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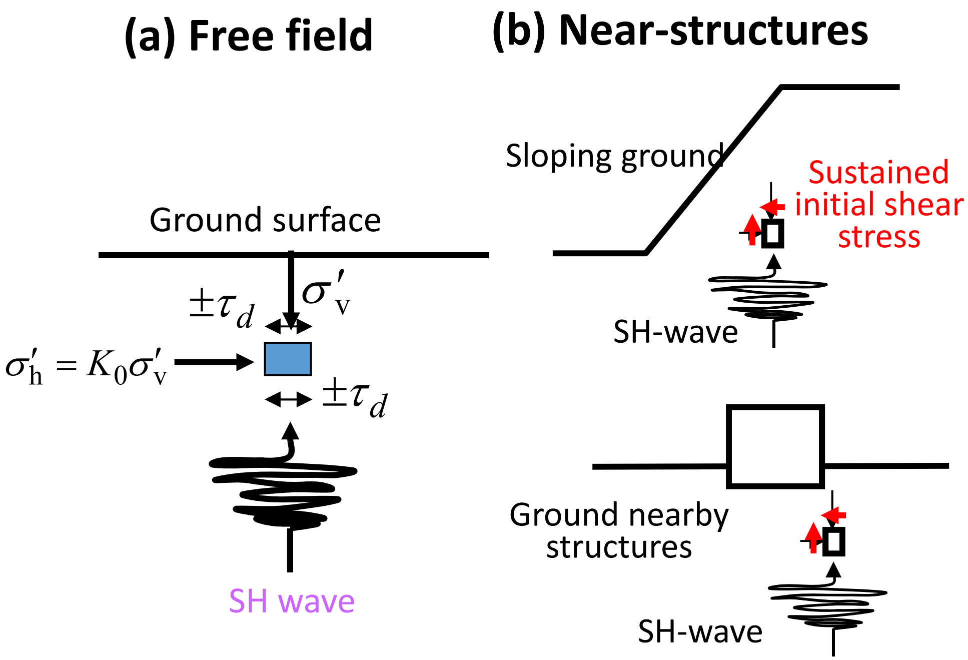
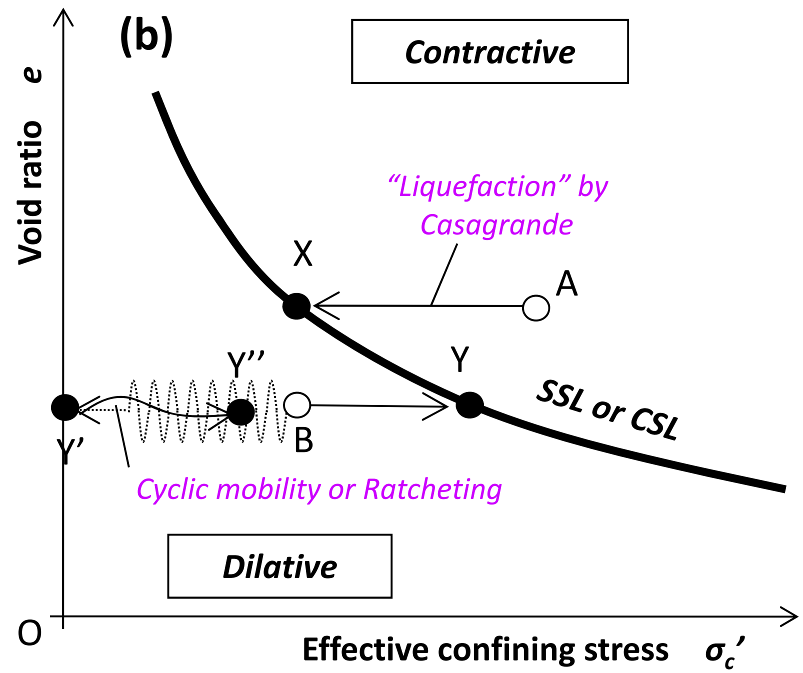
How to unify evaluations on liquefaction-induced flow/lateral spreading under Initial Shear Stress

Takaji Kokusho
Professor Emeritus, Chuo University,
Japan

中央大学

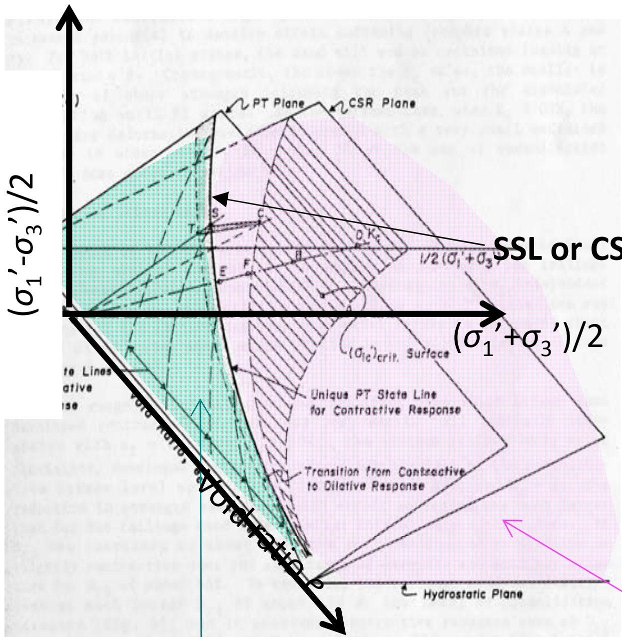
BACKGROUND for UNDRAINED MECHANISM

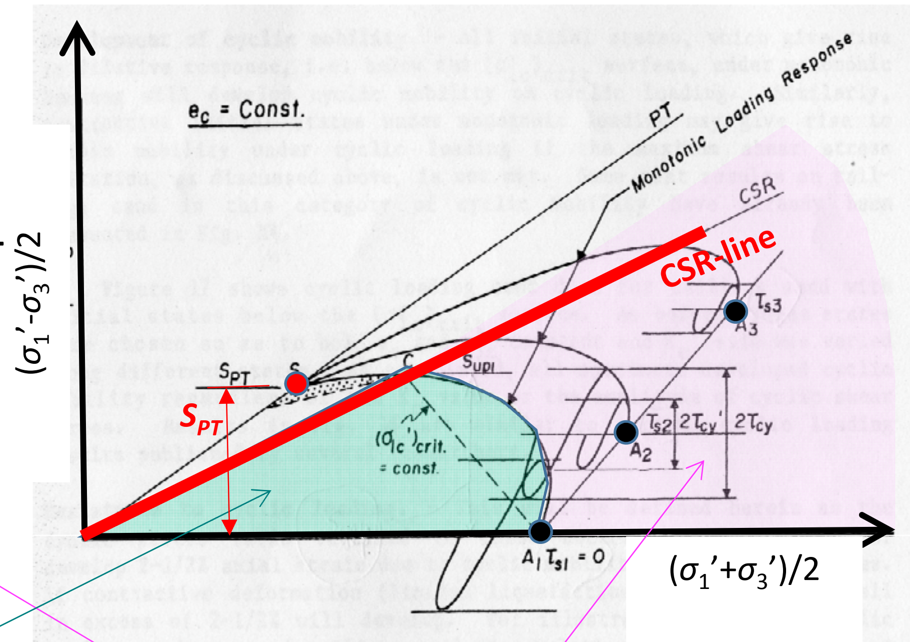




- ***Seed and Lee(1966) explained a liquefaction mechanism by cyclic loading of K_0-consolidated elements in level ground without sustained initial stress τ_s.***
- ***Casagrande (1971) provided a liquefaction mechanism focusing on flow-type failure by initial shear stress τ_s near slopes and superstructures.***
- ***State-Diagram ($e - \sigma_c'$ plane) is divided by Steady State Line into contractive & dilative zones, for flow-type liquefaction versus cyclic mobility-type liquefaction.***

Research for Merging Seed & Casagrande





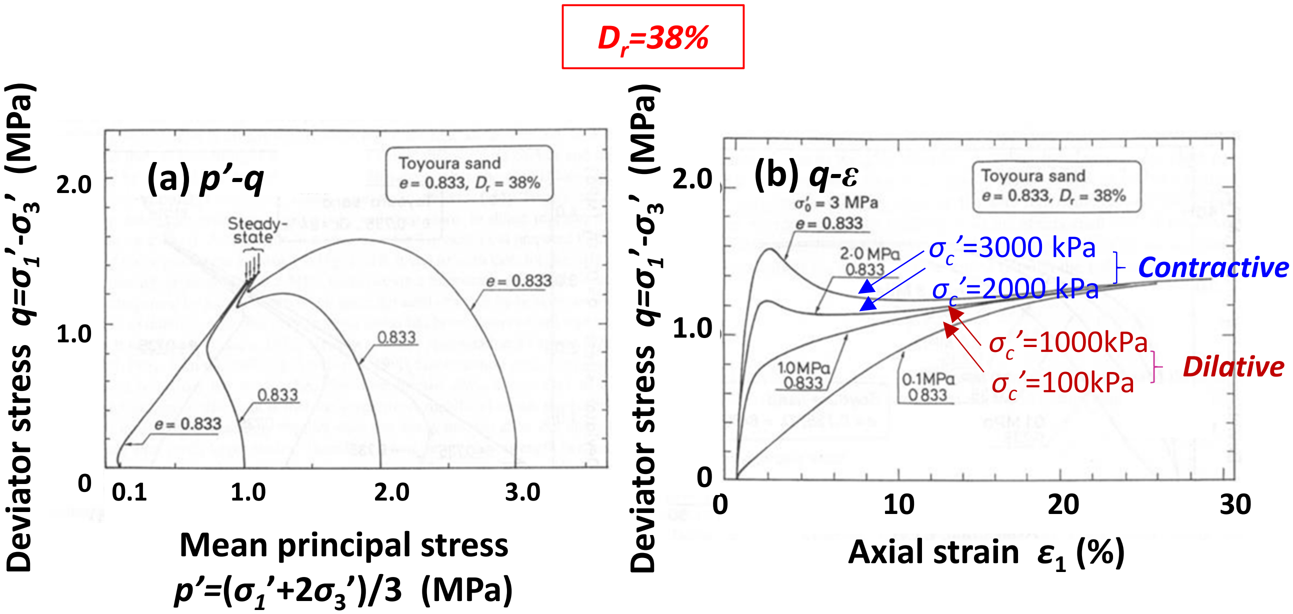
Dilative-Ductile cyclic failure zone

Contractive-Brittle flow failure zone

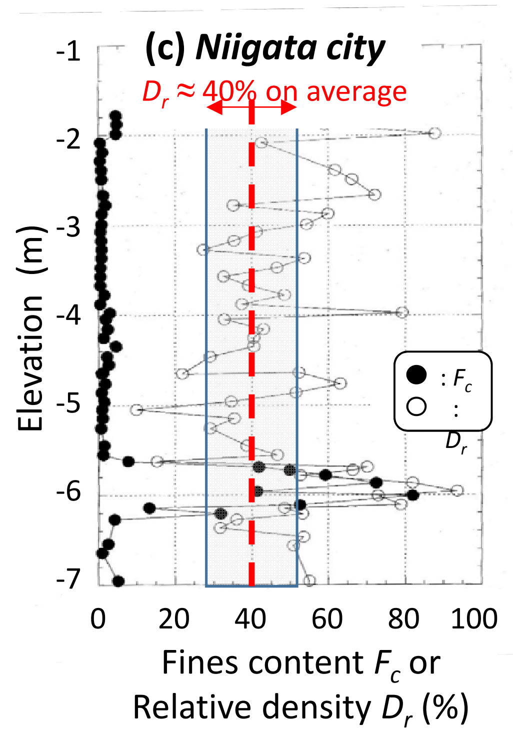
modified from Vaid and Chern (1985)

- ***A unified picture of Seed liquefaction & Casagrande liquefaction.***
- ***In 3D State Diagram, Flow liquefaction if (a) the stress path (monotonic/cyclic, without/with τ_s) starts from the contractive side of SSL and (b) arrives at "CSR-line" followed by strain-softening to S_{pt}. Otherwise, Cyclic mobility liquefaction.***

Which side of SSL normally sands are ?



(Ishihara 1993)

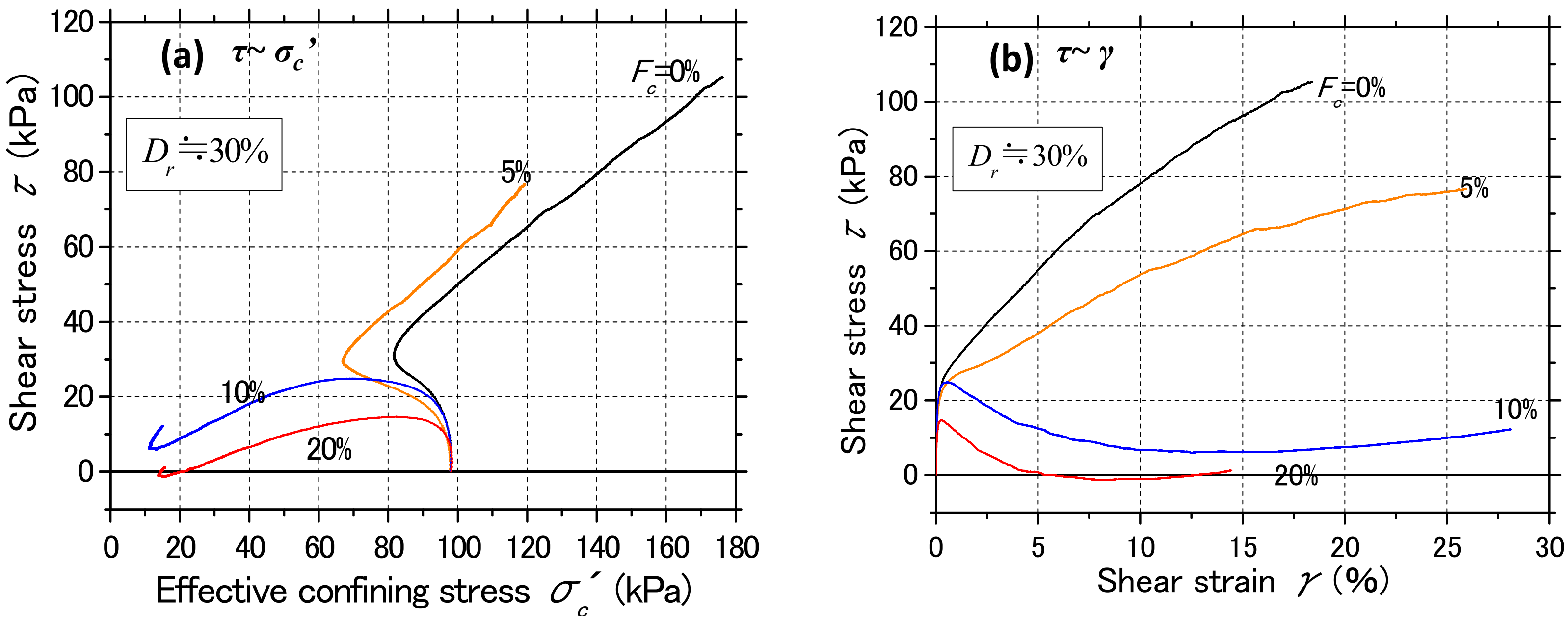


(Kamikawa 2004)

- ***Clean sands are dilative** even if loose (Dr=30-40%) under normal σ_c'.*
- ***Niigata clean sand** ($D_r \approx 40\%$ at GL-10 m or shallower) **was actually dilative**.*
- ***Liquefaction failure of clean sand** normally not flow-type but **cyclic-type**.*

However, non-plastic fines change sand drastically.

σ_c'=98 kPa

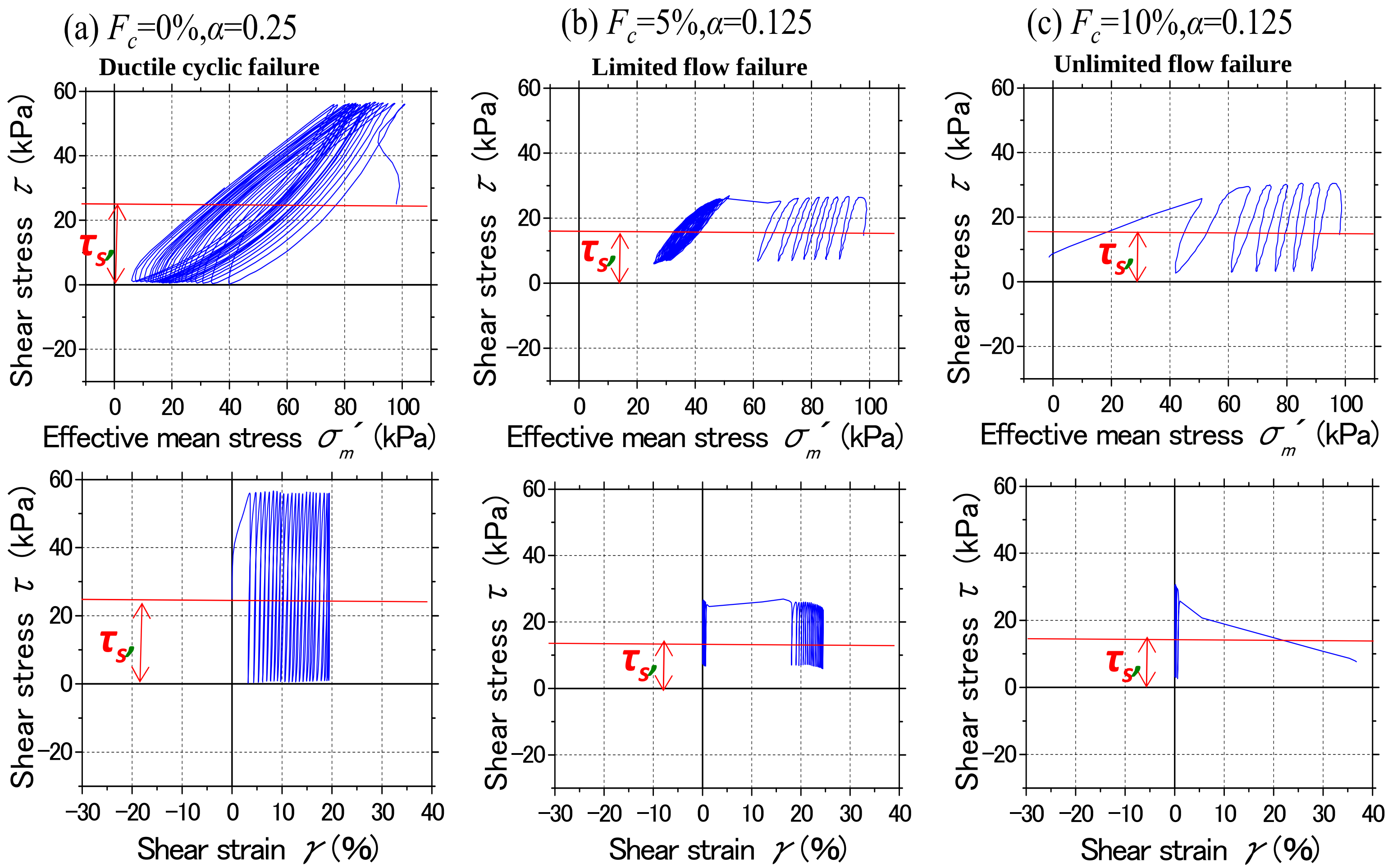


Torsional simple shear test

(Kusaka 2013)

In monotonic test, sand (D_r≈30%) changes dilative → contractive as Fc=0 → 10% .

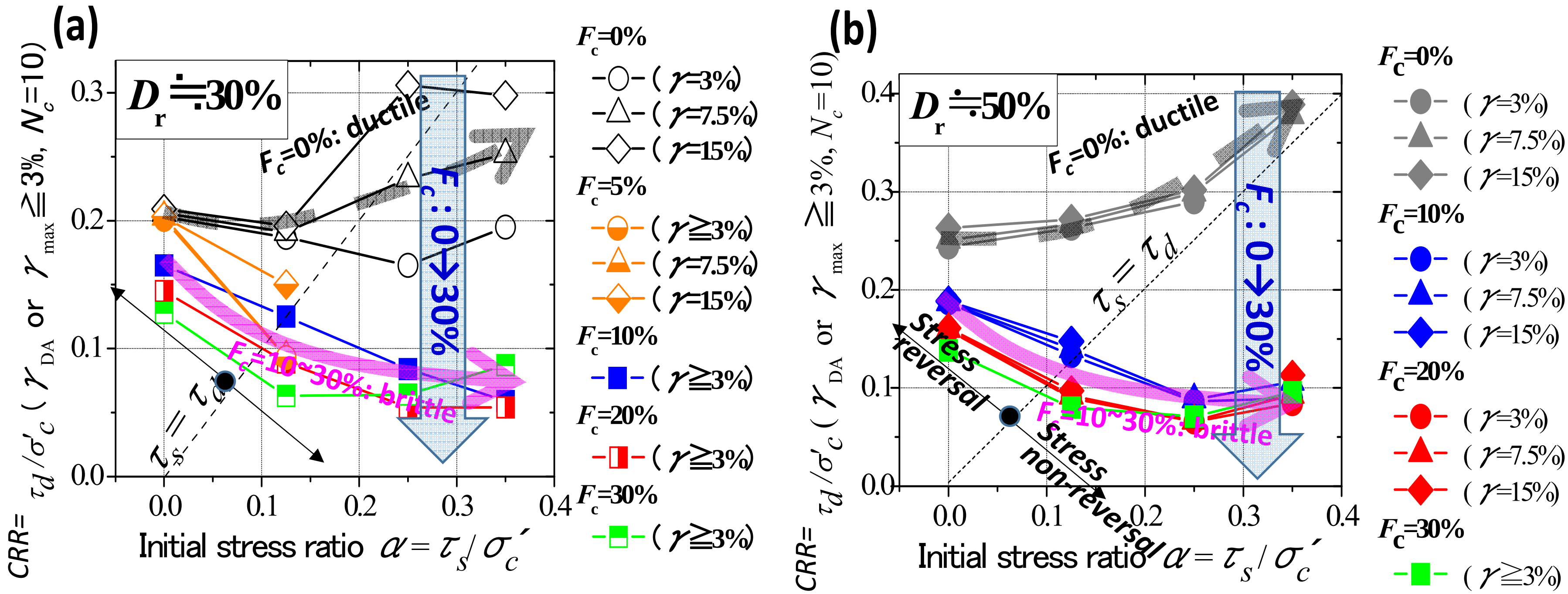
Similar change with increasing fines in cyclic loading.



(Arai 2014).

In cyclic loading with τ_s, sand (D_r≈30%) changes from cyclic failure to flow failure with increasing Fc=0→20% .

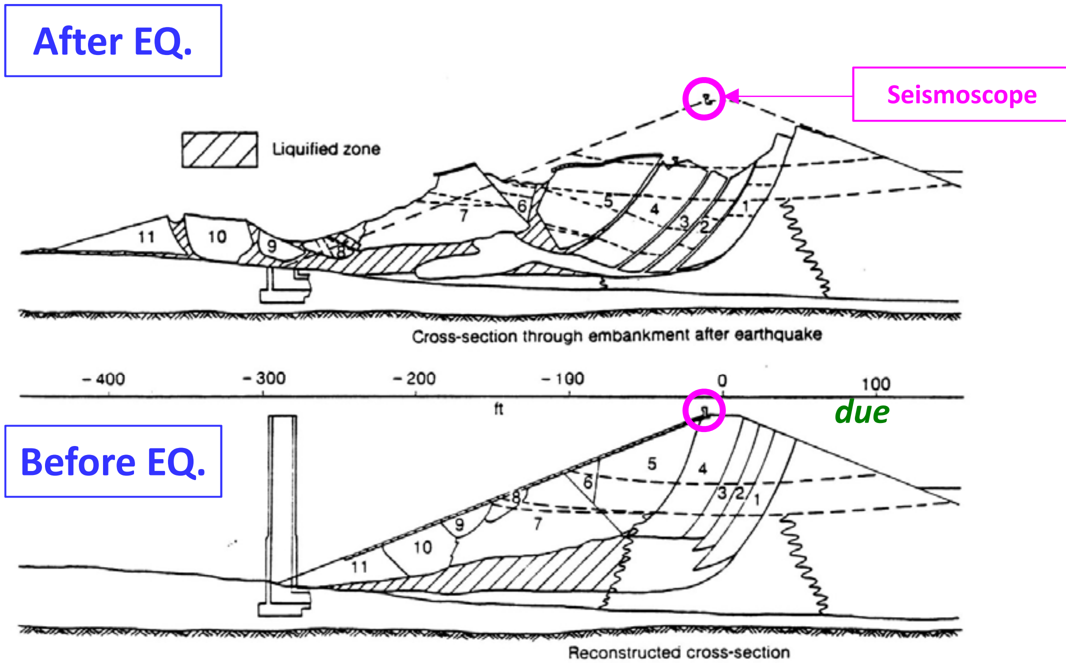
Variation of *CRR* with increasing τ_s for F_c : 0→30%

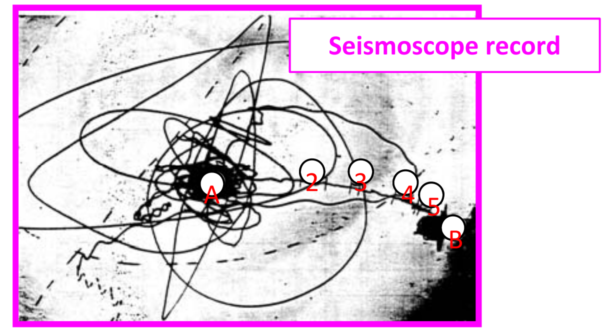


(Arai et al. 2014)

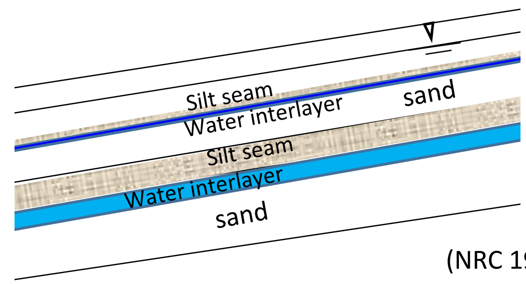
- ***Changes from dilative to contractive with increasing F_c.***
- ***Dilative clean sands: ductile cyclic failure, CRR increase with τ_s.***
- ***Contractive sands with F_c: brittle flow failure, where CRR decrease with τ_s.***

BACKGROUND for Void Redistribution MECHANISM





Water interlayer mechanism by NRC (1985)

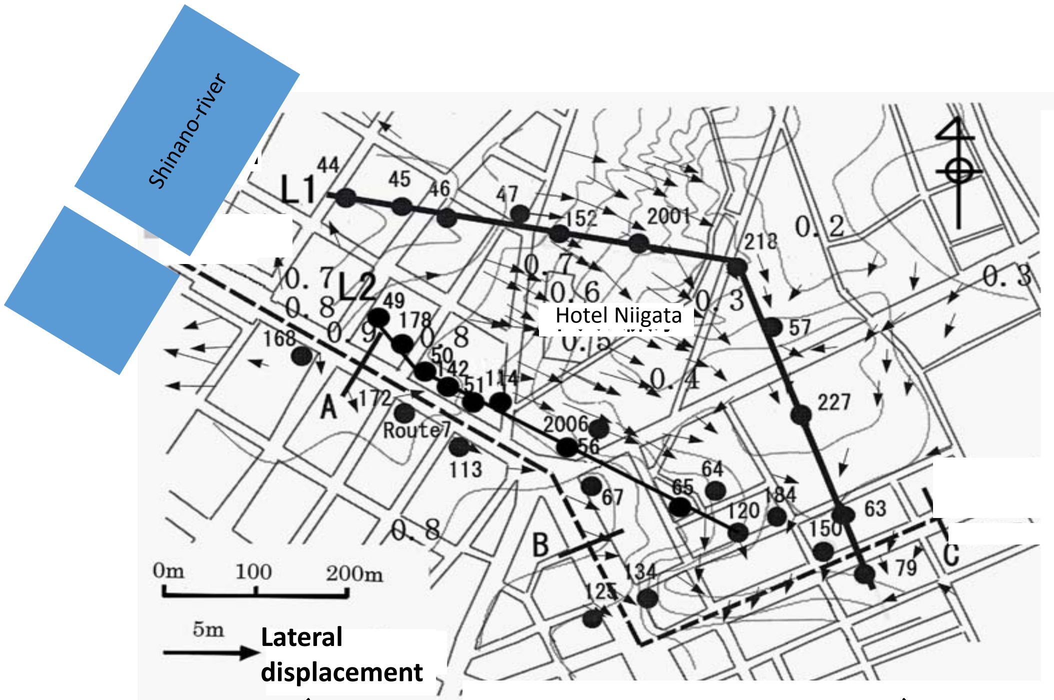


(NRC 1985)

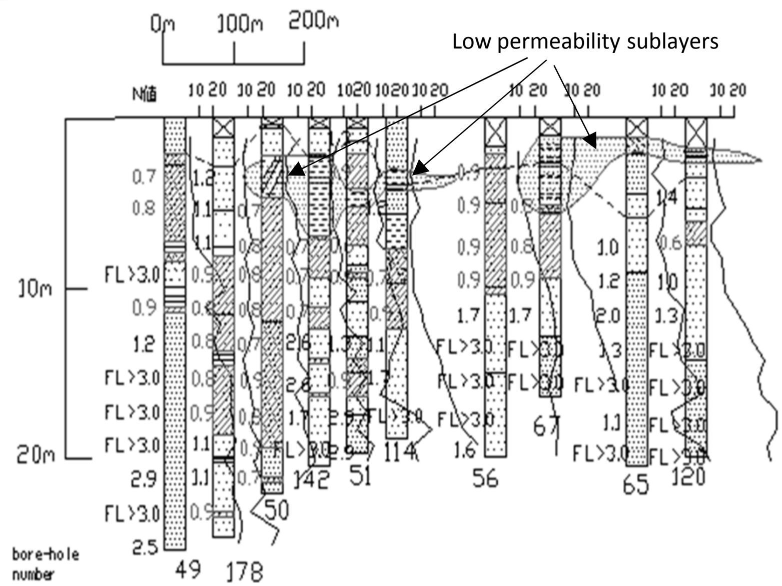
（Seed 1987）

- ***Lower San Fernando dam by hydraulic filling, sublayers of high/low permeability.***
- ***Void-redistribution, water interlayer, delayed failure (NRC USA 1985).***

Lateral flow of very gentle slope during 1964 Niigata EQ.



（Displacement vectors by Hamada et al. 1986）

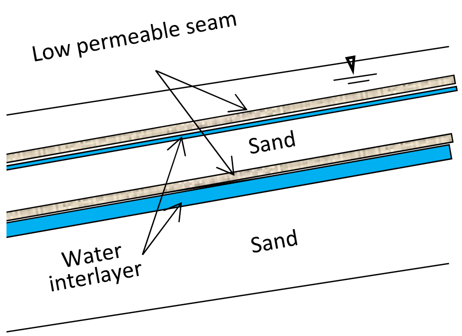


（Kokusho & Fujita 2002）

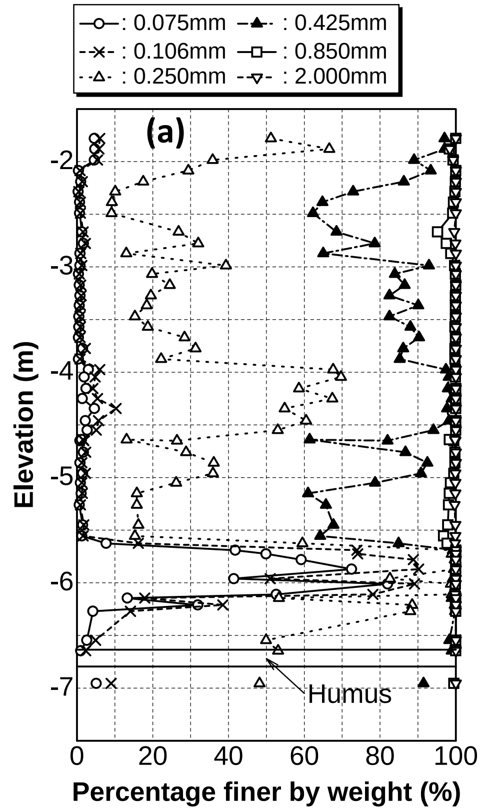
- ◆ ***Flat land of gradient <1% flowed max. 4 m normal to elevation contours.***
- ◆ ***Clean sand interbedded with low-permeability silts.***
- ◆ ***No possibility of undrained flow on dilative side of SSL but of Void-Redistribution.***

Particle size variation in Natural Sand (a) and Hydraulic Fill (b)

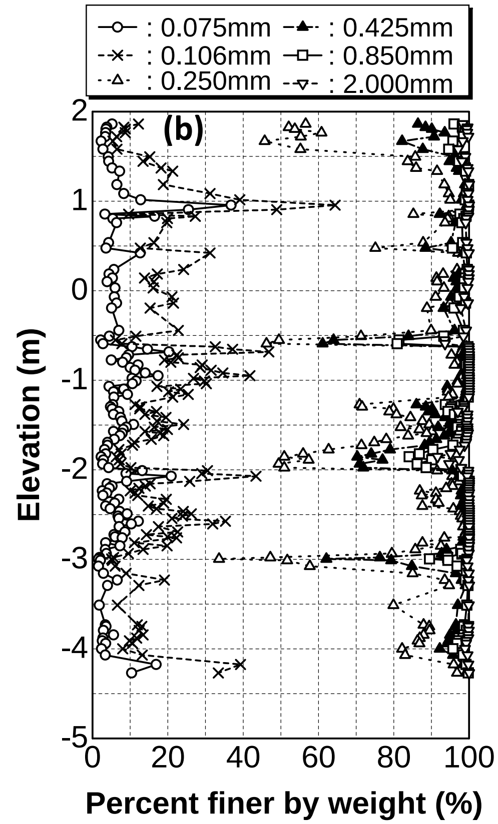
Void redistribution in layered sand



(NRC 1985)



Niigata city

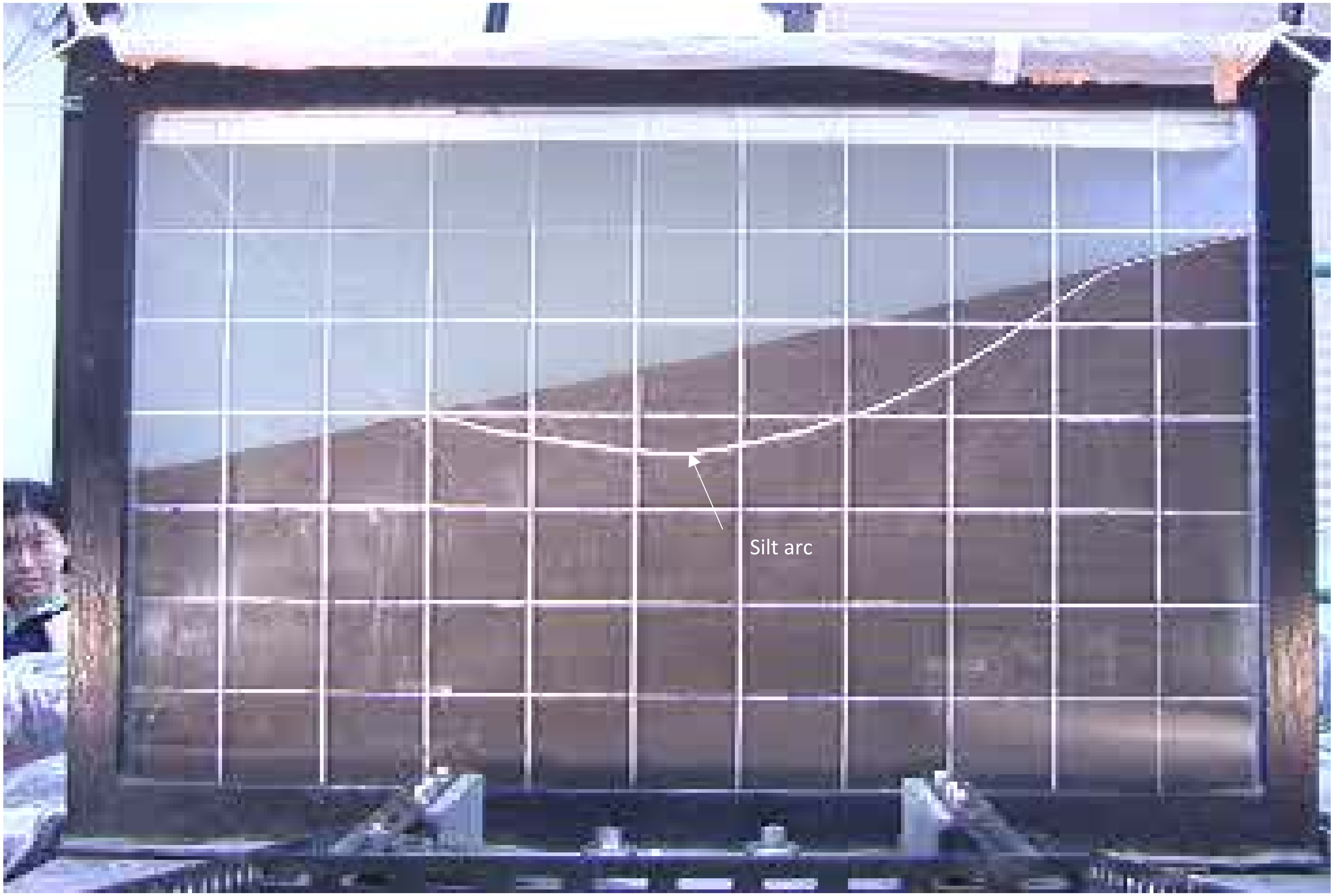


Hydraulic fill of Tokyo Bay

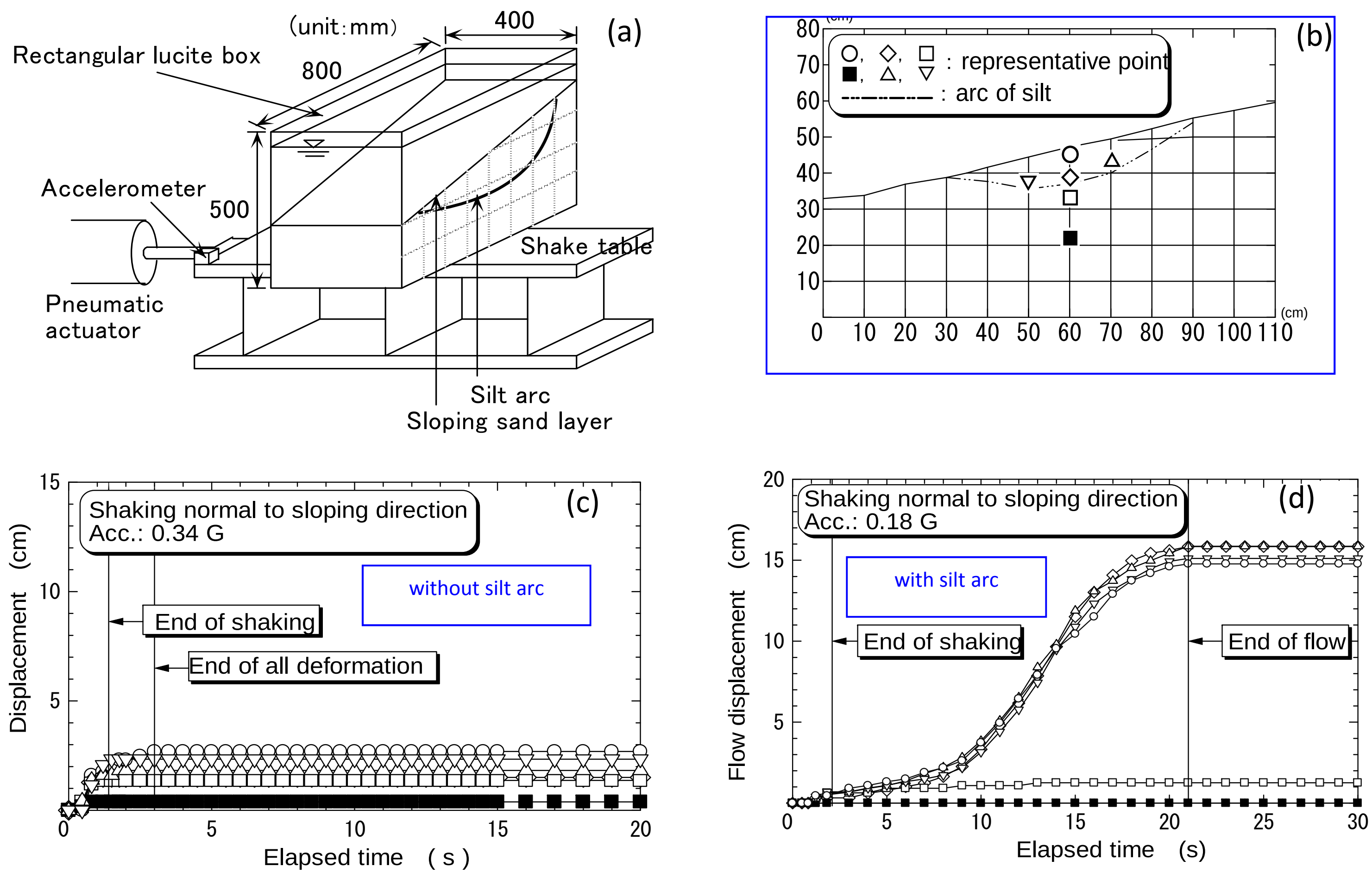
（Kokusho, T. and Fujita, K　2002）

In situ sands never uniform but very variable in particle size and permeability.

2-D submerged sand slope with arc-shape silt seam



2-D model tests without/with silt arc in sand slope

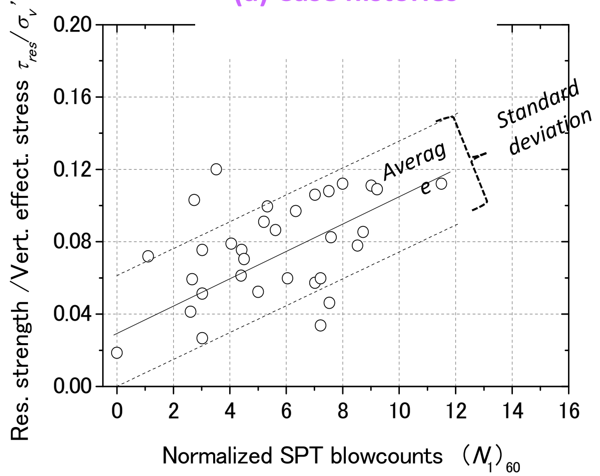


(Kokusho 2003)

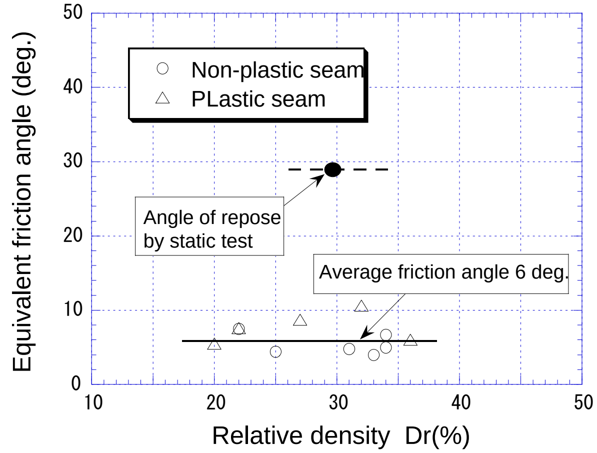
- ◆ ***Without silt arc, slope deforms only during shaking.***
- ◆ ***With silt arc, it deforms after the end of shaking along water film beneath silt arc.***
- ◆ ***Clean sand, though dilative, flows along water film, while uniform sand cannot.***

How much residual strength estimated considering void-redistribution ?

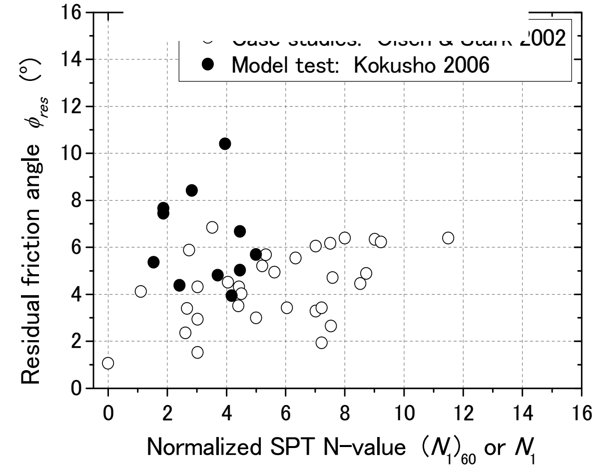
(a) Case histories



(b) Model tests



(c) Mobilized friction angle



(Olsen & Stark 2002)

(Kokusho 2003)

- ***Seed (1987) and others back-calculated residual strength from case histories.***
- ***Residual friction angle from the case histories and the model test are φ_{res} <10^{o}.***

2.1 CURRENT STATE-OF-THE-ART

- *CRR* is determined in practice without *Initial Shear Stress* $\boldsymbol{\tau_s}$.
- *ISS* is considered as $K_\alpha = (CRR)_\alpha / (CRR)_{\alpha=0}$ by $\alpha = \tau_s / \sigma_v'$ in US.
- Numerical methods used for residual deformations under *ISS*.
- Soil dilatancy sensitive to F_c etc. including *Void Redistribution*.
- Residual strengths back-calculated from case histories to reflect in situ behavior including *VR* in US.

2. 2 KEY UNDERLYING GEOLOGIC PROCESSES

- Liquefiable deposits consist of sublayers with different permeability that may induce *VR* during liquefaction.

- Even uniform sands tend to contain more or less LP/NP-fines that may greatly influence their dilatancy.

2. 3 PRIMARY MECHANISMS INVOLVED

Undrained Dilative mechanism *(Seed's liquefaction):*

Clean sands with low F_c is dilative even D_r≈30~40%, 10~20 m deep. Failure under *ISS* occurs gradually & cyclically. *CRR* increases with increasing α even in the stress reversal condition.

Undrained Contractive mechanism *(Casagrande's liquefaction)* :

Sands are contractive with increasing F_c . Then failure under *ISS* occurs suddenly in flow-type. *CRR* decreases with increasing α, with drastic change in failure modes.

Void Redistribution mechanism:

Gently-inclined loose sands (SPT N_1<10) with silt seams, *VR* may trigger time-delayed flow failure on both sides of SSL.

2.4 KEY CHALLENGES TO DEVELOPING BETTER EVALUATION PROCEDURES

To unify the 3 mechanisms to evaluate residual shear resistance and flow deformation under *Initial Shear Stress* in simplified formulas on both sides of SSL.

2.5 PATHS FORWARD

Lab element tests under *ISS* with parameters D_r, F_c, etc. on both sides of SSL;

(1) How sands change from dilative to contractive and what microscopic mechanism ?

(2) How post-liquefaction residual strength/strain is determined?

Centrifuge/1G model tests on lateral spreading/flow of slopes and uniform/non-uniform sands interbedded with silt seams beneath shallow foundations or slopes with parameters D_r, F_c, etc. on both sides of SSL;

(1) How uniform sand failure changes from ductile to brittle flow-type failure?

(2) How residual strengths of uniform/non-uniform sand back-calculated from test results and compared with soil element tests?

Collection & Interpretation of case histories of lateral spreading/flow with well-documented data on both sides of SSL;

(1) How in situ residual strengths back-calculated from case histories and how they are compared with soil element strengths (Some already done in US).

(2) How residual strains (displacements) are correlated with pertinent parameters.

Based on the above, unified evaluation procedures has to be established for simplified PBD, seamless on both sides of SSL concerning not only CRR but also differentiating ductile and brittle modes with associated strains (displacements).