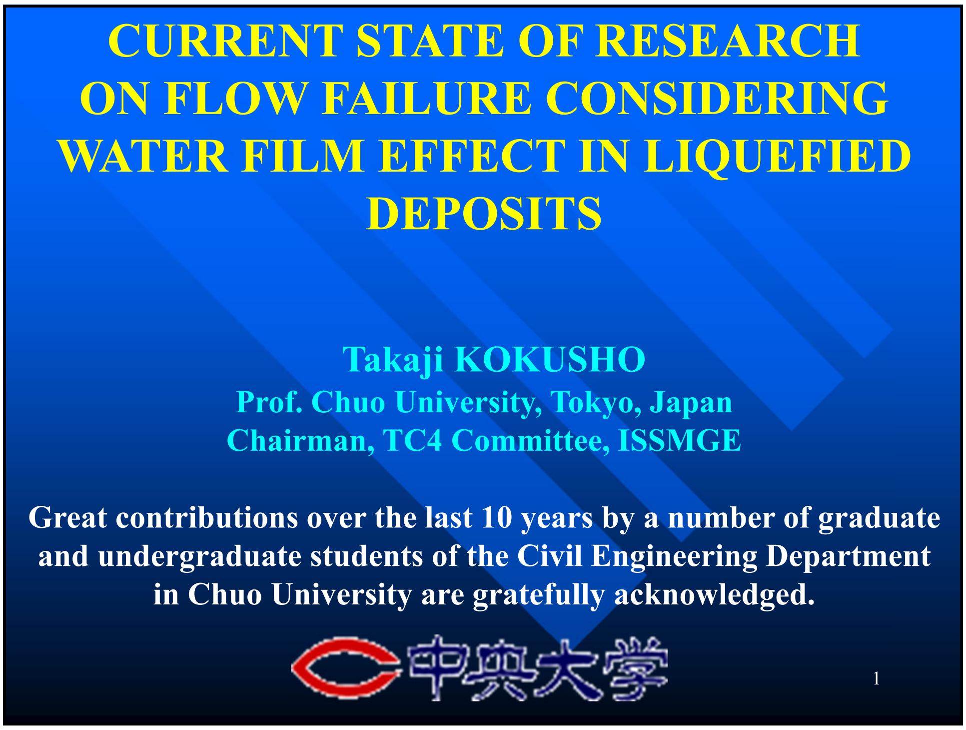
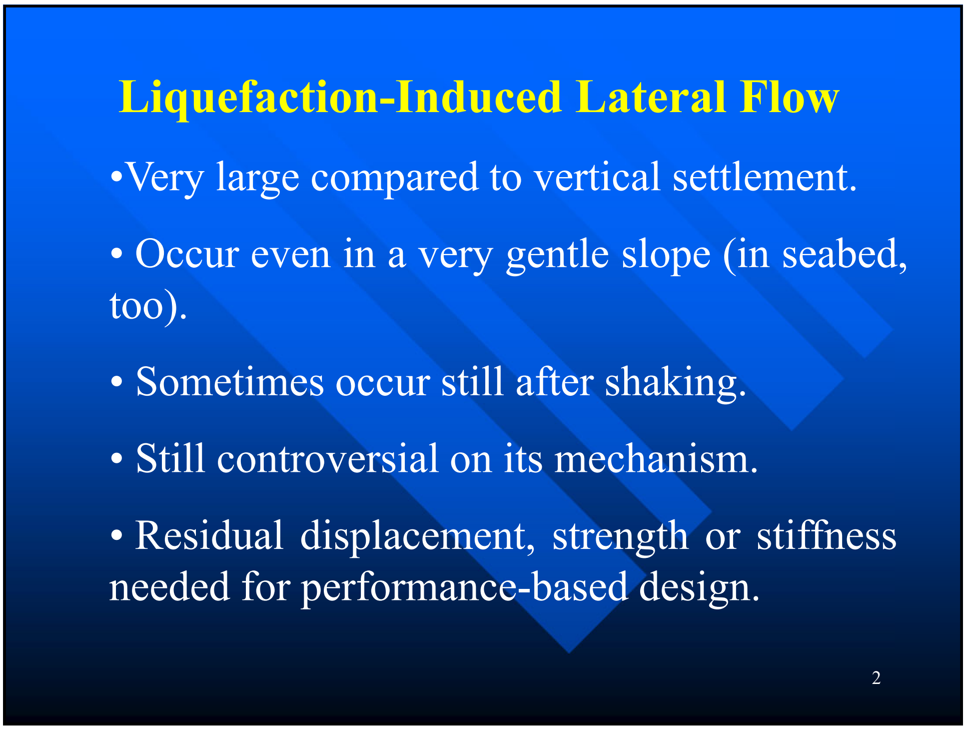


CURRENT STATE OF RESEARCH ON FLOW FAILURE CONSIDERING WATER FILM EFFECT IN LIQUEFIED DEPOSITS

Takaji KOKUSHO
Prof. Chuo University, Tokyo, Japan
Chairman, TC4 Committee, ISSMGE

Great contributions over the last 10 years by a number of graduate and undergraduate students of the Civil Engineering Department in Chuo University are gratefully acknowledged.

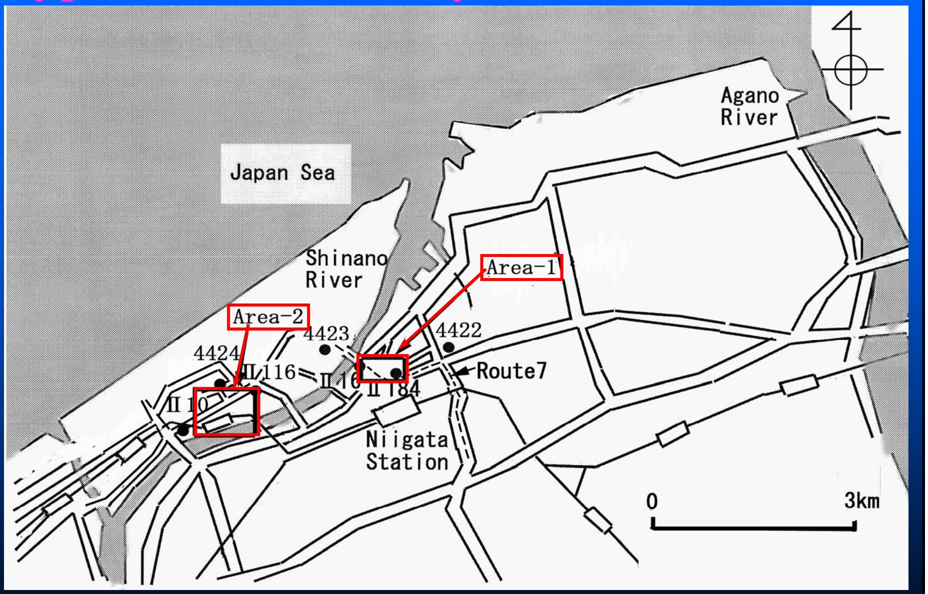
中央大学



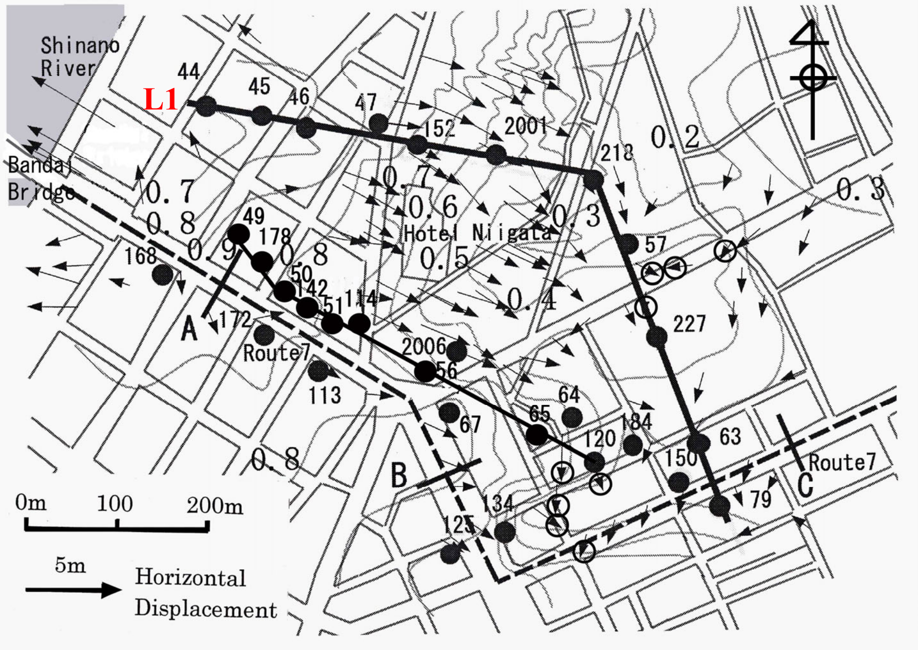
Liquefaction-Induced Lateral Flow

- Very large compared to vertical settlement.
- Occur even in a very gentle slope (in seabed, too).
- Sometimes occur still after shaking.
- Still controversial on its mechanism.
- Residual displacement, strength or stiffness needed for performance-based design.

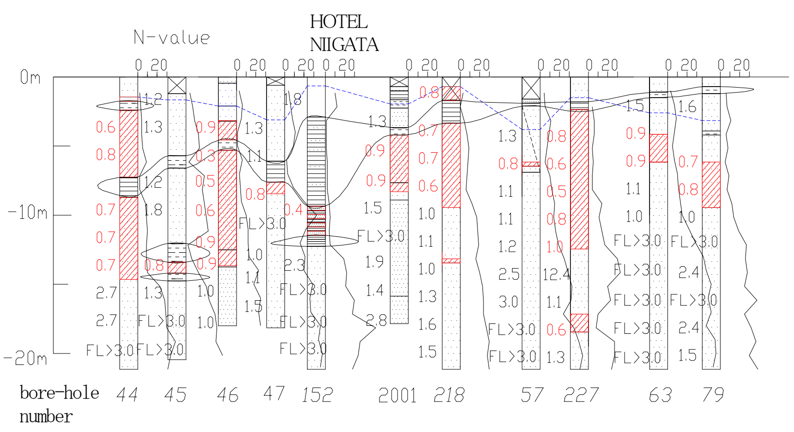
Typical Case History: Studies in Niigata City



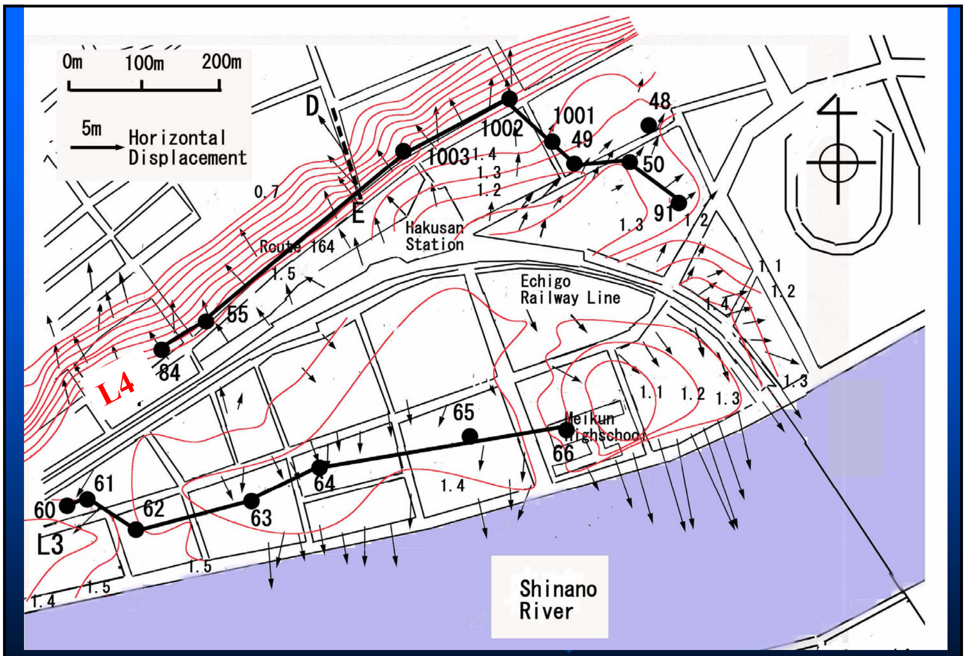
2 investigated areas in Niigata City



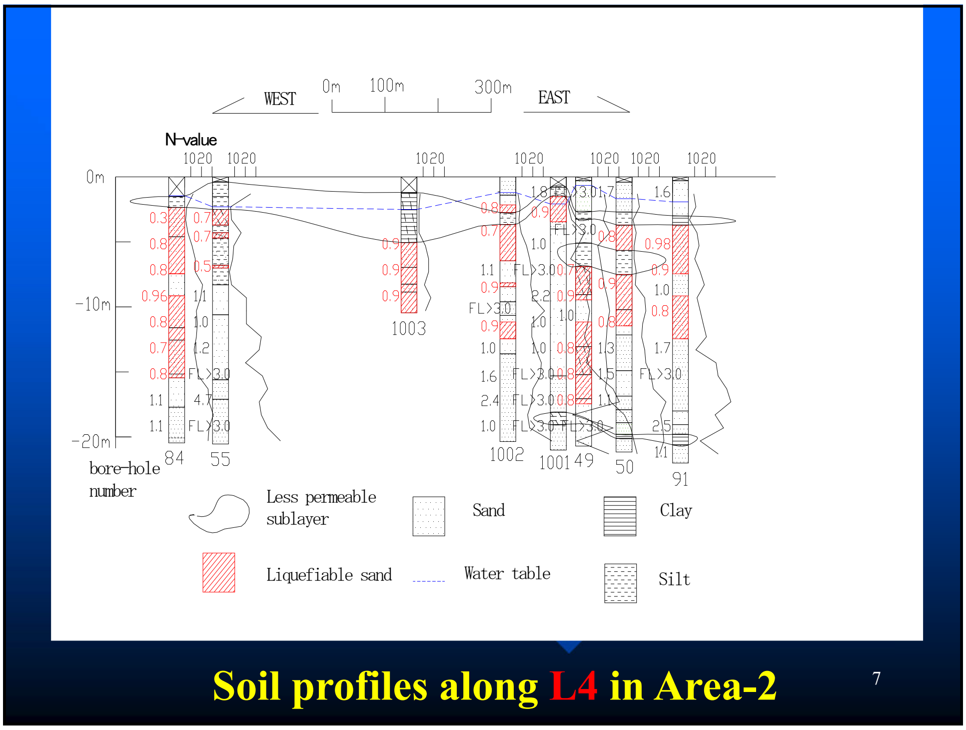
Flow vector and elevation contours in Area-1



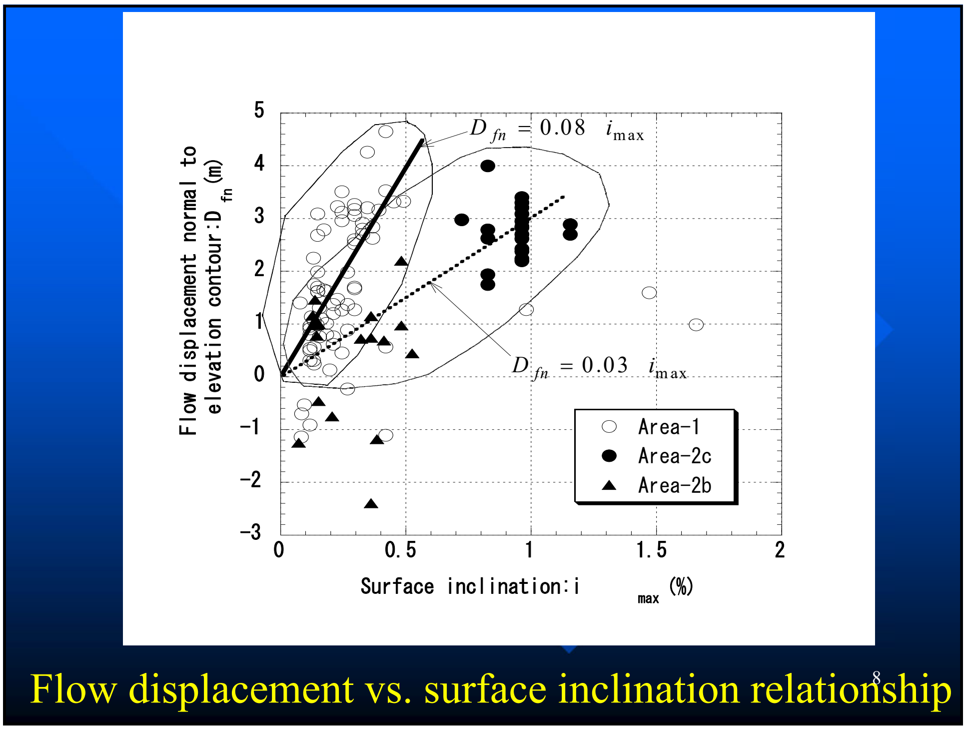
Soil profiles along L1 in Area-1



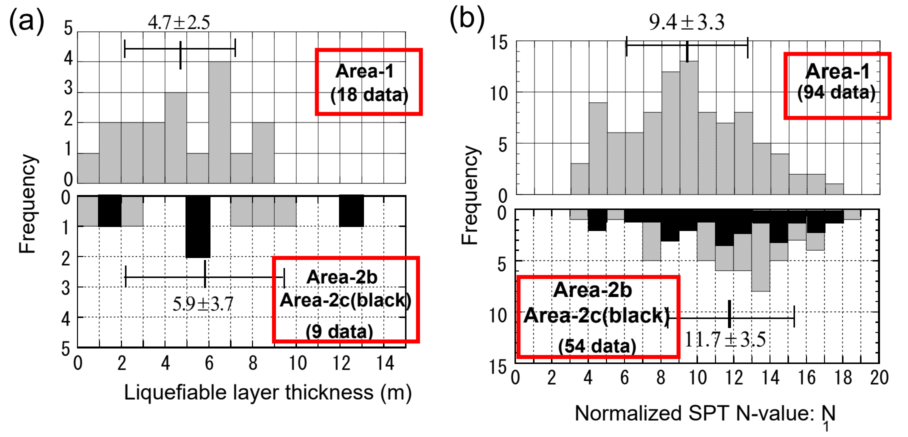
Flow vector and elevation contours in Area-2



Soil profiles along L4 in Area-2



Flow displacement vs. surface inclination relationship



Layer thickness

SPT N_1

Frequency of liquefiable layer thickness and N_1 in Area-1 & 2

DIFFERENT VIEWS ON POST-LIQ. RESIDUAL DISP./STRENGTH

UNDRAINED MECHANISM

(a) Inertia force during shaking accumulating residual displacement.

(b) Residual undrained strength lower than sustained static stress.

(c) (b)+ Effect of aftershock small tremors.

PARTIALLY DRAINED MECHANISM

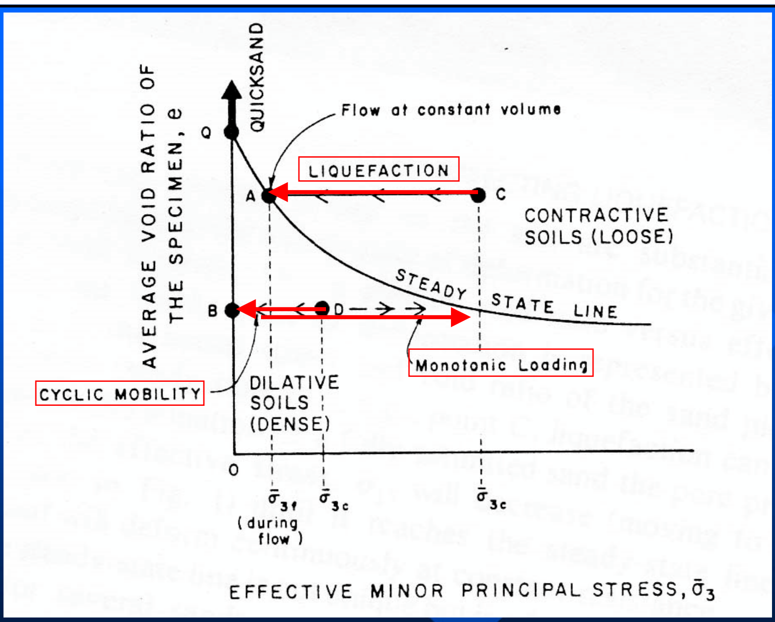
(d) Void-redistribution or water-film effect in layered soil.

Undrained mechanism (1)

Casagrande (1971) : Use of the term "liquefaction" for "sand developing substantial loss of its shear strength leading flow of soil mass."

Castro and Poulos (1977): using Steady State Line (SSL) interpreted "liquefaction" as "a result of undrained failure of a contractive sand looser than critical *e* "

Dilative sand, monotonically loaded, does not liquefy (does not flow). Dilative sand cyclically loaded reaches zero-effective stress, but does not flow, increasing resistance in subsequent monotonic loading (e.g. shake table test by Dobry et al. (1995)).

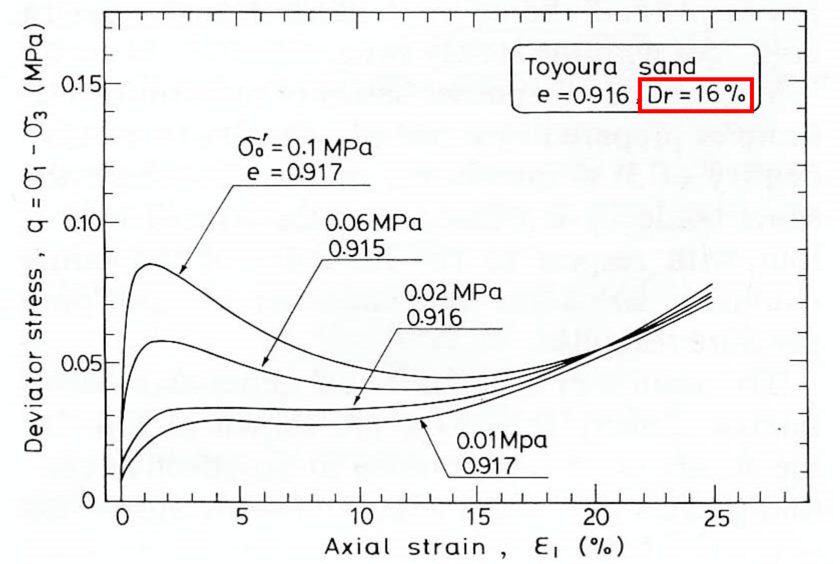


Steady state line on effective lateral stress versus void ratio (*e*) plane; liquefaction in contractive soils and cyclic mobility in dilating soils (Castro and Poulos 1977).

Undrained mechanism (2)

According to Castro and Poulos (1977), contractive sands looser than critical *e* exhibits flow-type failure without dilative response (under a high confining stress of 396 kPa). Undrained steady-state strength is defined as a function of *e* alone.

However, undrained tests under lower confining stresses (more realistic for liquefaction problems) indicate that shear stress tends to increase again after taking a minimum value even for very loose sands (e.g. Quasi-steady state strength by Ishihara 1993).



Typical stress–strain curves by undrained triaxial tests on very loose Toyoura sand under the confining stress of 0.1-0.01 MPa (Ishihara 1993).

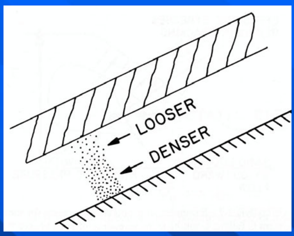
Undrained mechanism (3)

Meneses et al. (1998) showed that small aftershock tremors help reduce the residual strength to some extent, although it may not be generalized as a major cause of large lateral flow.

Thus, none of the undrained shear mechanisms seem to explain large lateral flow occurred in the past, because the sand is actually dilative in most circumstances and can not develop large flow deformation in the fully undrained condition.

Partially Drained Mechanism by Void Redistribution

First stated in NRC Report (1985), though intuitively suspected before.



Formation of water interlayers beneath low-permeability seams demonstrated in 1G or centrifuge tests by Liu & Qiao 1984, Fiegel, & Kutter (1994), Kokusho et al. (1998, 1999, 2000) and others.

Delayed sliding along a water film beneath low permeability seams demonstrated by Kokusho et al. (1998, 1999, 2000).

Soil stratification is a key of this mechanism.

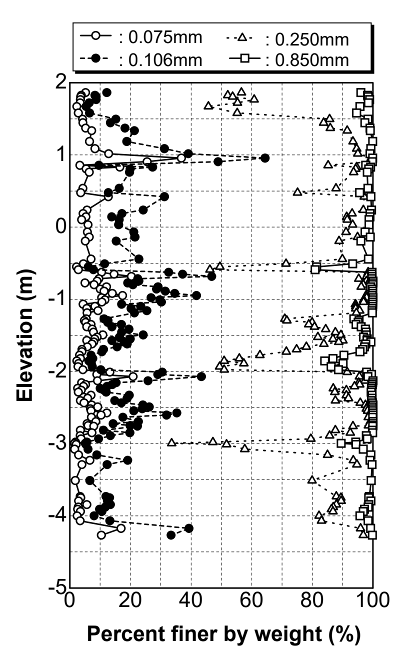
Soil Investigation

How much in situ soil is stratified?

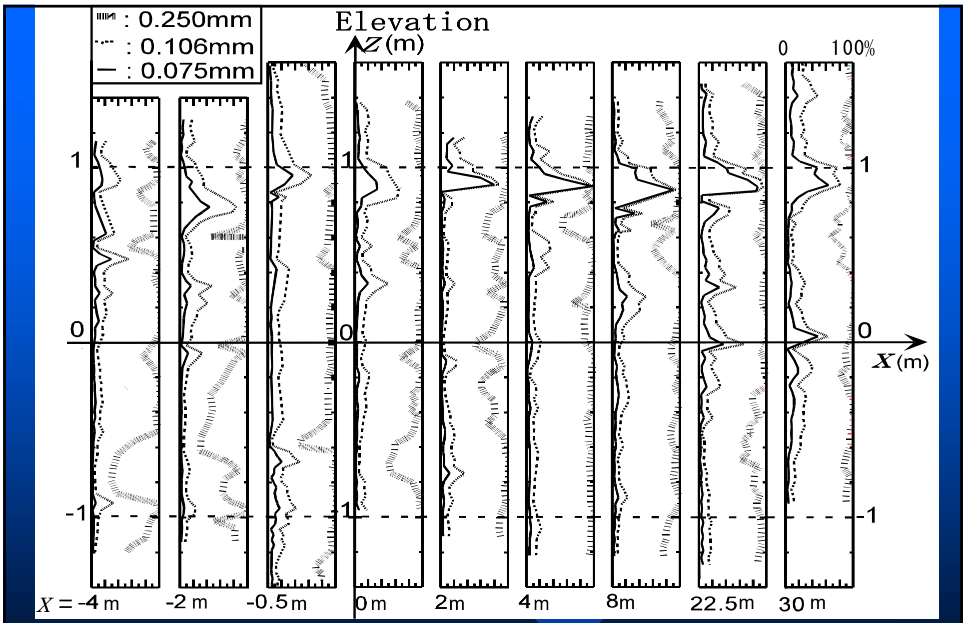
Reclaimed ground by hydraulic filling in Tokyo Bay area.

How soil stratification is investigated.

How soil stratification is investigated.

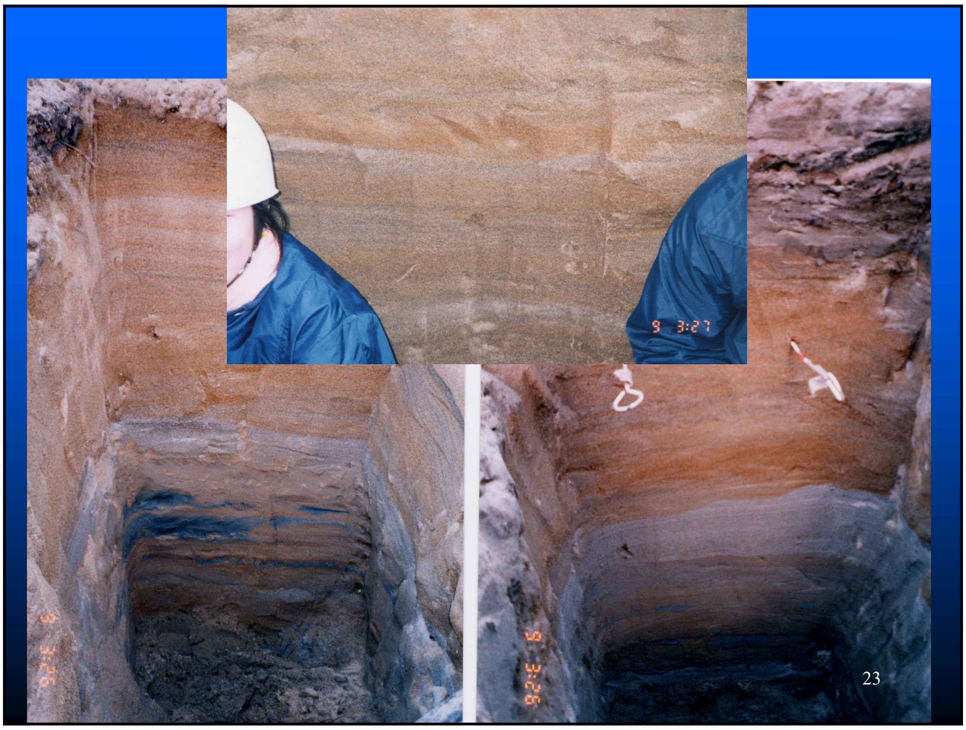


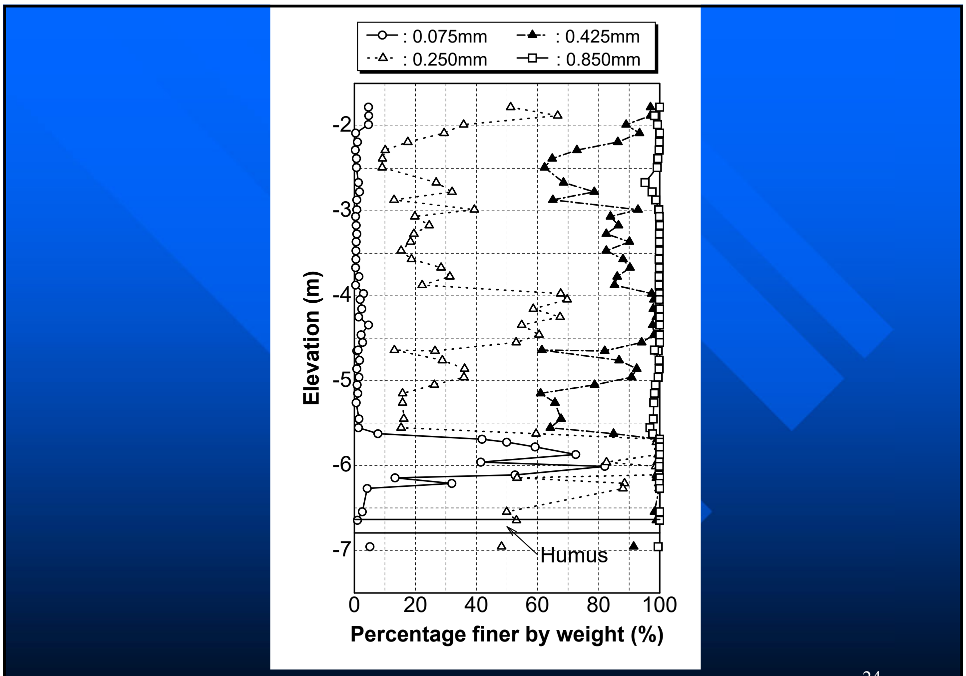
Reclaimed ground in Tokyo Bay Area



Horizontal continuation of fine soils in Reclaimed ground in Tokyo Bay Area

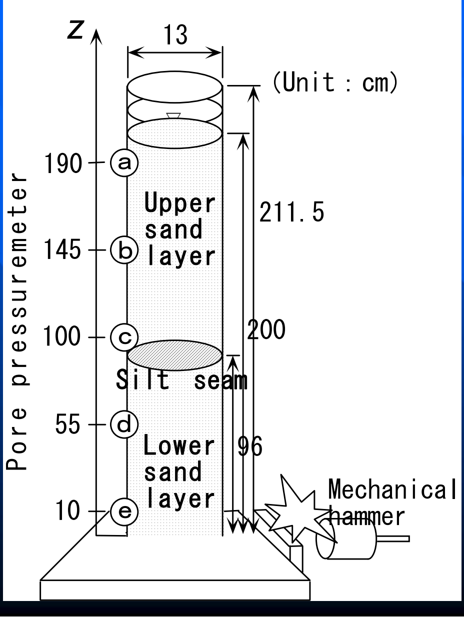
Alluvial sand deposit in Niigata City at the mouth of Shinano River

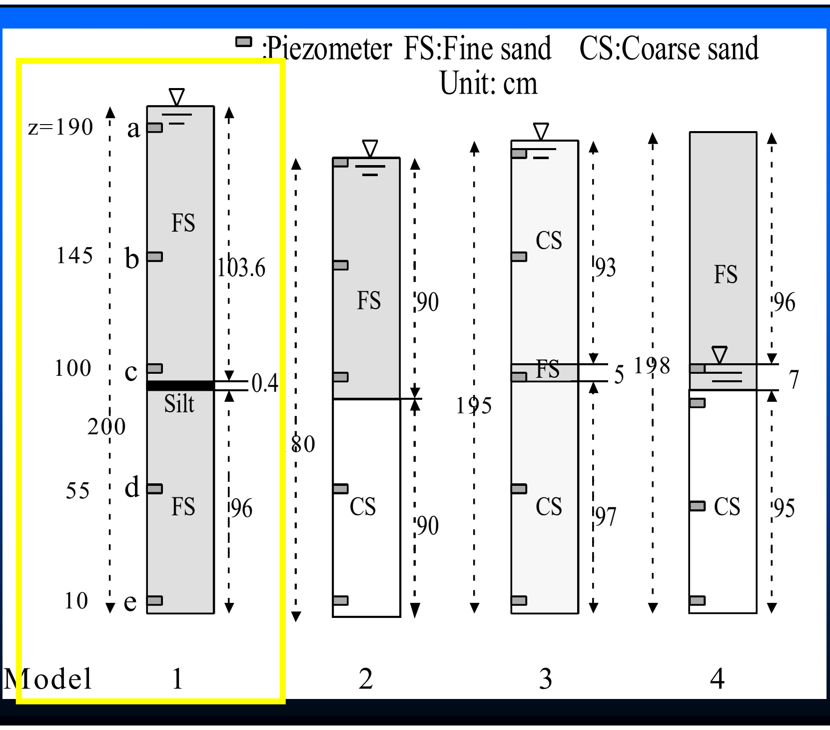


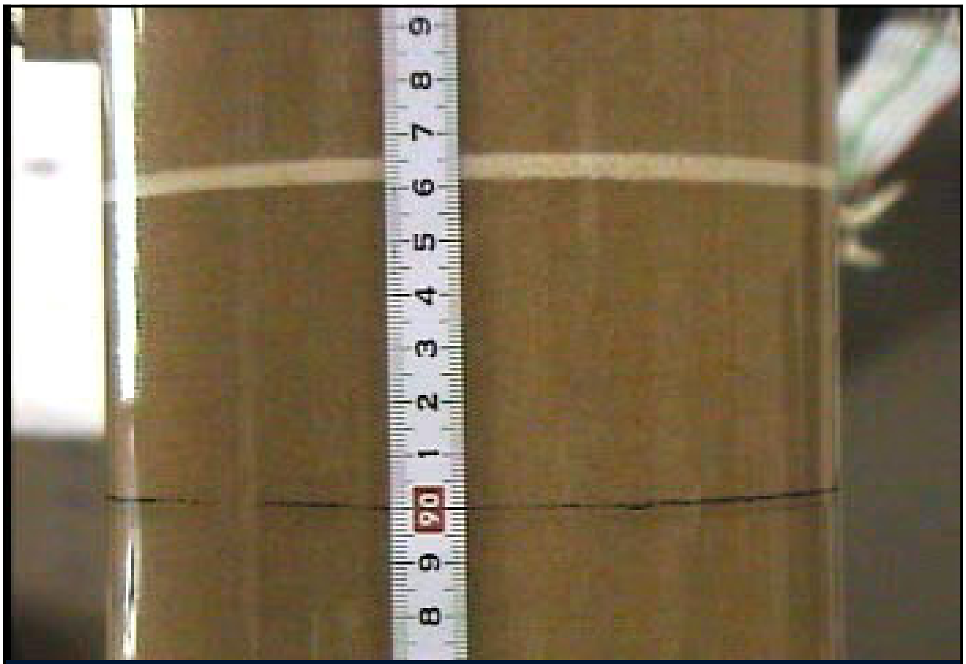


Alluvial ground in Niigata City liquefied in 1964

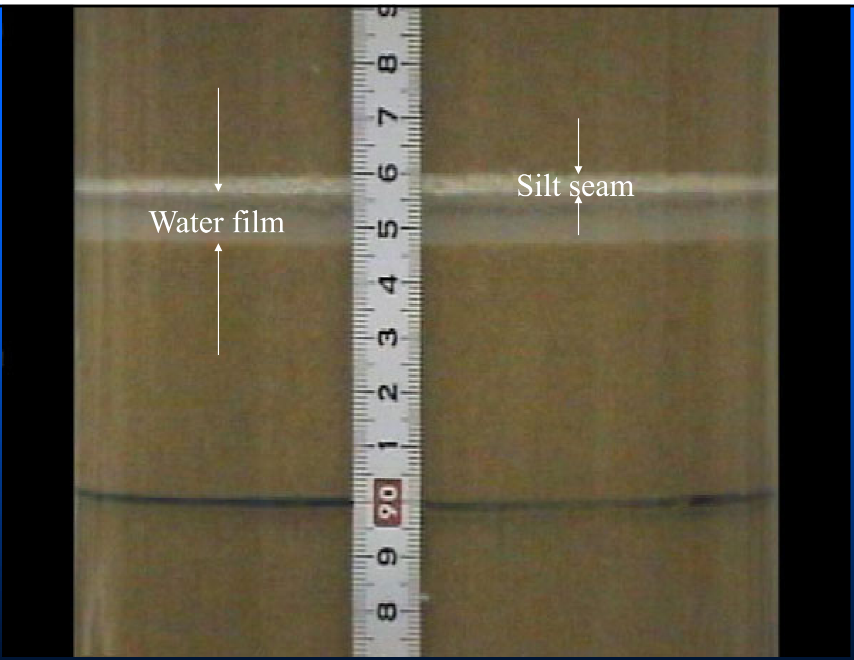
1-dimensional tube test for layered sand



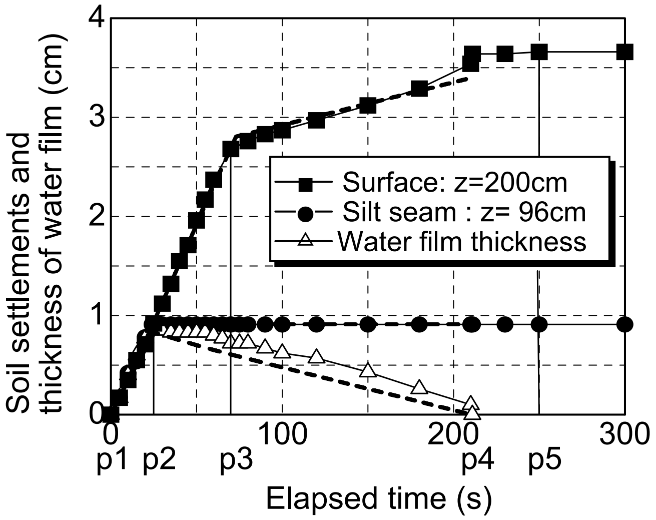




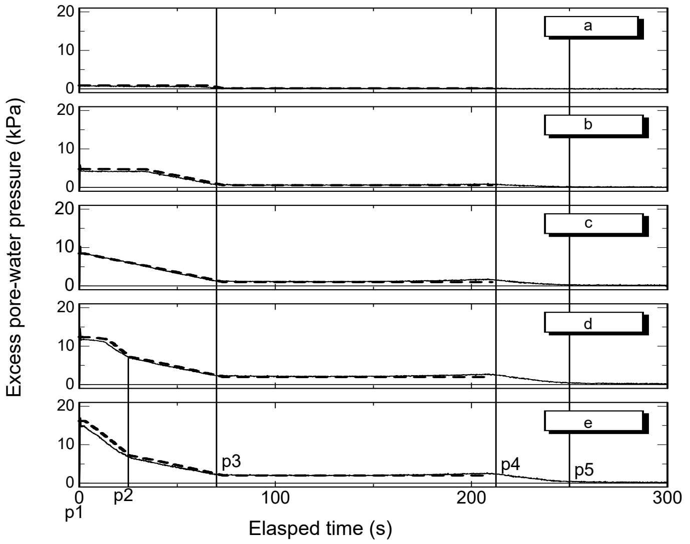
Sand with sandwiched non-plastic silt seam



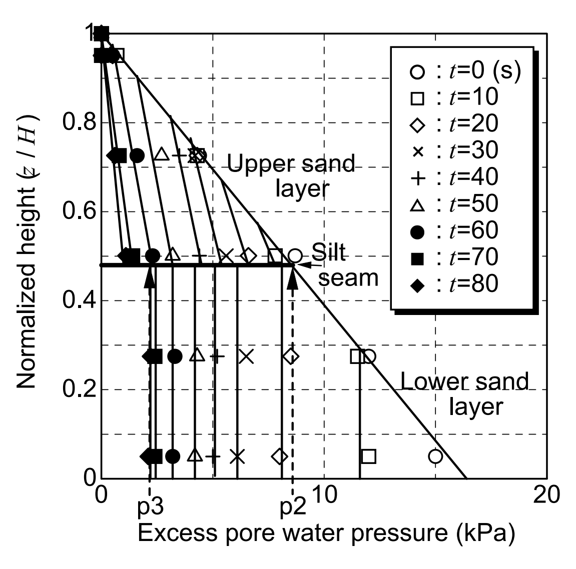
Sand with sandwiched non-plastic silt seam



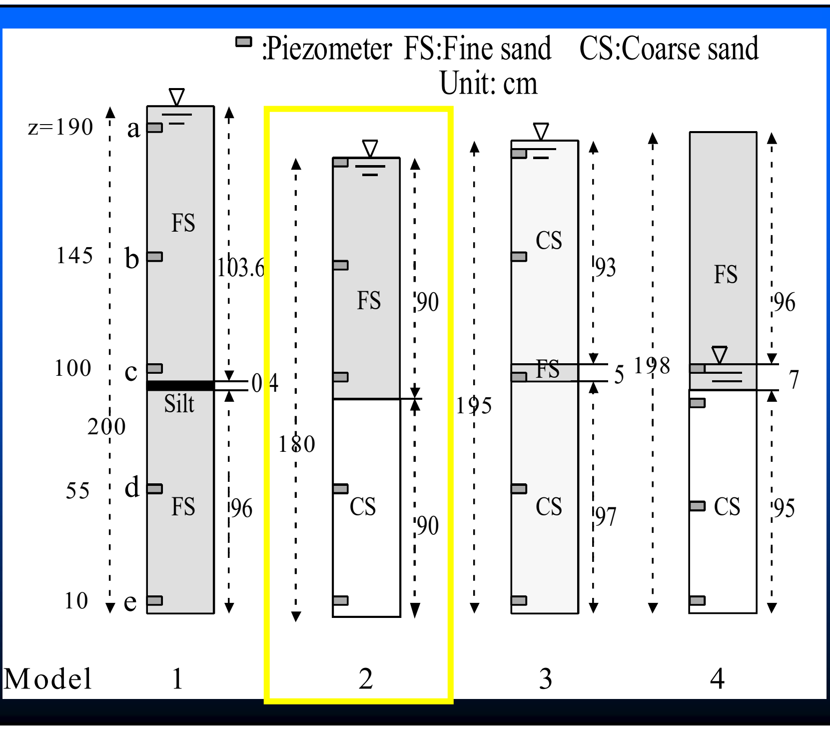
Time-histories of sand settlement and W.F. thickness in sand with sandwiched non-plastic silt seam



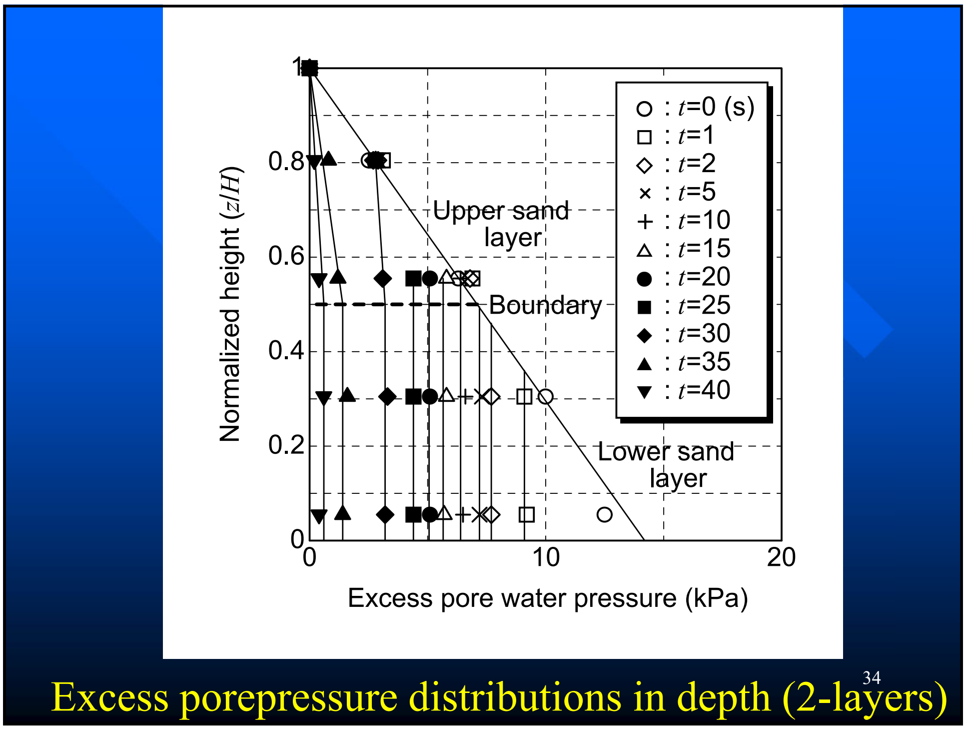
Excess porepressure time-histories at 5 levels in sand sandwiching silt seam



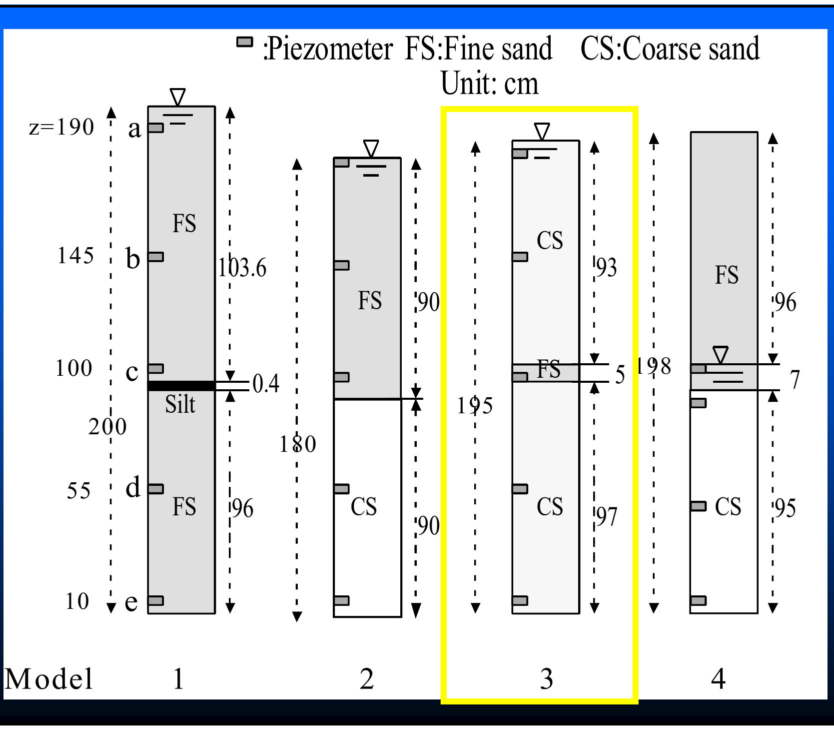
Excess porepressure distributions in depth



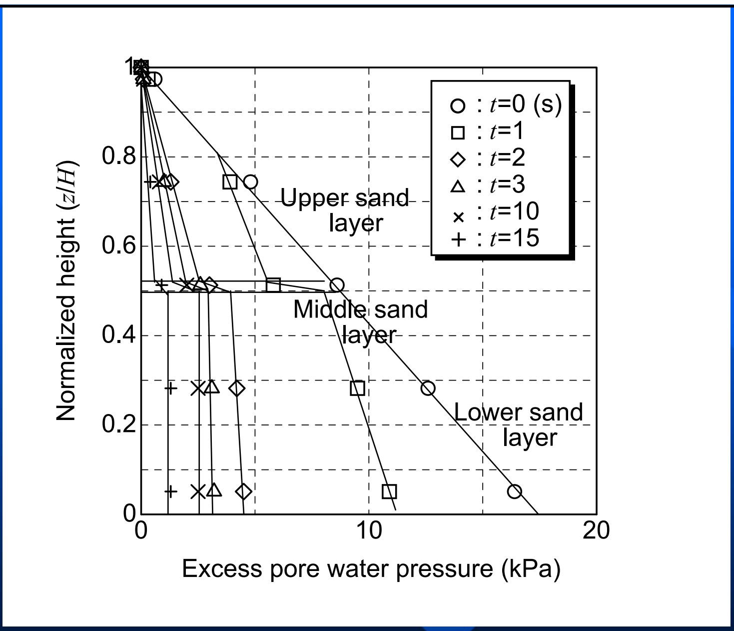
2-layers system (Upper fine-Lower coarse)



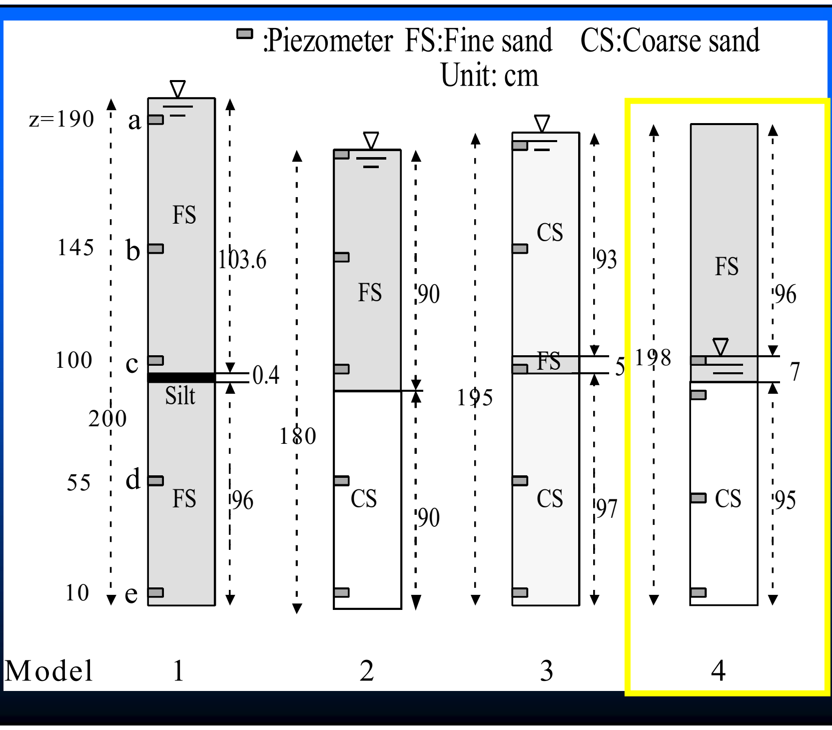
Excess porepressure distributions in depth (2-layers)

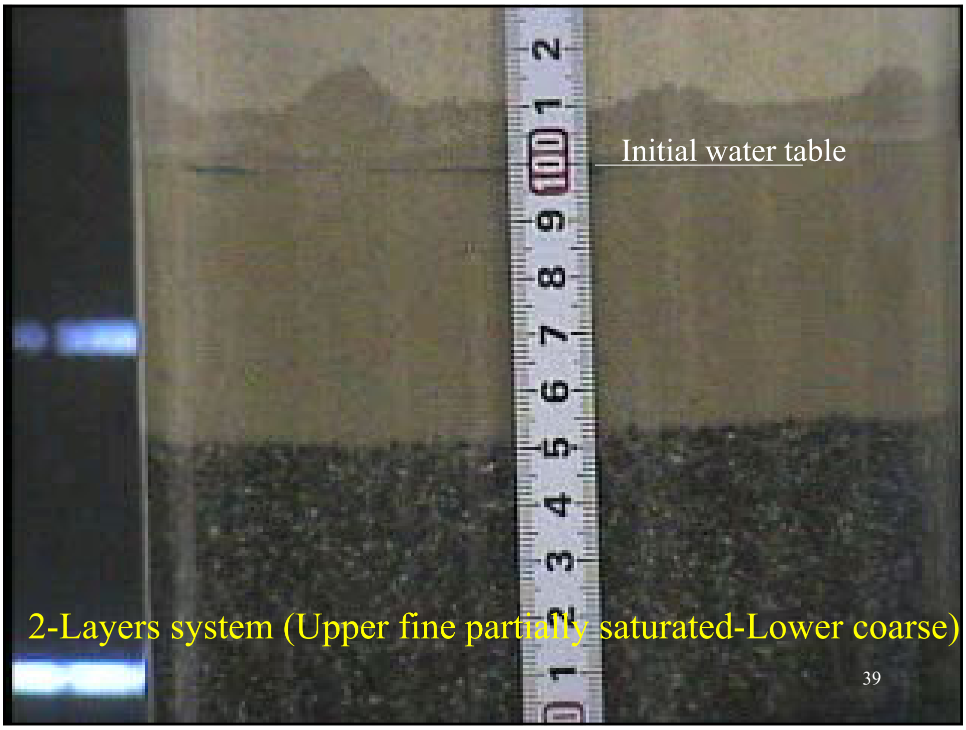


3-Layers system (Coarse-Fine-Coarse)

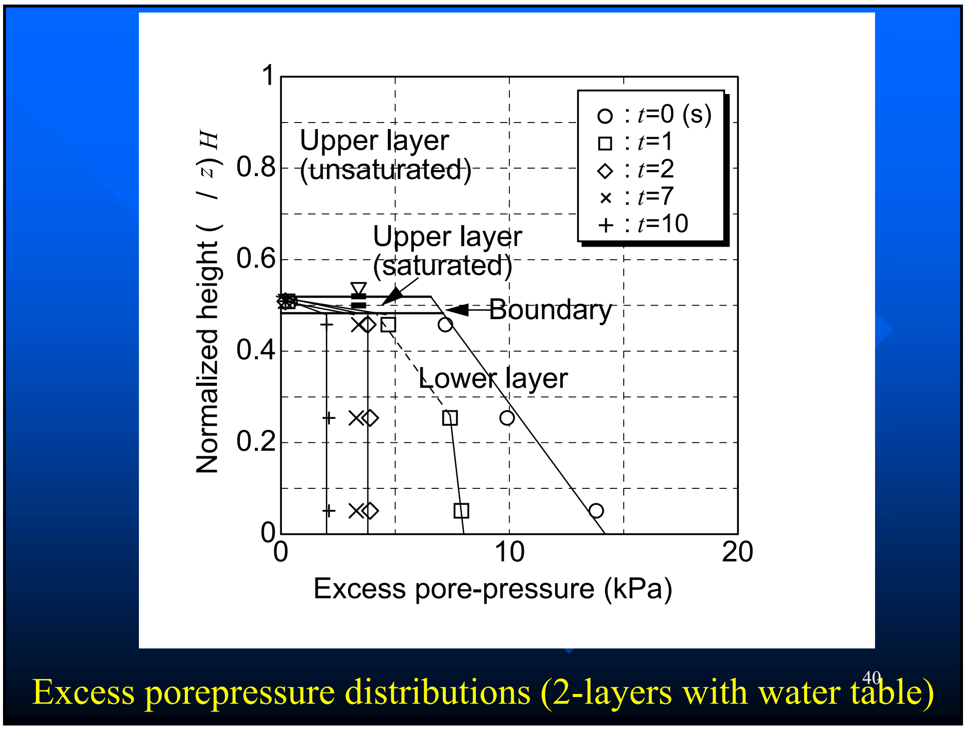


Excess porepressure distributions in depth (3-layers)

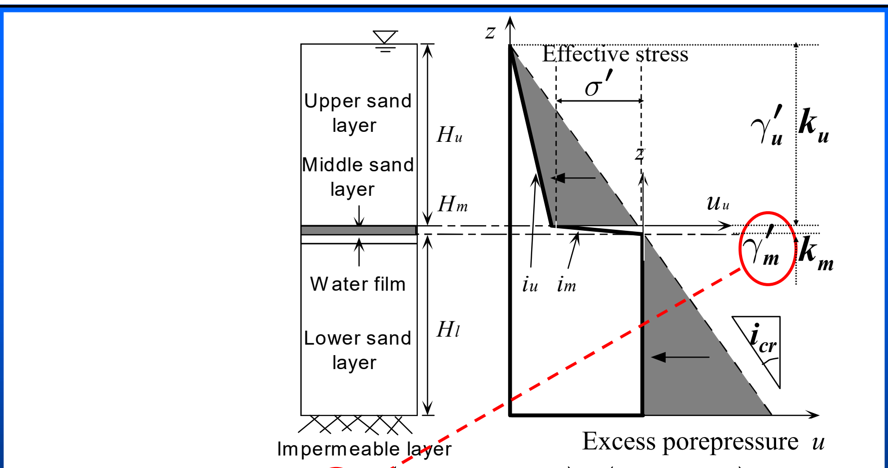




2-Layers system (Upper fine partially saturated-Lower coarse)



Excess porepressure distributions (2-layers with water table)

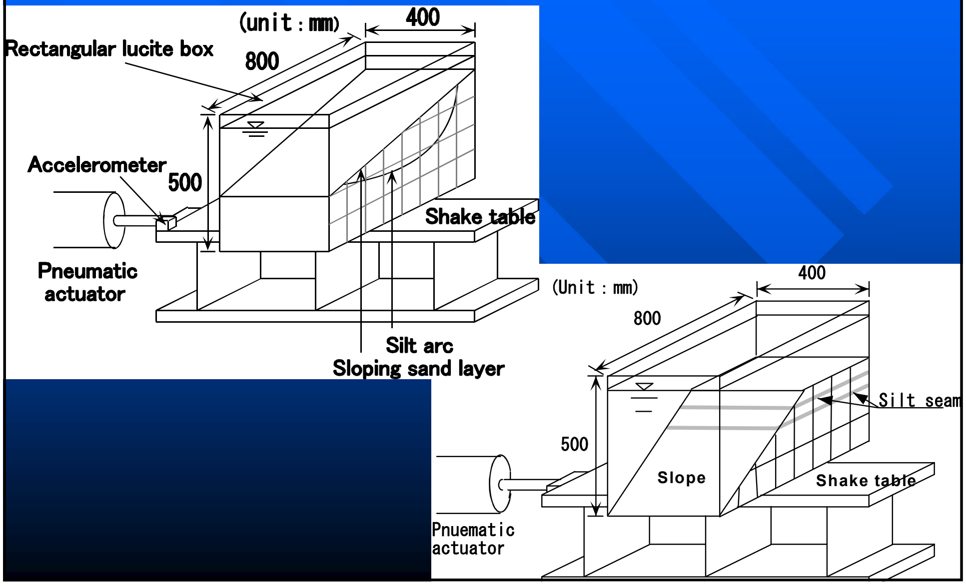


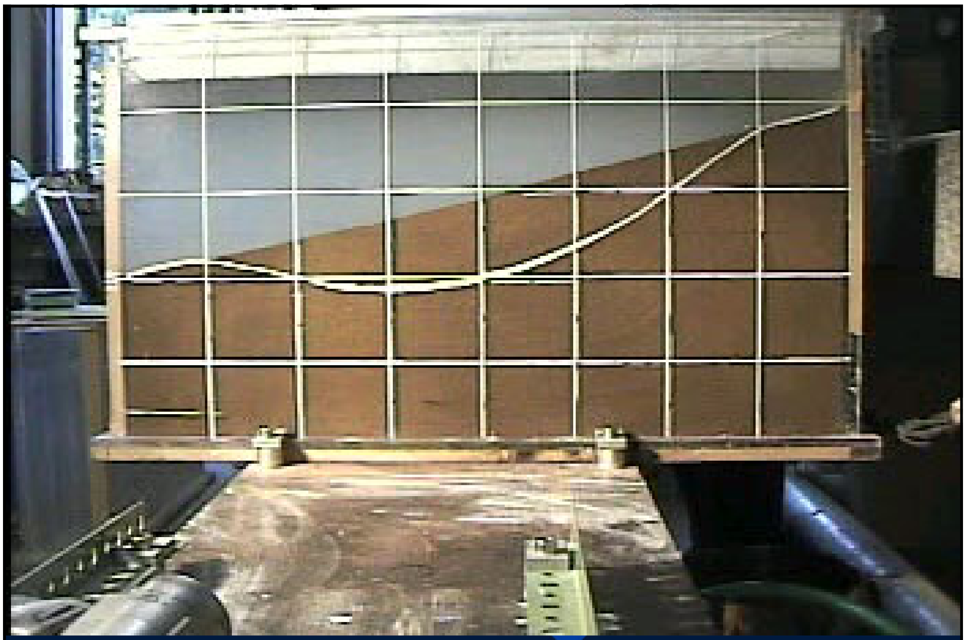
Excessive hydraulic gradient:

$$i_m = \frac{(\gamma'_m H_m + \gamma'_u H_u) - (\gamma'_u H_u - \sigma')}{\gamma_w H_m} = \frac{\gamma'_m}{\gamma_w} + \frac{\sigma'}{\gamma_w H_m} = i_{cr} + \frac{\sigma'}{\gamma_w H_m}$$

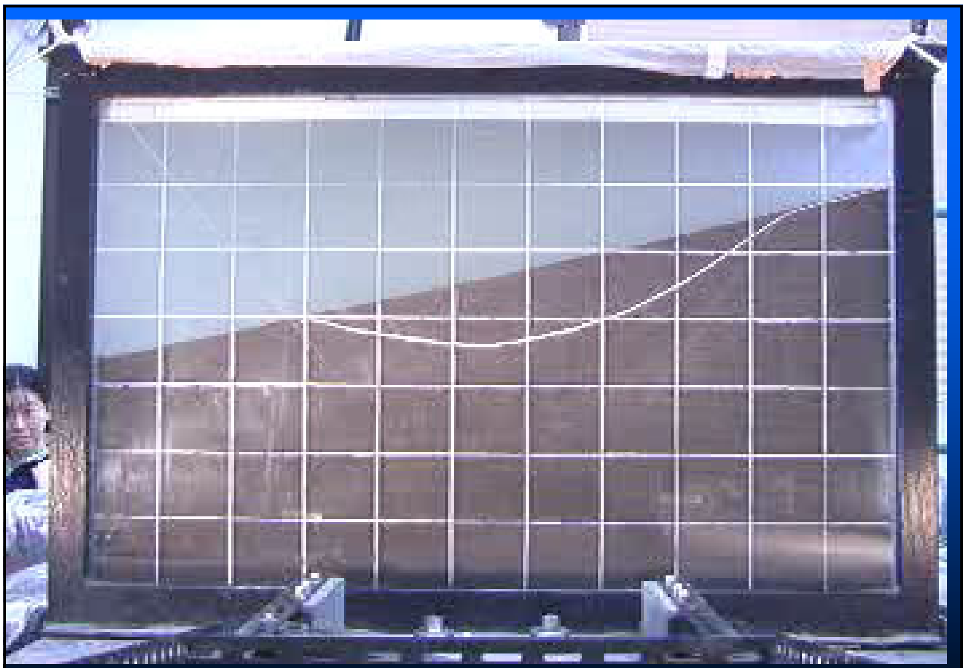
Water film formation mechanism

2-D Model Tests for Sand Slopes with Silt Seams



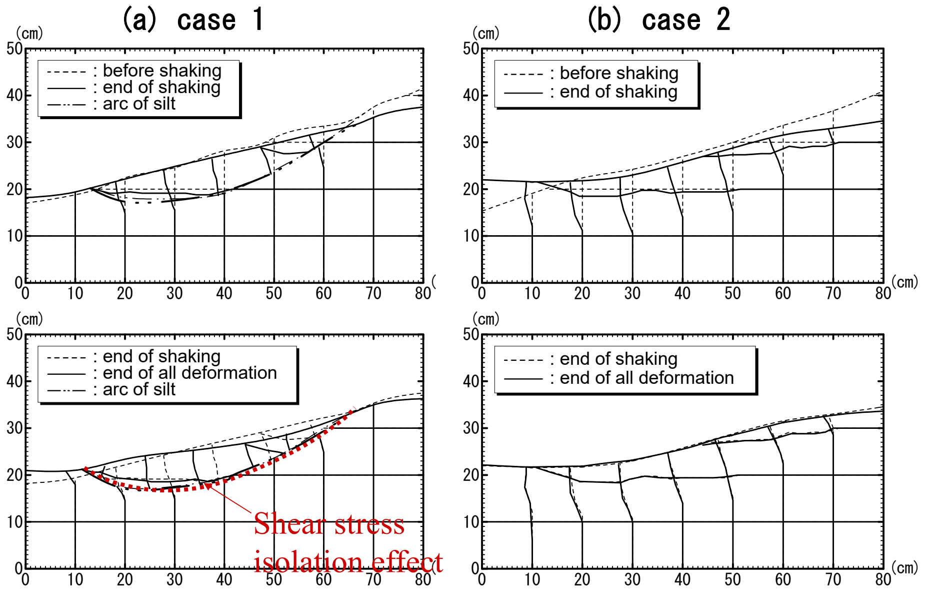


Silt arc in sand slope



Larger scale mode test with larger shake table

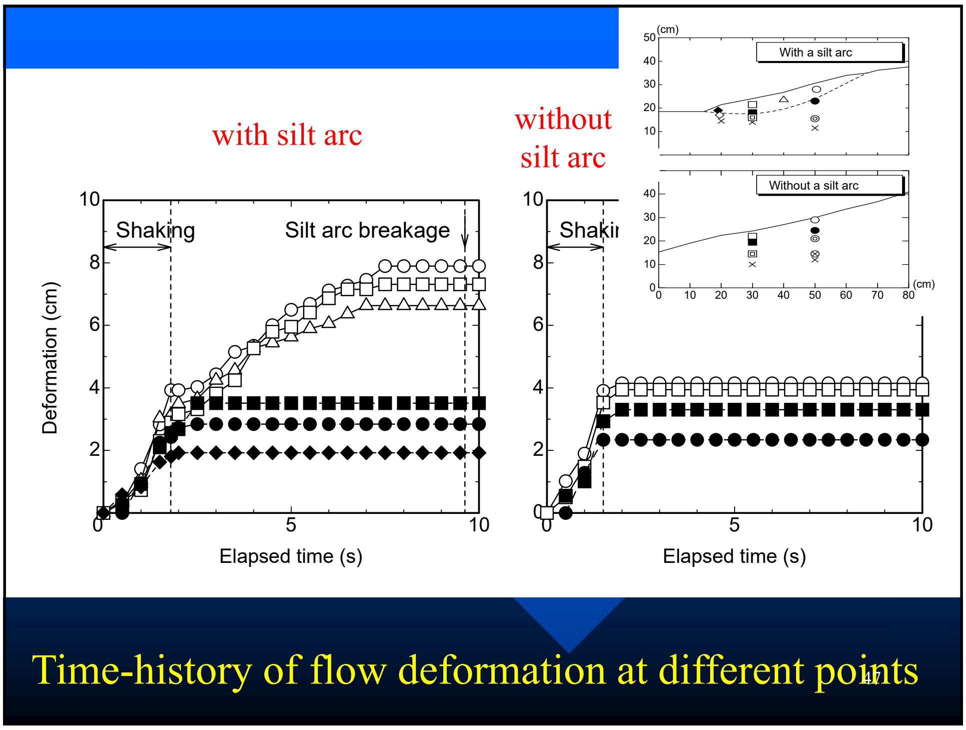
Two horizontal silt seams in sand slope



Shear stress isolation effect

With silt seam

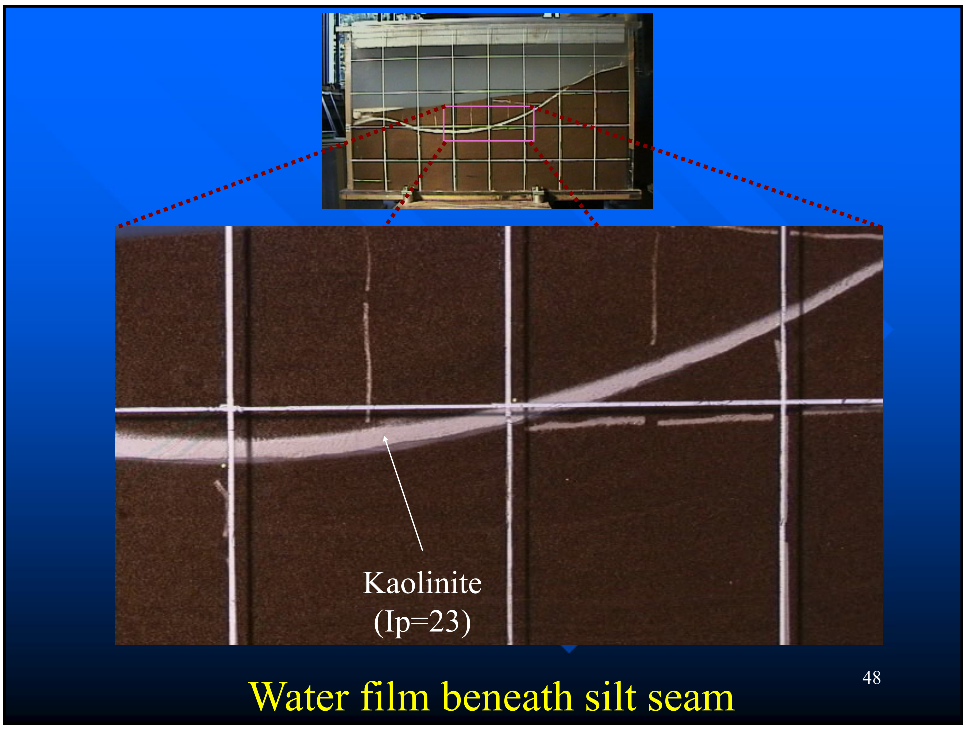
Without silt seam



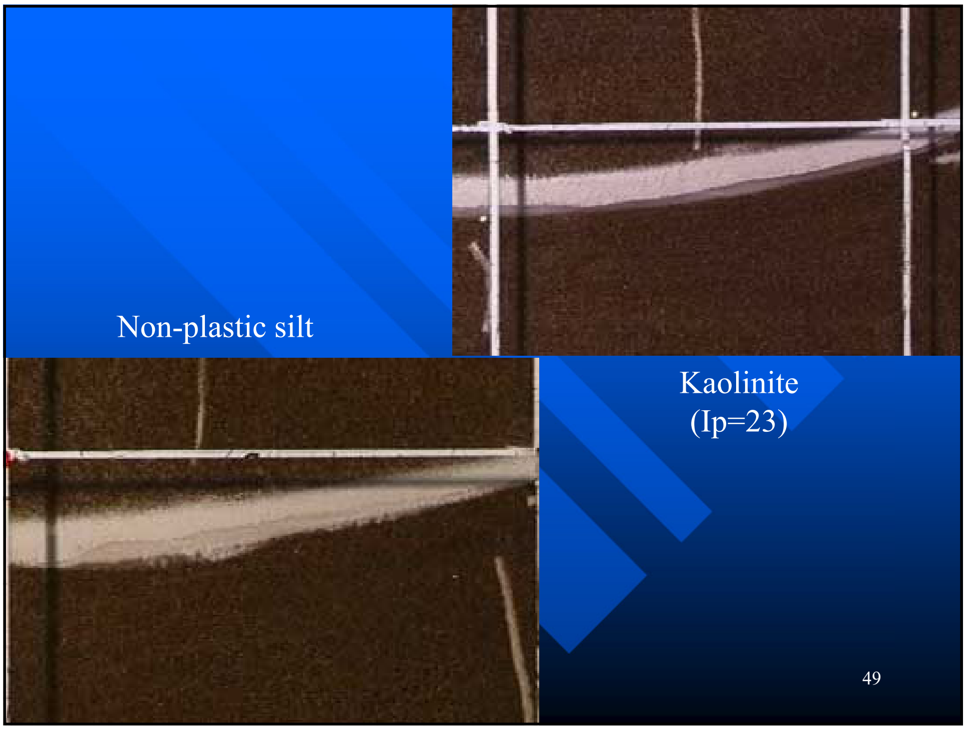
with silt arc

without silt arc

Time-history of flow deformation at different points

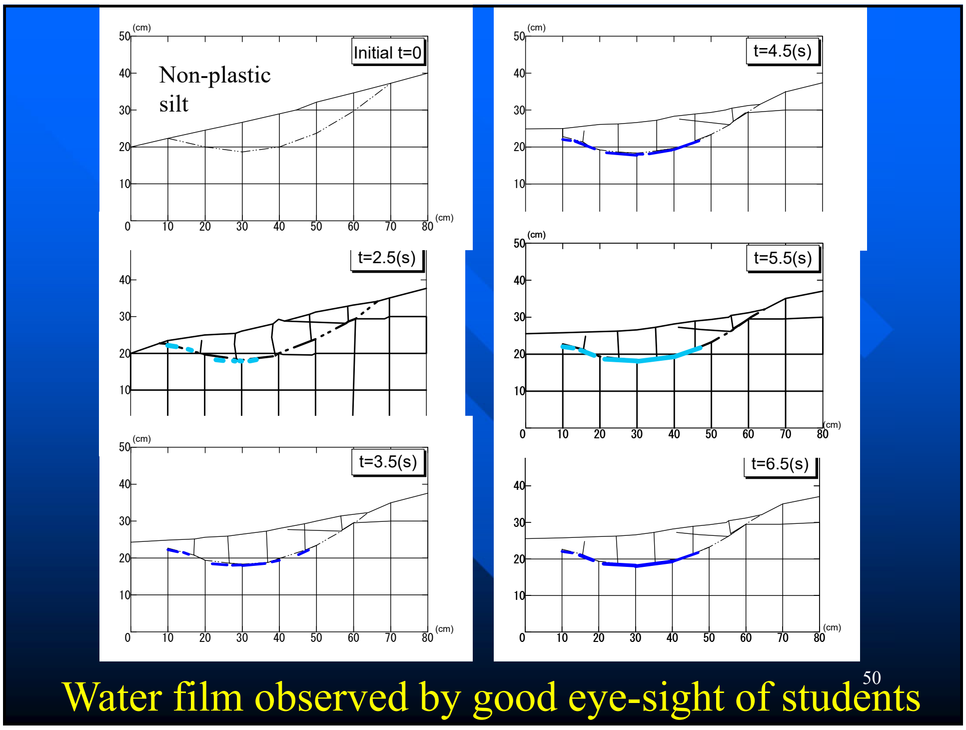


Water film beneath silt seam

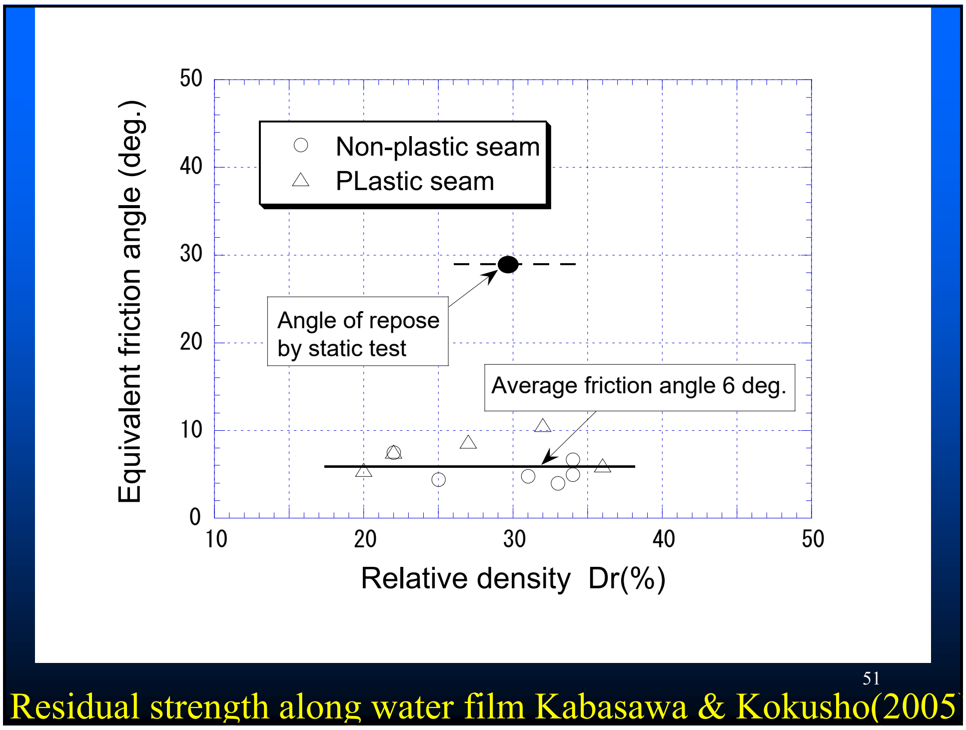


Non-plastic silt

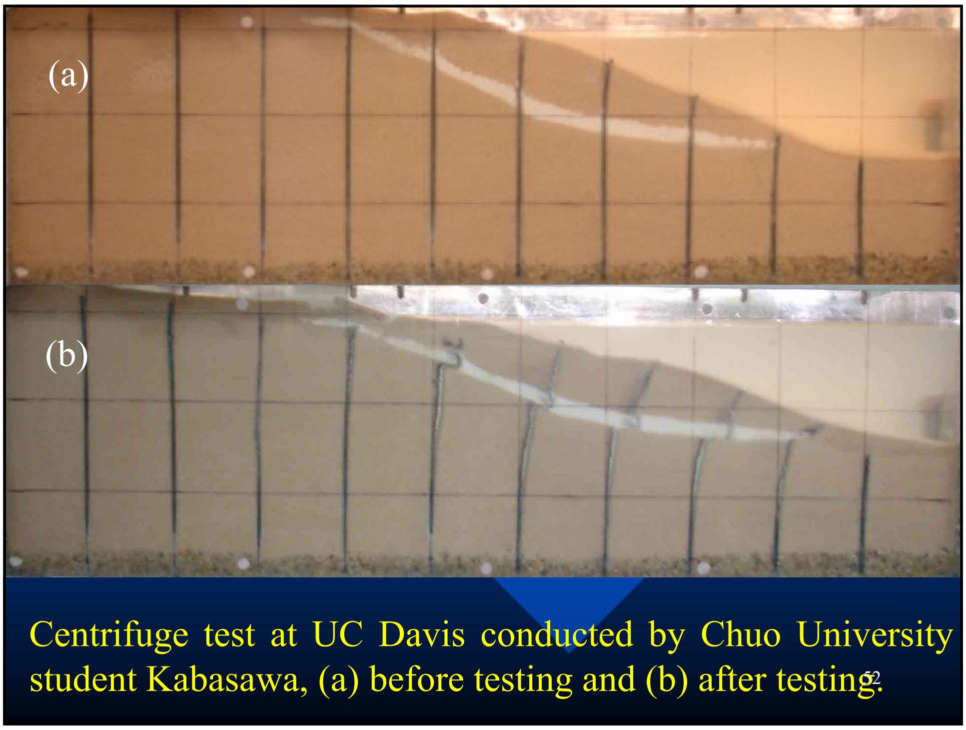
Kaolinite
(Ip=23)



Water film observed by good eye-sight of students



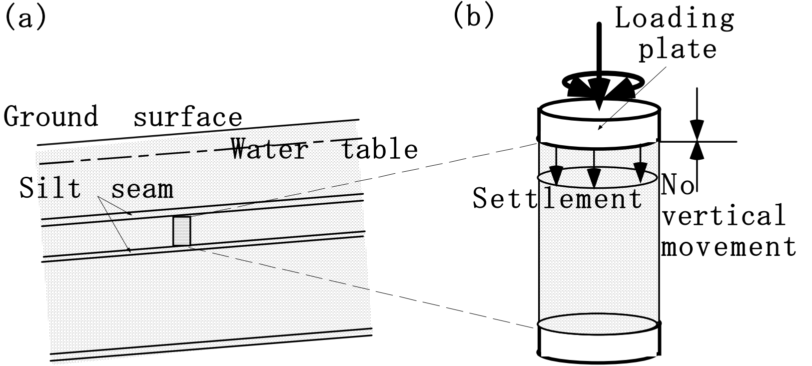
Residual strength along water film Kabasawa & Kokusho(2005



Centrifuge test at UC Davis conducted by Chuo University student Kabasawa, (a) before testing and (b) after testing.

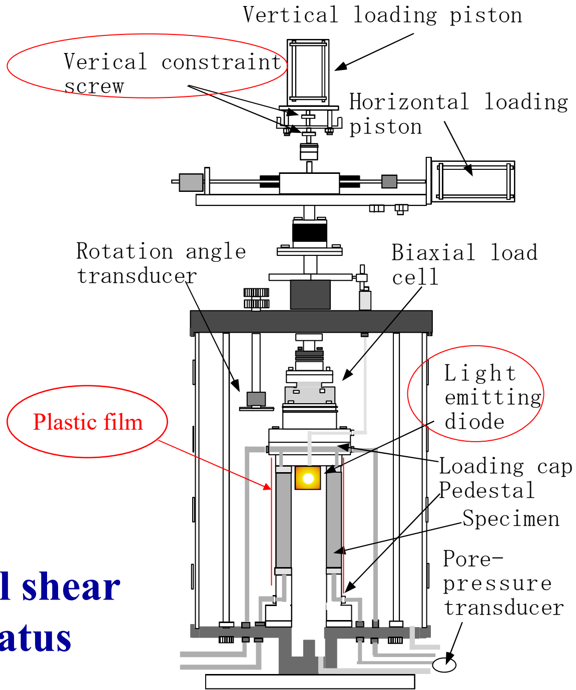
Centrifuge test at UC Davis conducted by Chuo University student Kabasawa, (a) before testing and (b) after testing.

Undrained Cyclic Shear Test for Water Film Generation

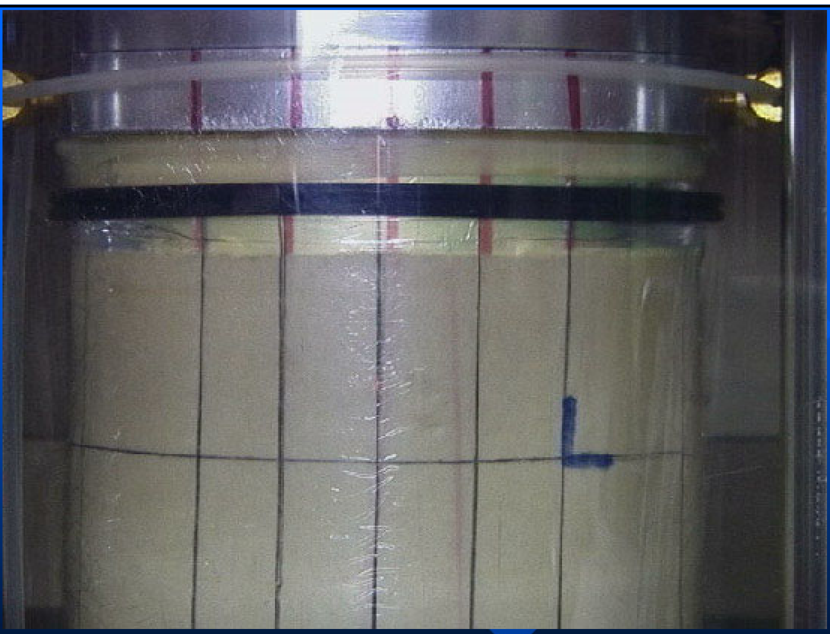


A soil element in a level or inclined sand layer beneath a sandwiched low permeable sublayer under cyclic loading.

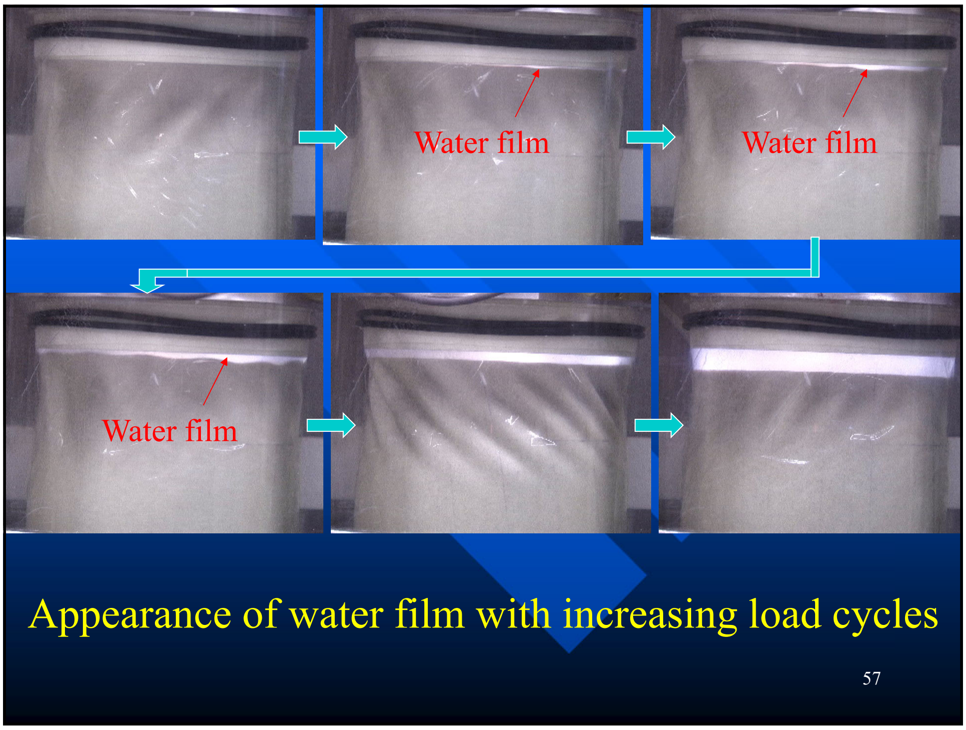
Hollow cylindrical torsional test apparatus simulating the soil element.



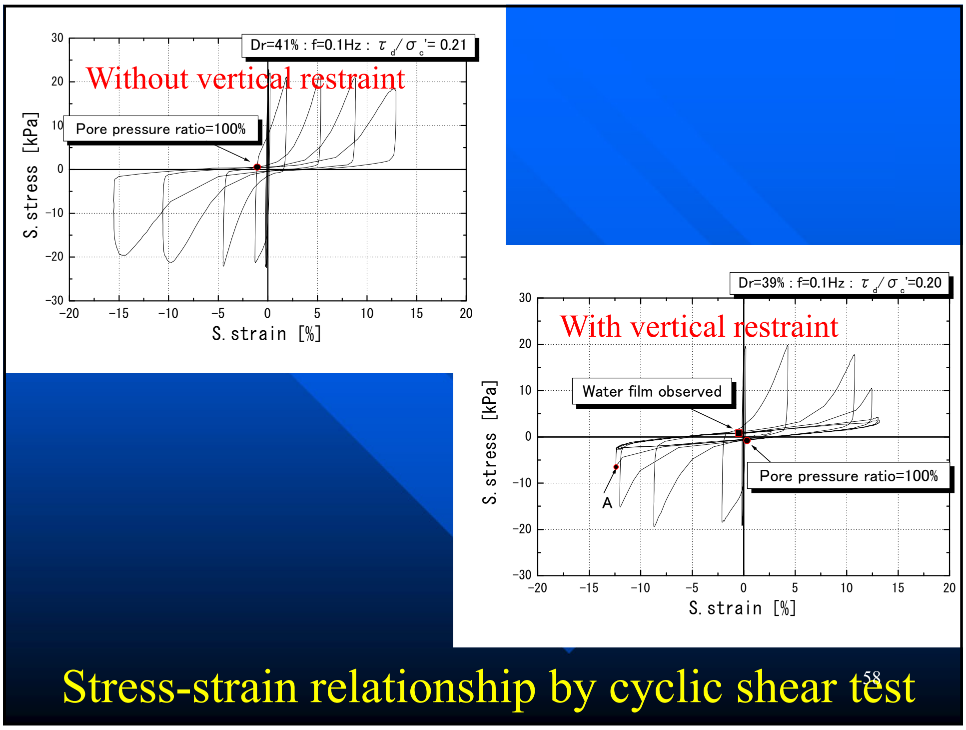
Torsional shear apparatus



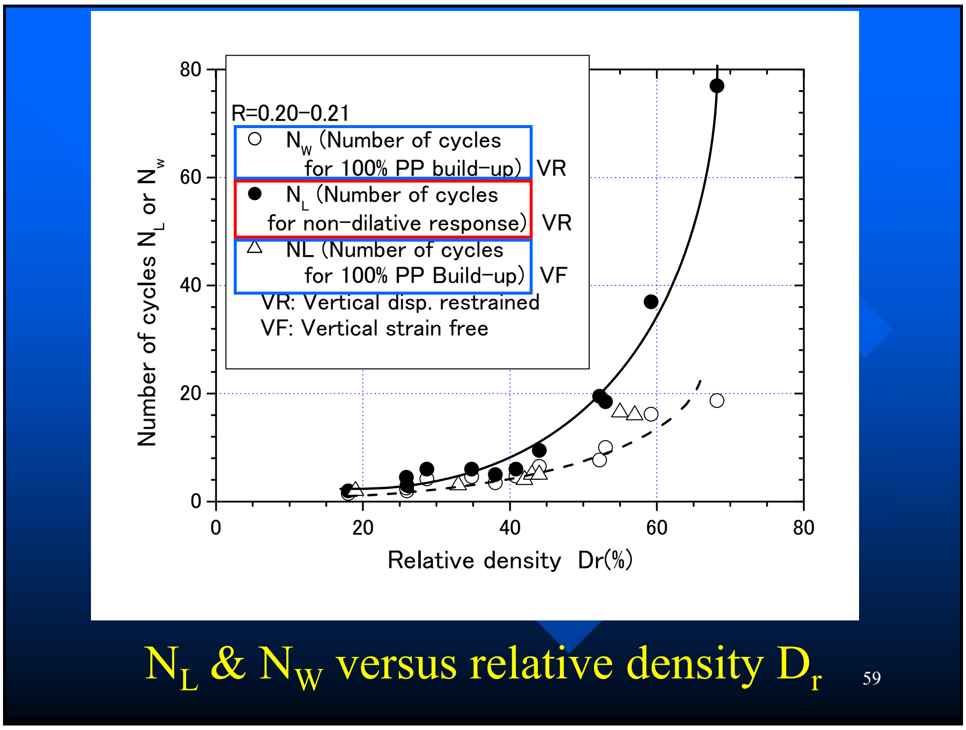
Top of specimen and loading cap covered with plastic film



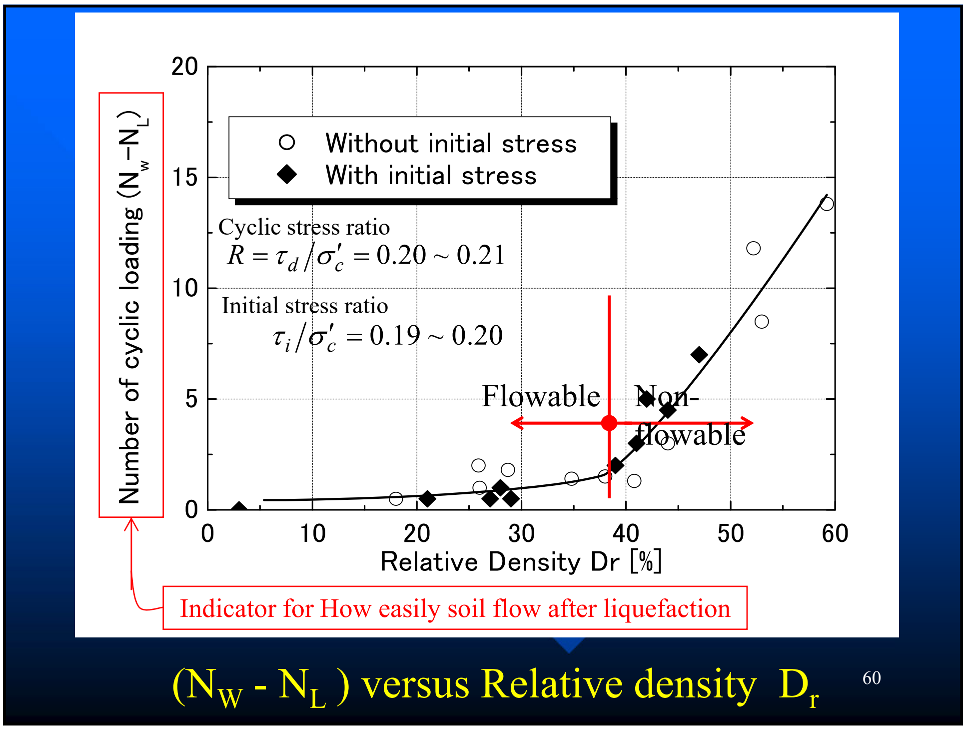
Appearance of water film with increasing load cycles



Stress-strain relationship by cyclic shear test



N_L & N_W versus relative density D_r



Indicator for How easily soil flow after liquefaction

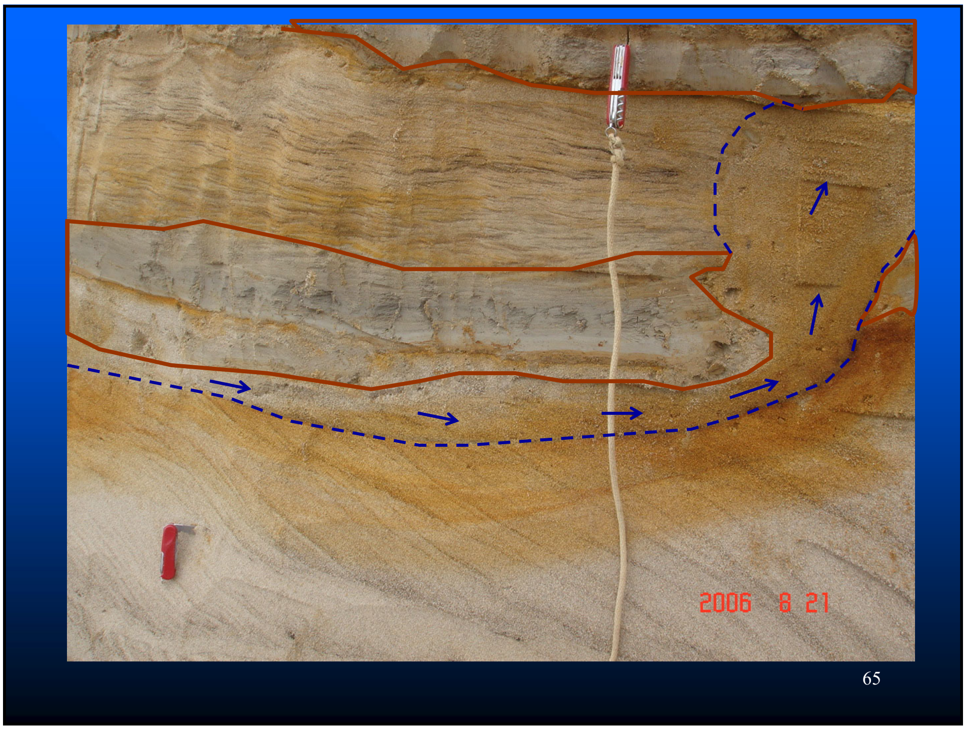
(N_W - N_L) versus Relative density D_r

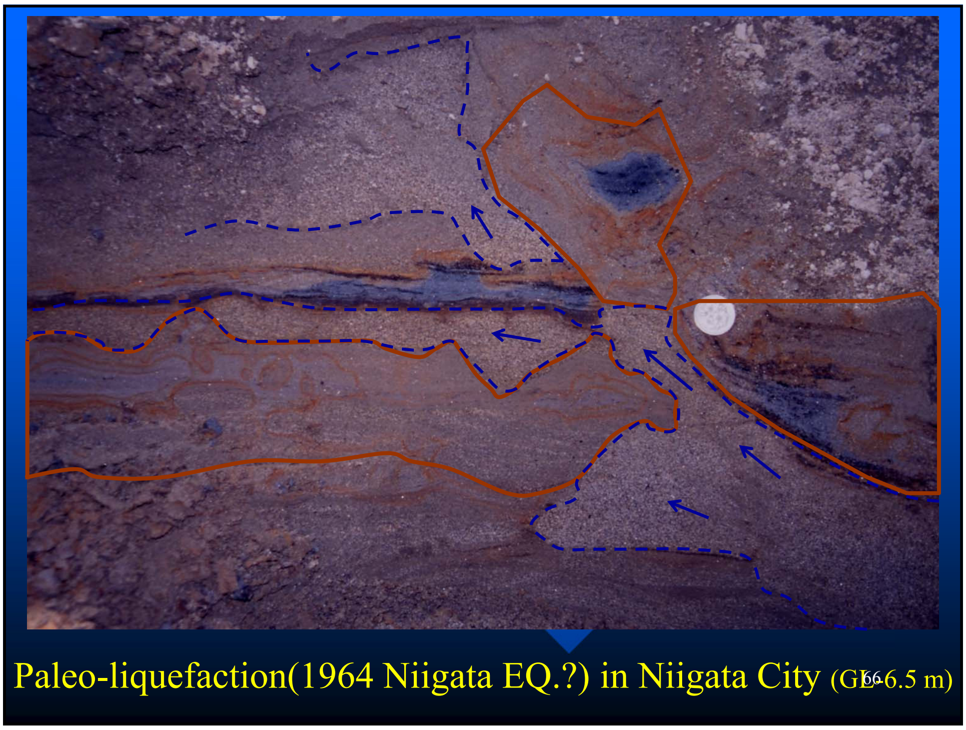
Is there any evidence of water films in nature ?

Paleo-liquefaction in Illinois, USA, 5000 yrs

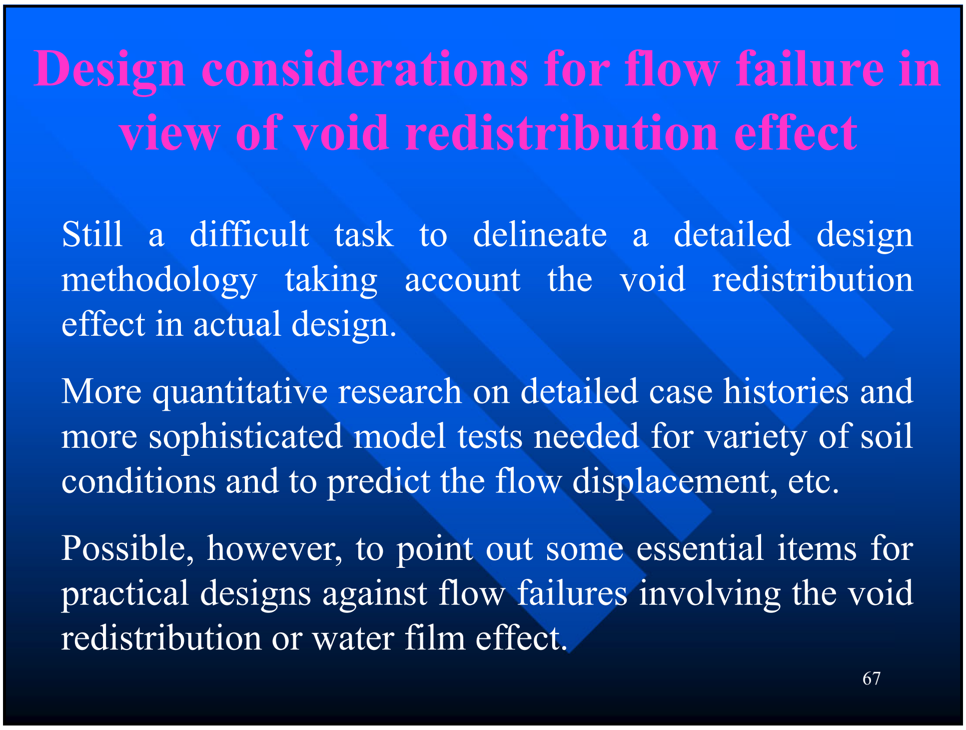

2006 6 20


2006 21





Paleo-liquefaction(1964 Niigata EQ.?) in Niigata City (GL-6.5 m)

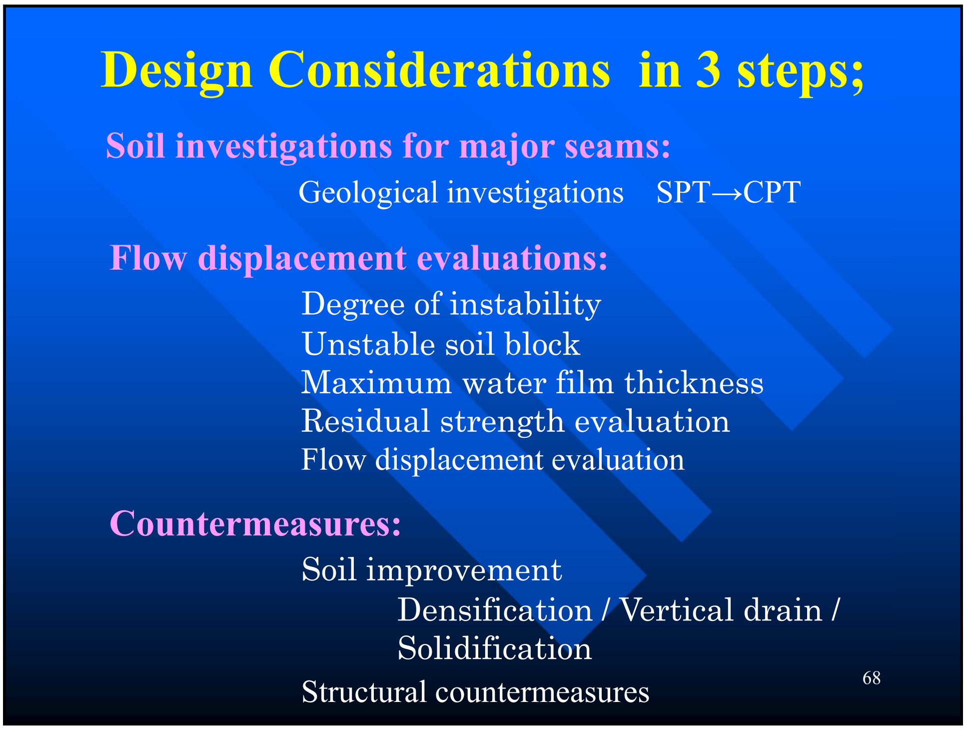


Design considerations for flow failure in view of void redistribution effect

Still a difficult task to delineate a detailed design methodology taking account the void redistribution effect in actual design.

More quantitative research on detailed case histories and more sophisticated model tests needed for variety of soil conditions and to predict the flow displacement, etc.

Possible, however, to point out some essential items for practical designs against flow failures involving the void redistribution or water film effect.



Design Considerations in 3 steps;

Soil investigations for major seams:

Geological investigations SPT→CPT

Flow displacement evaluations:

- Degree of instability
- Unstable soil block
- Maximum water film thickness
- Residual strength evaluation
- Flow displacement evaluation

Countermeasures:

- Soil improvement
  - Densification / Vertical drain / Solidification
- Structural countermeasures

Soil Investigations;

Geological/geomorphological studies to estimate stratification including vertical variability and horizontal continuity.

In situ sounding tests for reliable evaluation of detailed soil stratification. CPT is recommended for detecting soil seams too thin to be identified in conventional soil surveys.

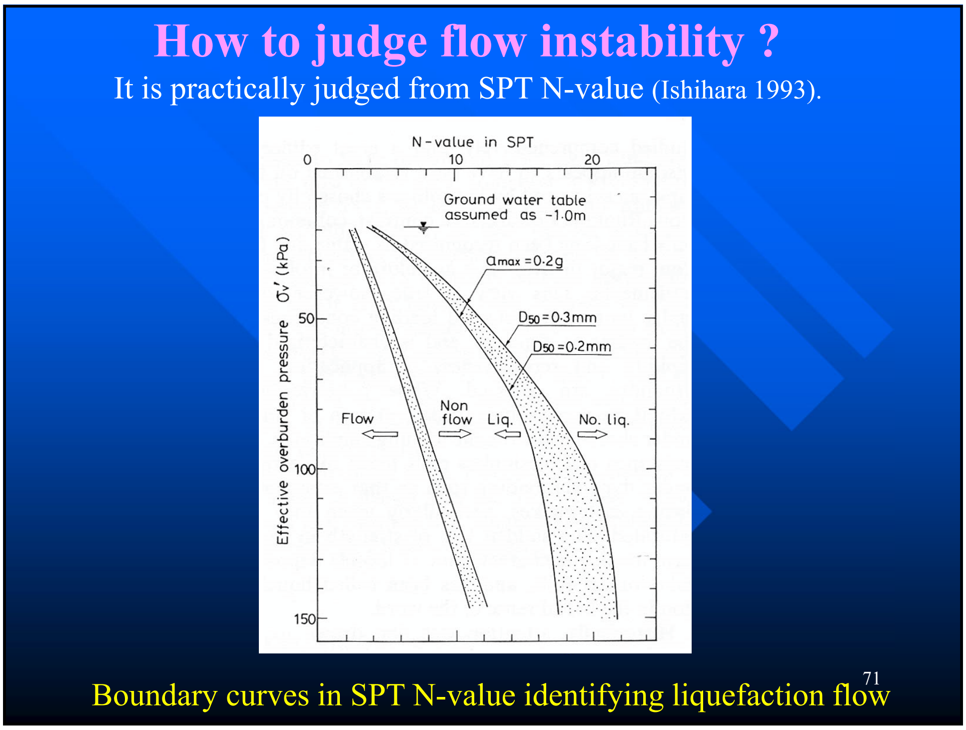
Combination of CPT data and the geological interpretations will yield 2 or 3-dimensional soil profiles with the information of continuous fine soil seams.

Flow displacement evaluations;

In a loose sand layer, a potential for water film-induced instability needs to be considered in addition to the normal liquefaction potential assessment.

Major continuous silt seams are principal focus. Max. water film thickness may be roughly assumed equal to the estimated post-earthquake settlement of individual major layers.

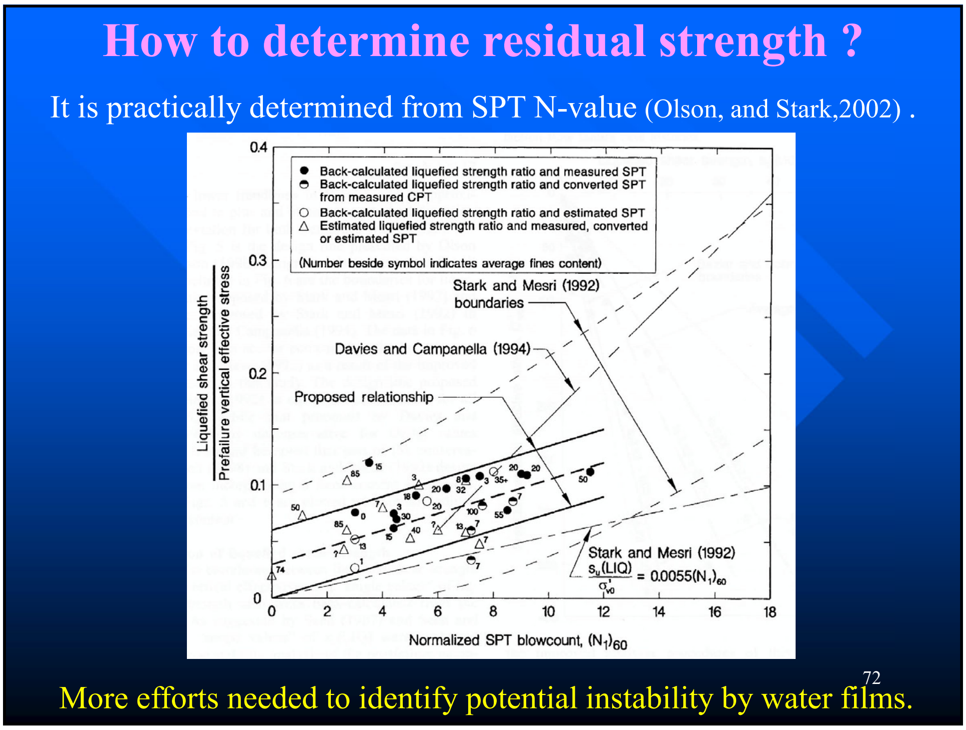
Require a lot of engineering judgment to identify potentially unstable soil blocks and determine residual strength and flow displacement considering tortuosity of water films.



How to judge flow instability ?

It is practically judged from SPT N-value (Ishihara 1993).

Boundary curves in SPT N-value identifying liquefaction flow



How to determine residual strength ?

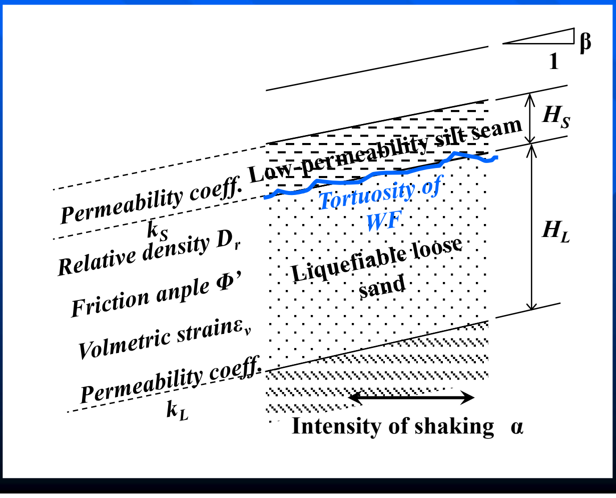
It is practically determined from SPT N-value (Olson, and Stark,2002) .

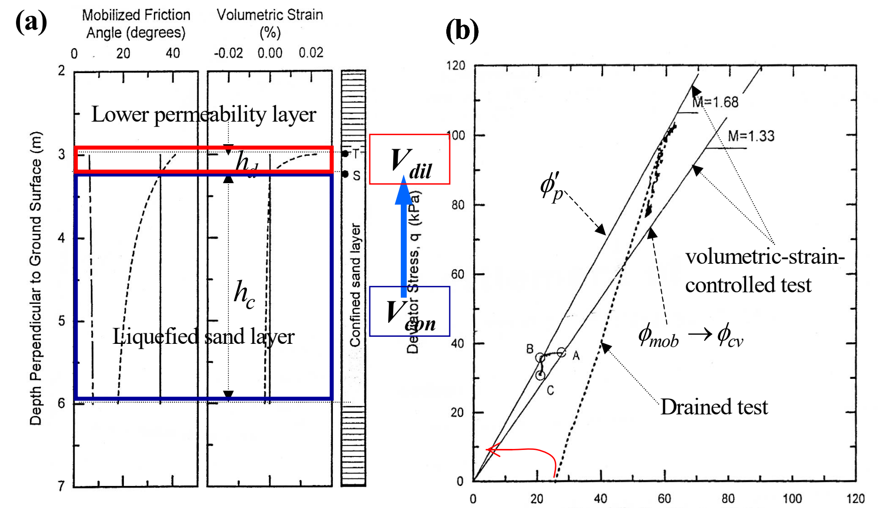
More efforts needed to identify potential instability by water films.

How to judge the onset of instability considering water film effect ?

Many influencing factors; **β, H_S, k_S, H_L, D_r, φ', ε_v, k_L, α,**

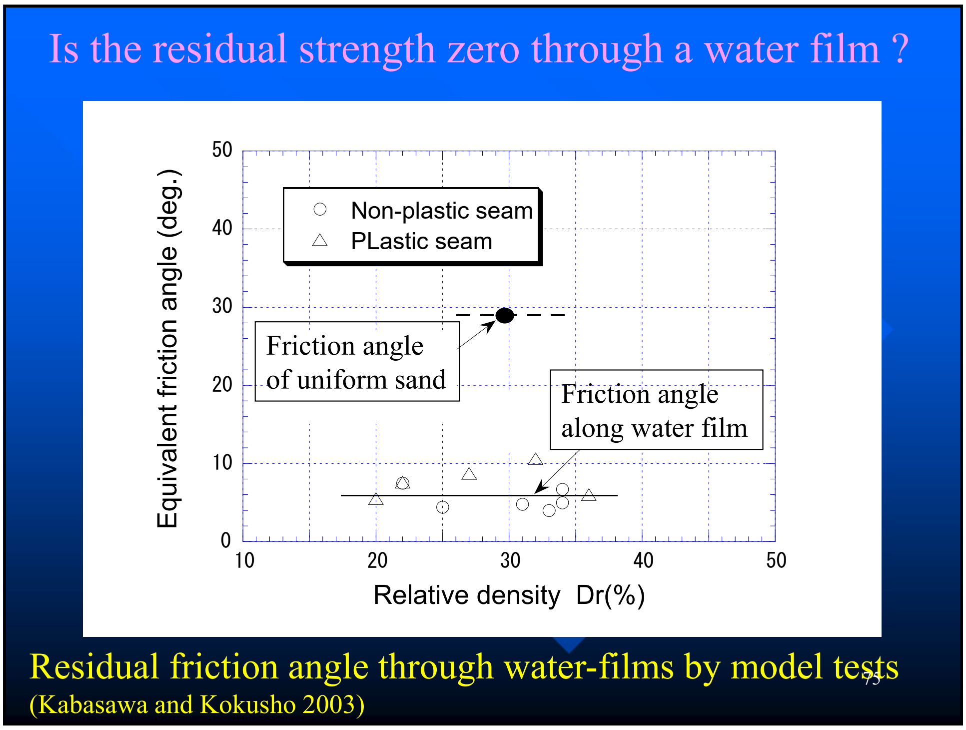
Tortuosity of WF, etc.





$V_{dil} < V_{con}$, then instability occurs.

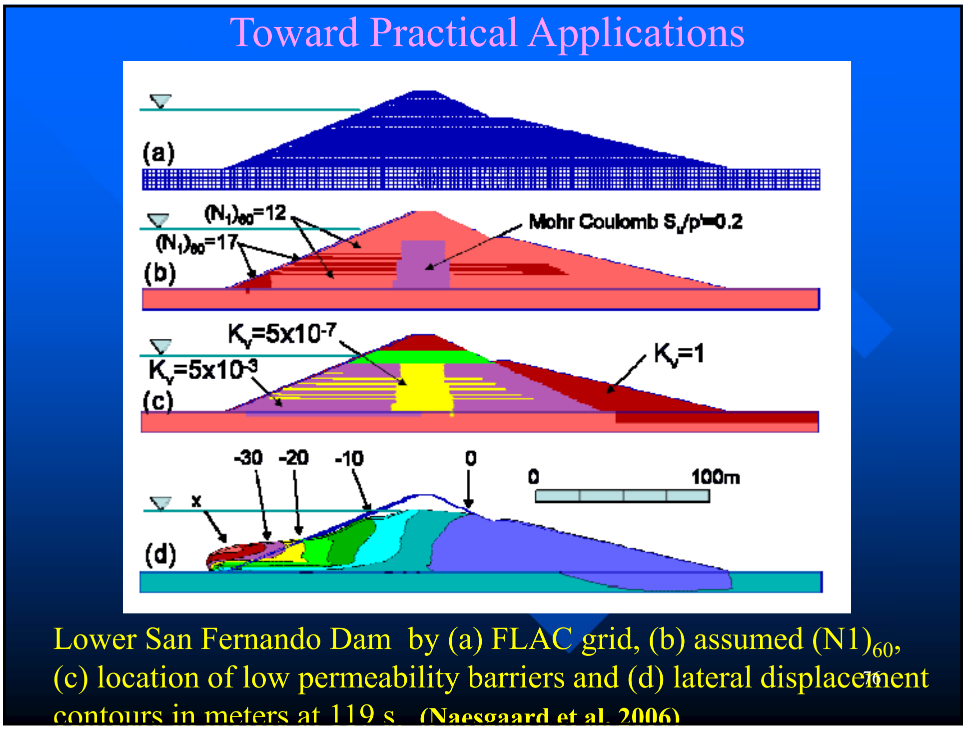
Dilating and contracting zones beneath an inclined low-permeability seam (Boulanger and Truman 1996)



Is the residual strength zero through a water film ?

Residual friction angle through water-films by model tests

(Kabasawa and Kokusho 2003)



Toward Practical Applications

Lower San Fernando Dam by (a) FLAC grid, (b) assumed $(N1)_{60}$, (c) location of low permeability barriers and (d) lateral displacement contours in meters at 119 s. **(Naesgaard et al. 2006)**

Countermeasures;

Soil densification will reduce post-liquefaction volumetric strain and hence water film thickness and its duration.

Vertical drains promote quick drainage and become more effective due to horizontally continuous water films.

Wall-type solidification will be effective in resisting to lateral movement by the improved soil mass.

These countermeasures already available should be revaluated in view of the water film effects.

CONCLUSIONS

Sand deposits in the field consist of sublayers with different particle sizes and permeability which are mostly continuous in the horizontal direction.

Sand deposits consisting of sublayers of different permeability are easy to develop post-liquefaction void redistribution; stable water films or transient turbulence, at sublayer boundaries.

In sand deposits consisting sublayers, void redistribution or water film mechanism can facilitate large flow displacements without mobilizing dilatancy effect, while a uniform sand deposit develop flow displacement only during shaking.

CONCLUSIONS (continued)

In undrained cyclic shear tests simulating sand sublayers beneath silt seams, a non-dilative response appears immediately after the 100% pore-pressure build-up in loose clean sands with Dr ~ 40% or less, indicating that loose sand has a high flow potential.

Case study in Niigata City strongly suggests the involvement of water films in large lateral flow in almost level ground.

Some essential items for practical designs against flow failures involving the void redistribution or water film effect are pointed out in terms of soil investigations, flow potential evaluations and countermeasures.