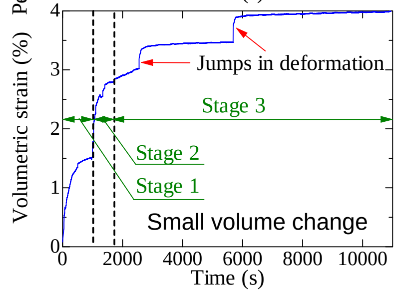
Example of erosion test

Fc = 35%, σ_c = 50kPa



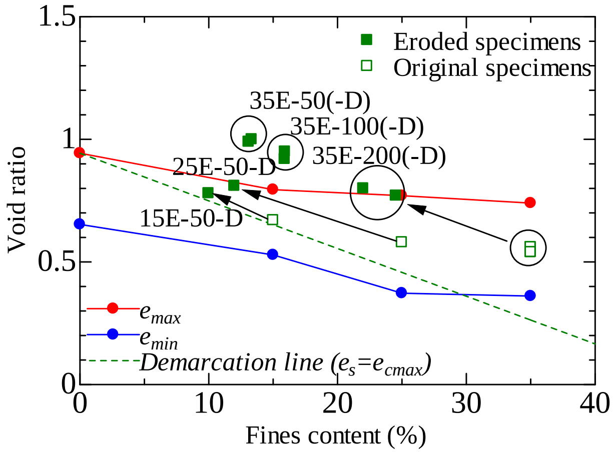






Summary of erosion tests

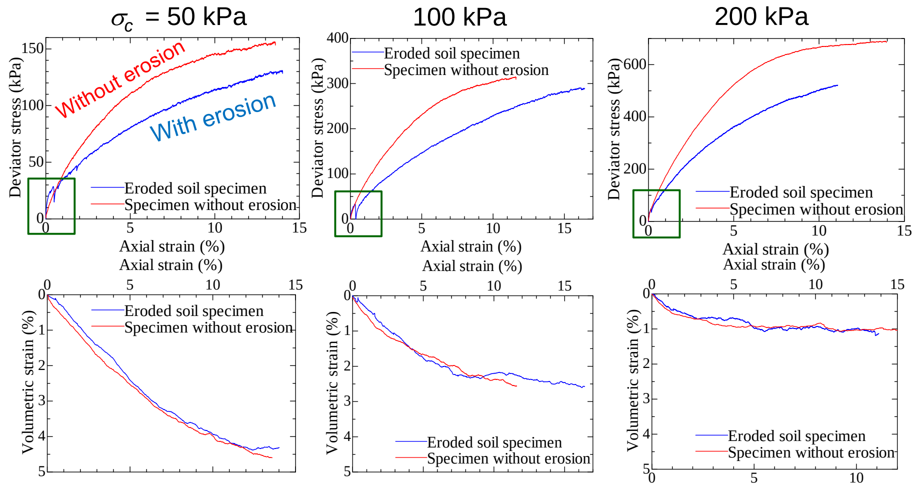
Marked increase of void ratio after erosion



- Demarcation line:
  Intergranular void ratio is equal to maximum void ratio of skeleton sand.

Drained triaxial compression tests

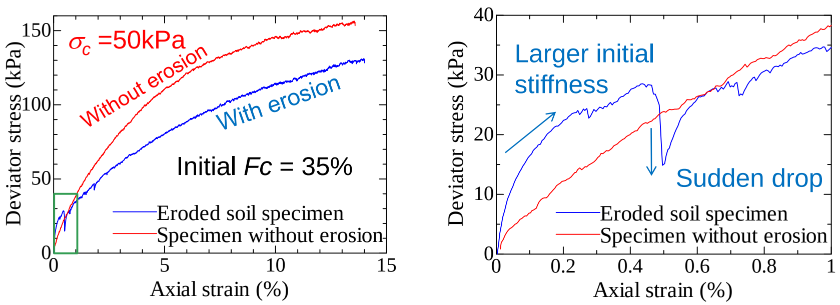
Fc = 35%, σ_c = 50, 100 & 200 kPa



- Strength of eroded samples is smaller than those without erosion.
- Stiffness at small strain level is larger in eroded samples.

Drained triaxial compression tests (cont'd)

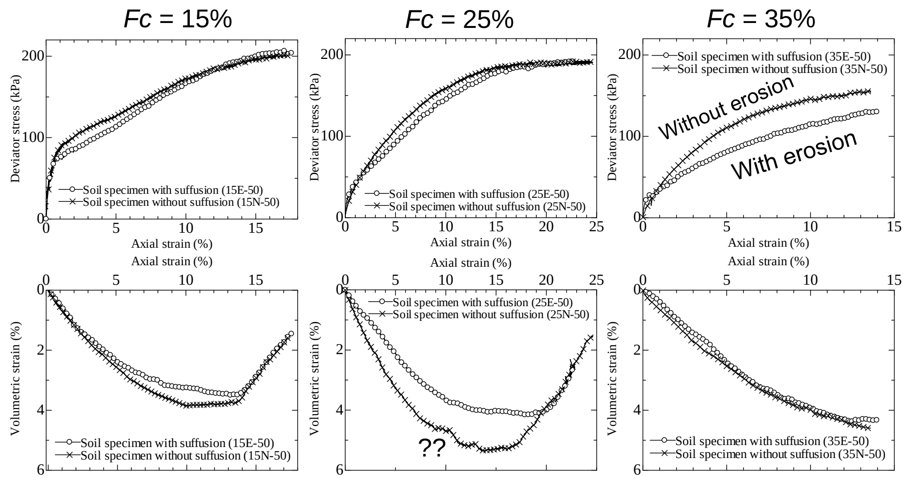
Drained response at small strain level



- Drained strength of eroded soil is obviously smaller than uneroded one.
- In the seepage (internal erosion) stage, fines got trapped around contact points of coarse particles, which may have formed local reinforcement.
  - Stiffness of the eroded soil at the beginning of shearing is large.
  - Due to deterioration of the reinforcement with the progress of shearing, strength of the eroded soil becomes smaller than that without erosion.

Drained triaxial compression tests (cont'd)

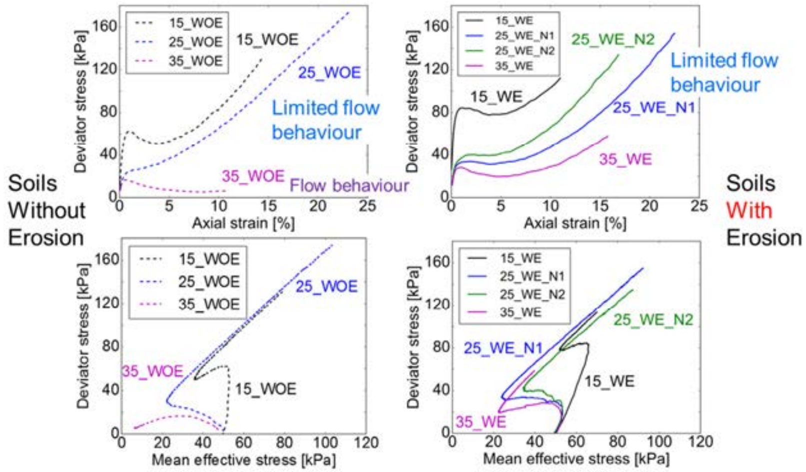
Fc = 15, 25 & 35%, σ_c = 50 kPa



- Strength of eroded samples is smaller than those without erosion, especially soil with larger fines content.

Undrained triaxial compression tests

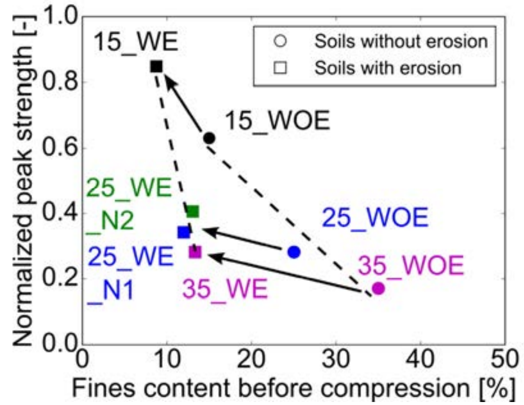
Fc = 15, 25 & 35%, σ_c = 50 kPa



- Peak strength of eroded soils is larger, while plateau after the peak, i.e., quasi-steady state, in stress-strain curve is longer for eroded soils.

Undrained triaxial compression tests (cont'd)

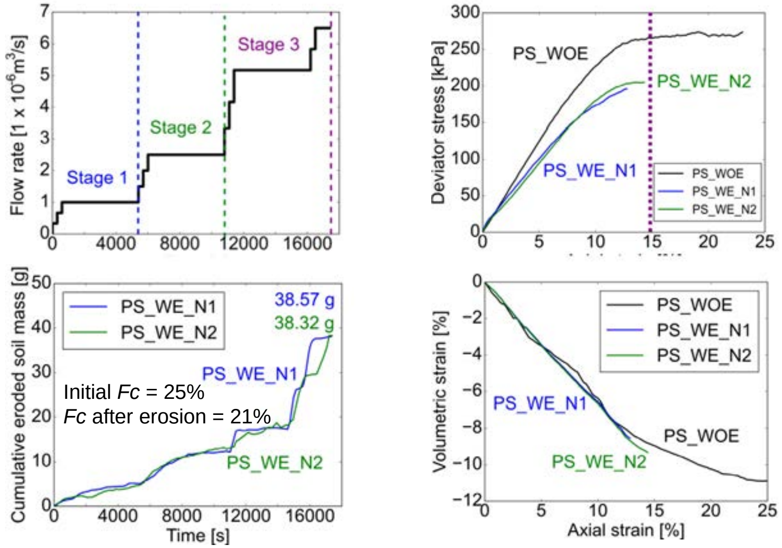
Strength normalised by initial confining pressure



- Soil with smaller fines content shows larger normalised peak strength.
- Normalised peak strength increases after internal erosion within the scope of this study.

Overall response in plain strain drained tests

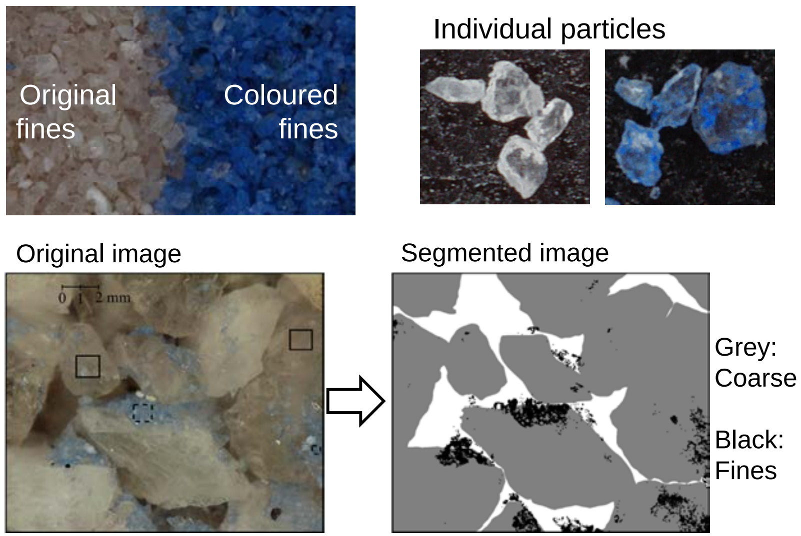
Erosion stage / Shearing stage



- Very similar to the triaxial drained tests.

Optical observation using microscope

Coloured fines are used



Estimation of fines engaged in force chain

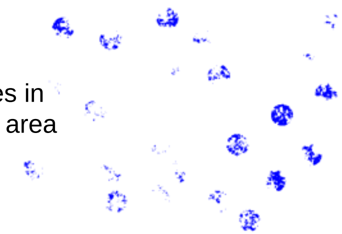
Fines at contact point of coarse particles are evaluated

(1) Original image

Pick up coordinates of contact points

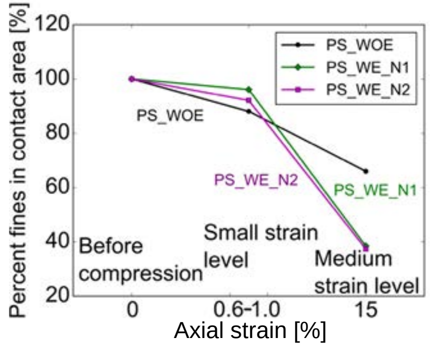
(2) Enclose contact area [Contact area: 0.085 mm^2]

(3) Fines in contact area



(4) Calculate average percentage of fines in contact area by image analysis.

Change in percentage of fines in contact area



- At <u>small strain</u> level (strain of 0.6-1.0%), <u>more fines remain in the contact area for eroded soil</u> comparing with that without erosion.
  - ➢ More fines are engaged in force chain for eroded soil.
- At <u>medium strain</u> level (strain of 15%), <u>percentage of fines in contact area for soil with erosion is smaller</u> than that for soils without erosion.
  - ➢ As void size larger for eroded soil, fines released from force chain can easily disappear.

Summary

Mechanical response of internally eroded soil

- Tests on gap-graded soils reveal that
  - ➢ Internal erosion makes <u>drained strength smaller</u>, while <u>undrained strength larger</u>.
  - ➢ <u>Stiffness of eroded soil is larger</u> than that without erosion.

Microscopic observation

- Fines trapped around contact point of coarse particles during seepage stage seem to be engaged in force chain at small strain level.
- Marked decrease in strength can occur even with localised / channelised internal erosion.

Related publications

- Ouyang, M. & Takahashi, A., Influence of initial fines content on fabric of soils subjected to internal erosion, *Canadian Geotechnical Journal*, Vol. 53, No. 2, 299-313, 2016. (DOI: 10.1139/cgj-2014-0344)
- Ouyang, M. & Takahashi, A., Optical quantification of suffosion in plane strain physical models, *Géotechnique Letters*, Vol. 5, No. 3, 118-122, 2015. (DOI: 10.1680/jgele.15.00038)
- Ke, L. & Takahashi, A., Drained monotonic responses of suffusional cohesionless soils, *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, Vol. 141, No. 8, 04015033, 2015. (DOI: 10.1061/(ASCE)GT.1943-5606.0001327)
- Ke, L. & Takahashi, A., Experimental investigations on suffusion characteristics and its mechanical consequences on saturated cohesionless soil, *Soils and Foundations*, Vol. 54, No. 4, 713-730, 2014. (DOI: 10.1016/j.sandf.2014.06.024)
- Ke, L. & Takahashi, A., Triaxial erosion test for evaluation of mechanical consequences of internal erosion, *Geotechnical Testing Journal, ASTM*, Vol. 37, No. 2, 347-364, 2014. (DOI: 10.1520/GTJ20130049)
- Ke, L. & Takahashi, A., Strength reduction of cohesionless soil due to internal erosion induced by one-dimensional upward seepage flow, *Soils and Foundations*, Vol.52, No.4, 698-711, 2012. (DOI: 10.1016/j.sandf.2012.07.010)