Mechanism of PALU Liquefaction EQ 2018-Delayed flow failure

July 24, 2021

FLIP Consortium, Japan
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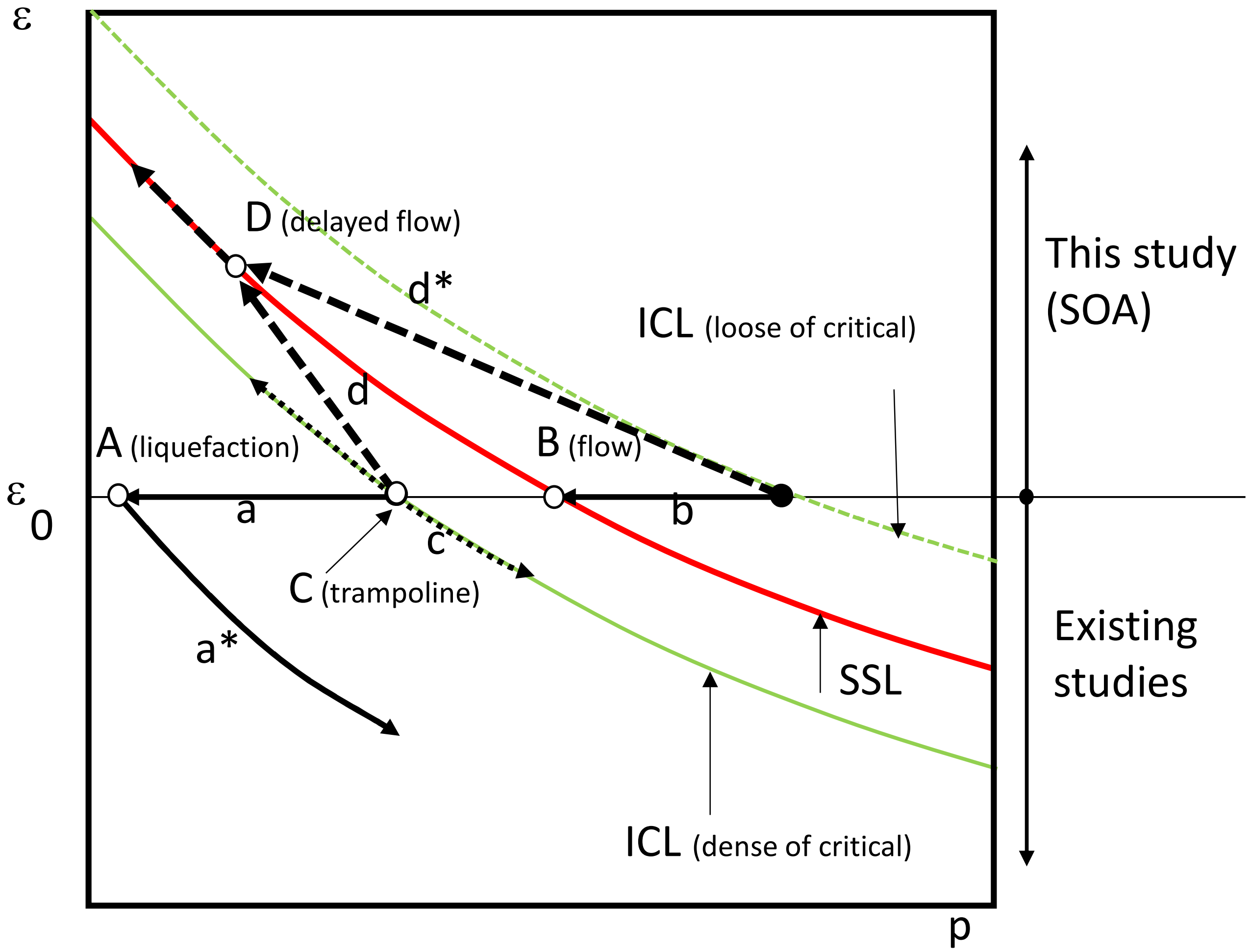
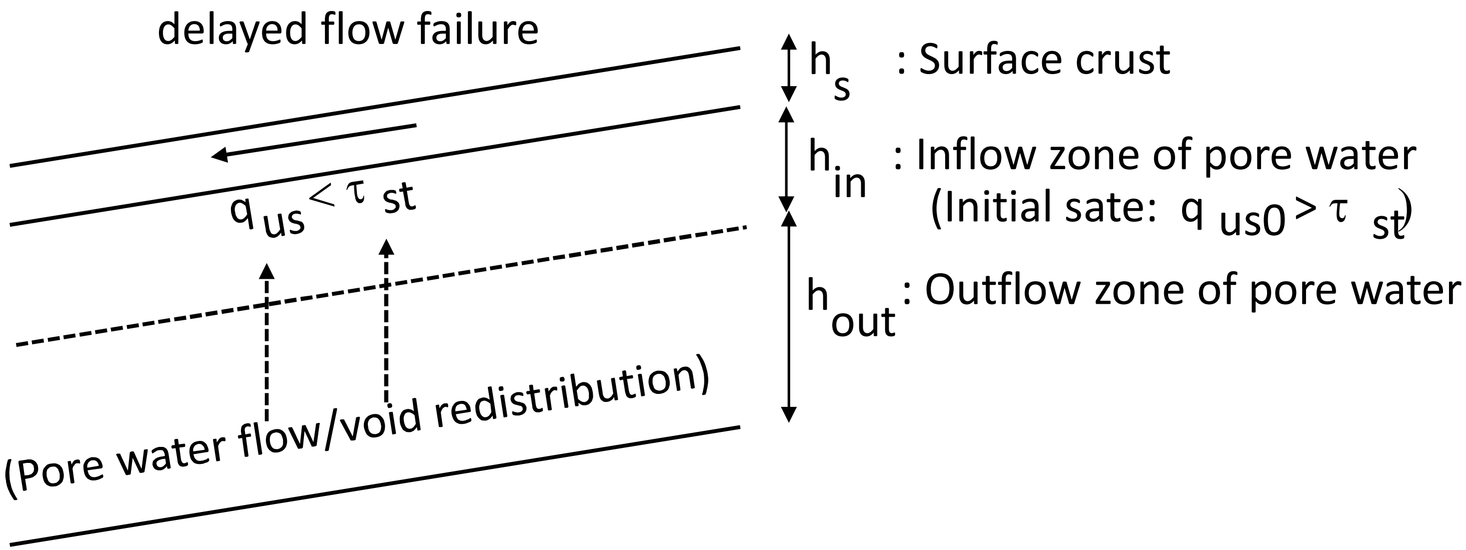
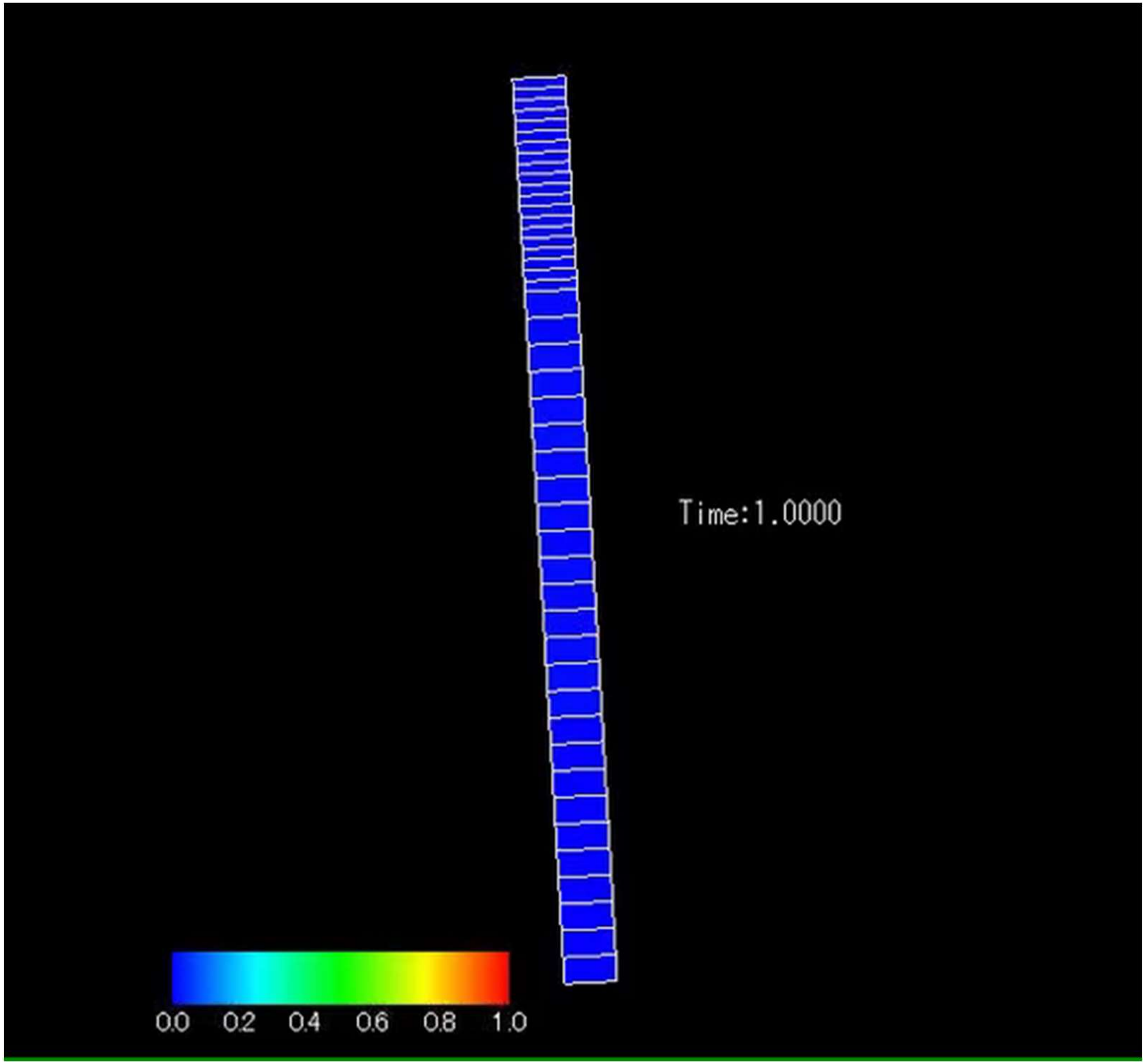
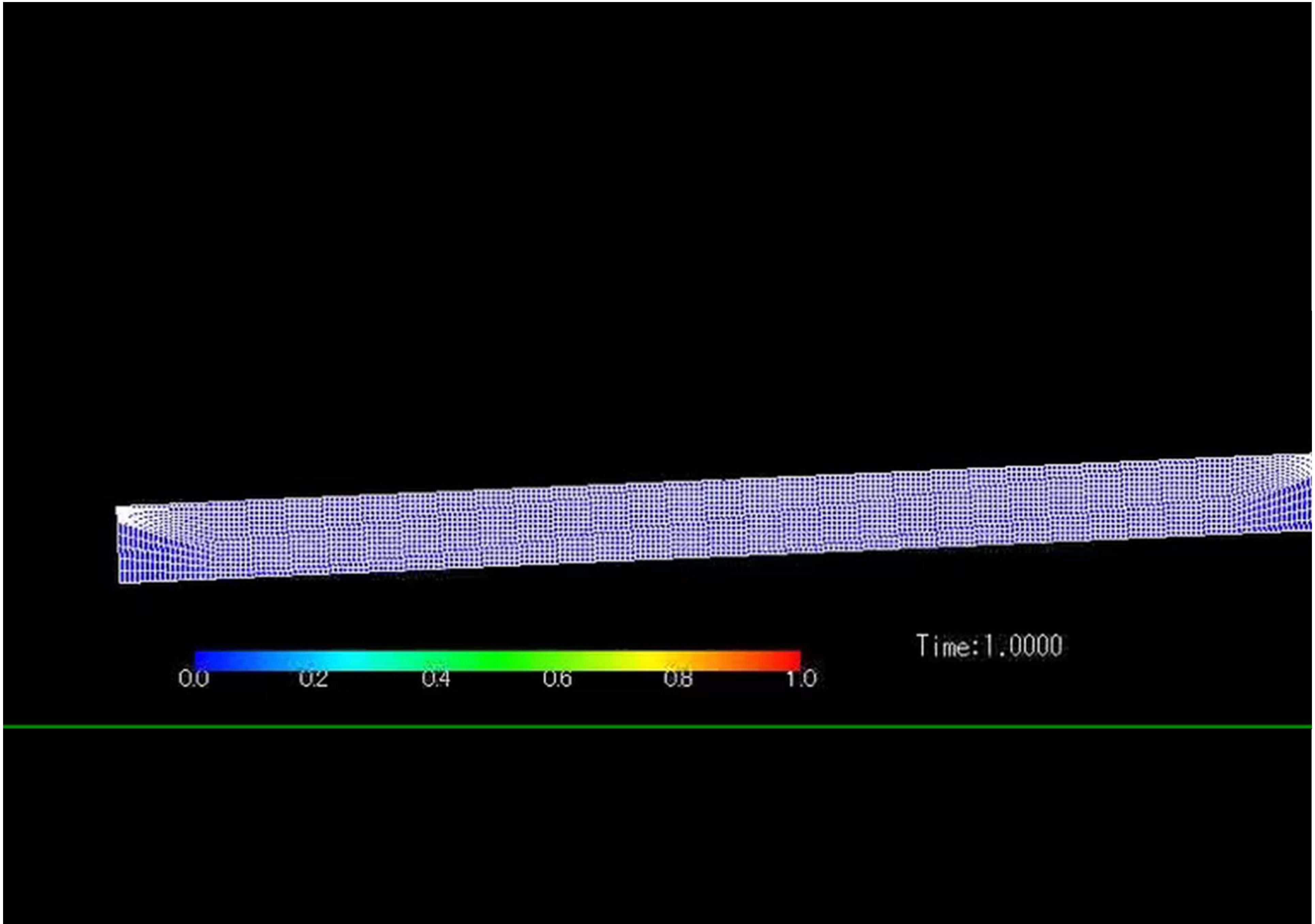


ε
D (delayed flow)
d*
ICL (loose of critical)
d
A (liquefaction)
B (flow)
ε
0
a
b
c
C (trampoline)
a*
SSL
ICL (dense of critical)
p
This study
(SOA)
Existing
studies

Delayed flow failure



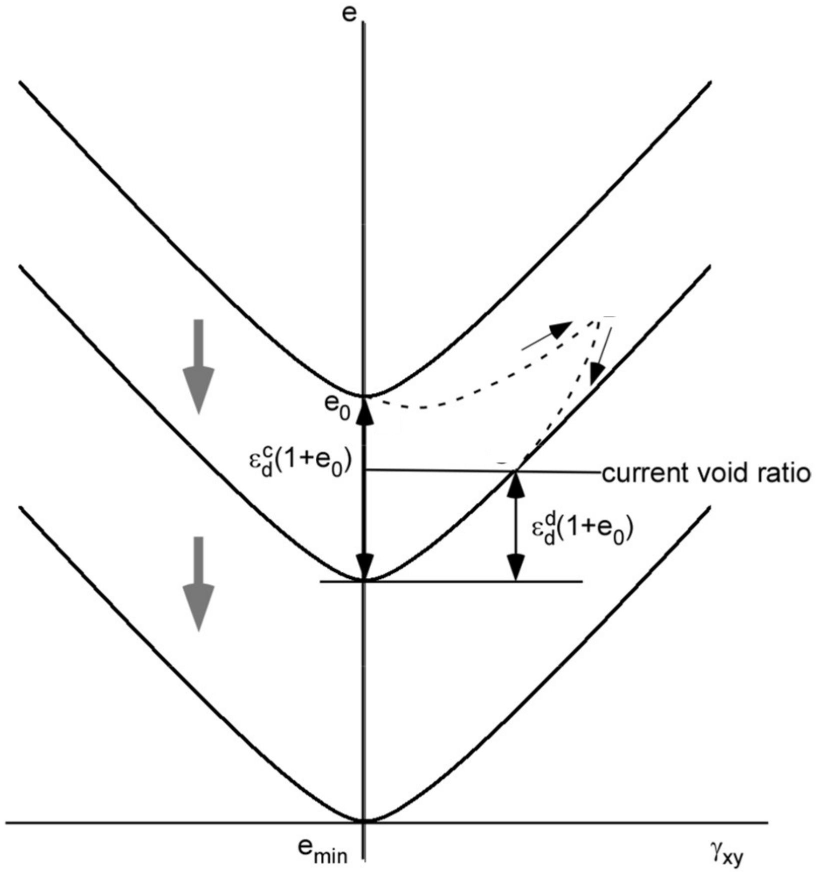

Time:1.0000
0.0 0.2 0.4 0.6 0.8 1.0

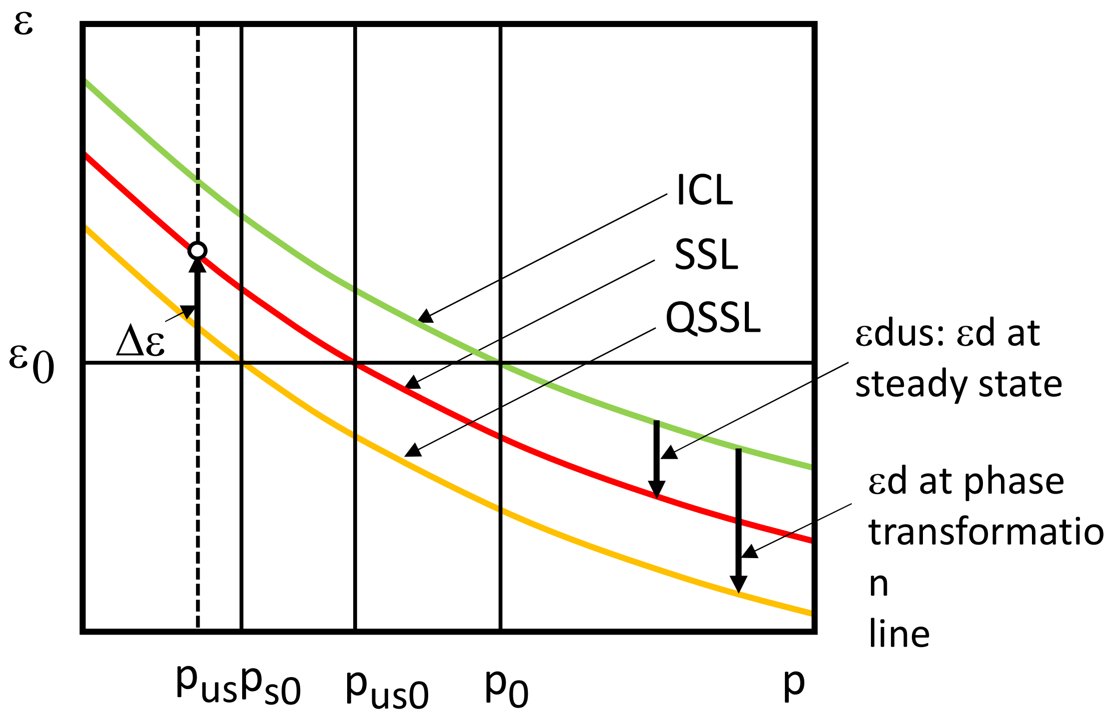

0.0
0.2
0.4
0.6
0.8
1.0
Time:1.0000

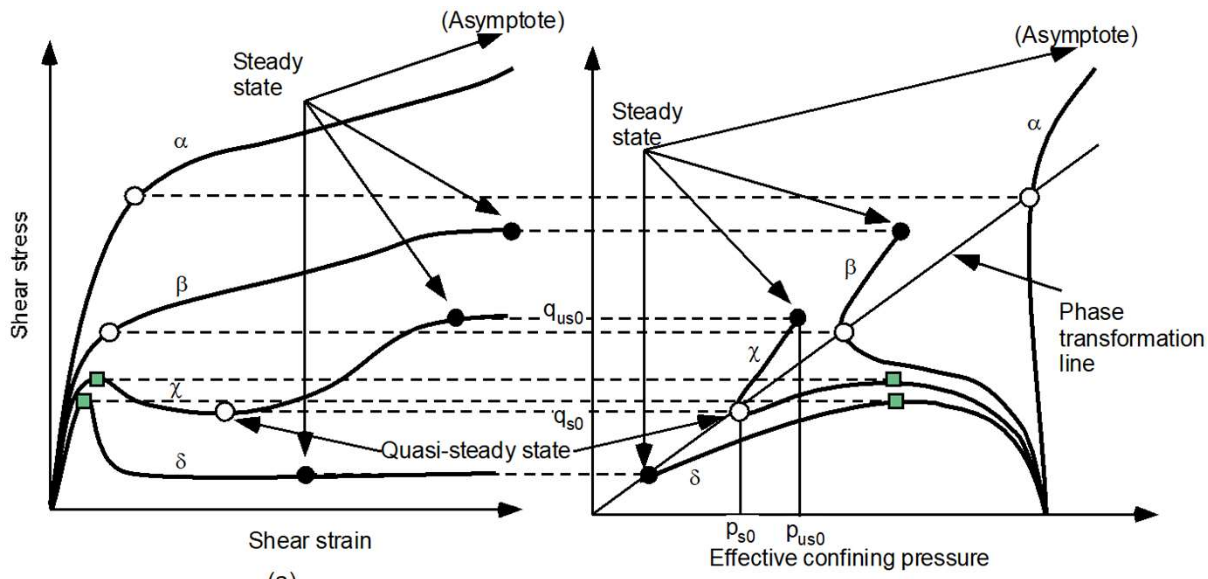
Cocktail glass model (volumetric mechanism)

$$K_{\mathrm{L/U}} = -\frac{\mathrm{d}p}{\mathrm{d}\varepsilon'} = r_K K_{\mathrm{U0}} \left(\frac{p}{p_0} \right)^{l_K}$$

$$\varepsilon' = \varepsilon - \varepsilon_{\mathrm{d}}$$



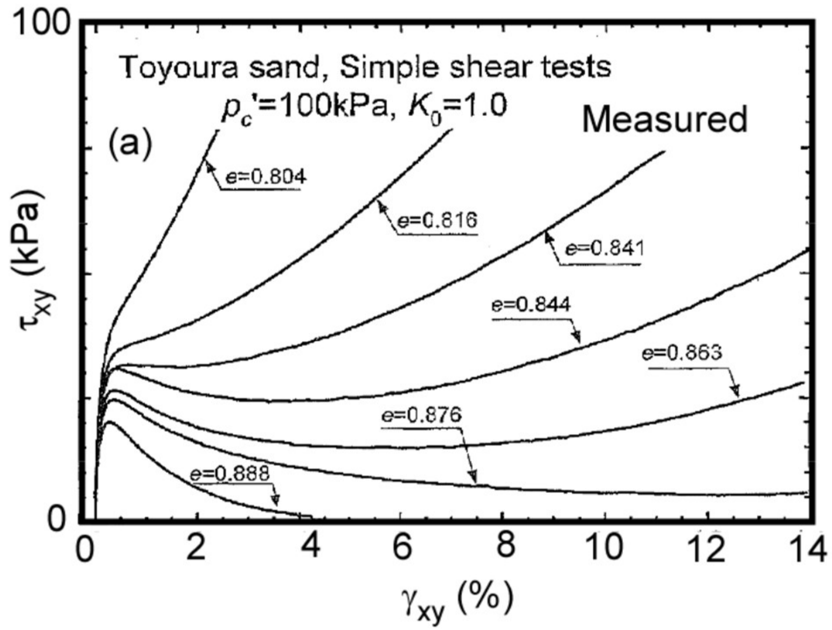

ε
ε0
Δε
ICL
SSL
QSSL
εdus: εd at steady state
εd at phase transformatio n line
pus ps0
pus0
p0
p

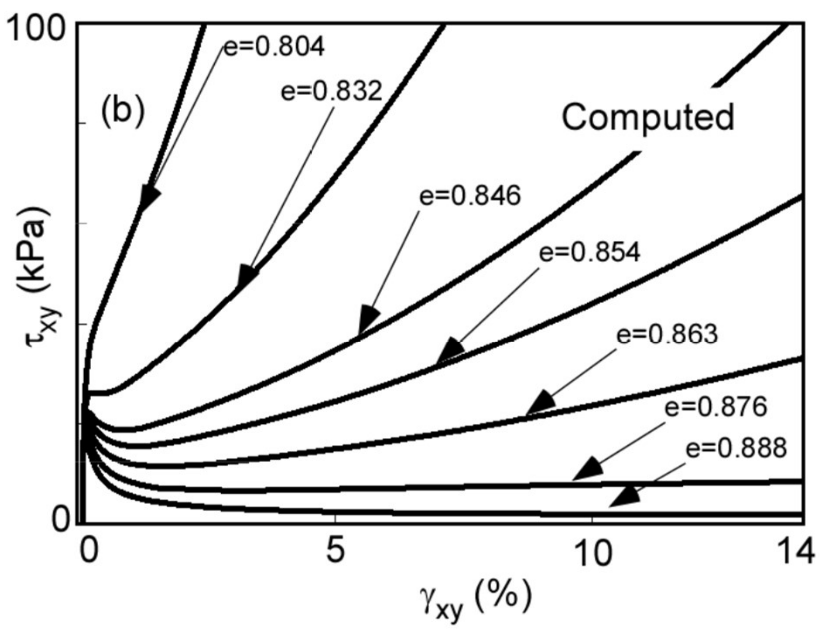

(Asymptote)
Steady state
α
β
χ
δ
Shear stress
Shear strain
Quasi-steady state
qus0
qs0
Phase transformation line
ps0
pus0
Effective confining pressure

(a)

(b)

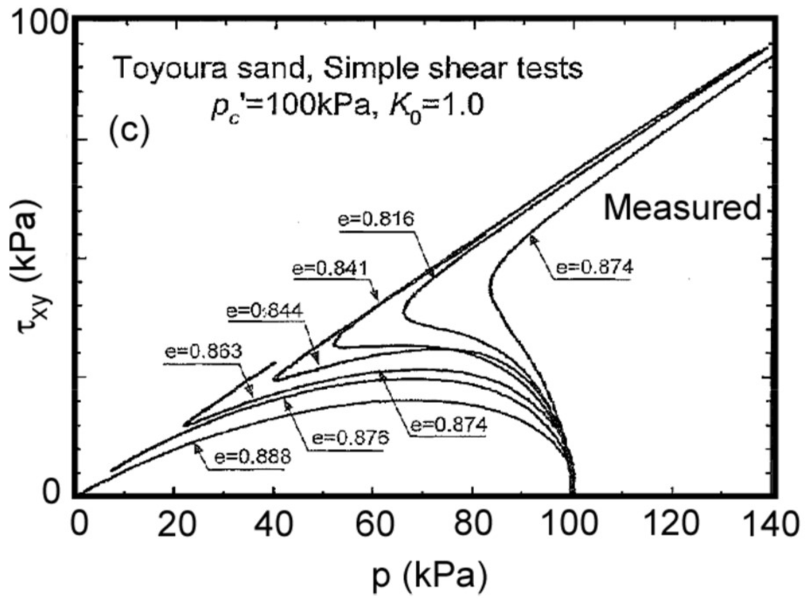
Undrained monotonic shear (review)

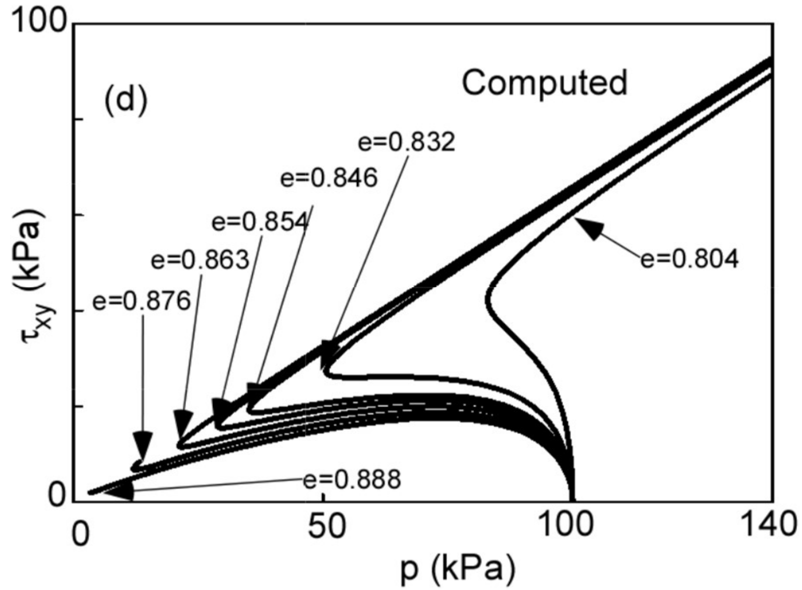




Yoshimine et al (1998), Iai et al (2011)

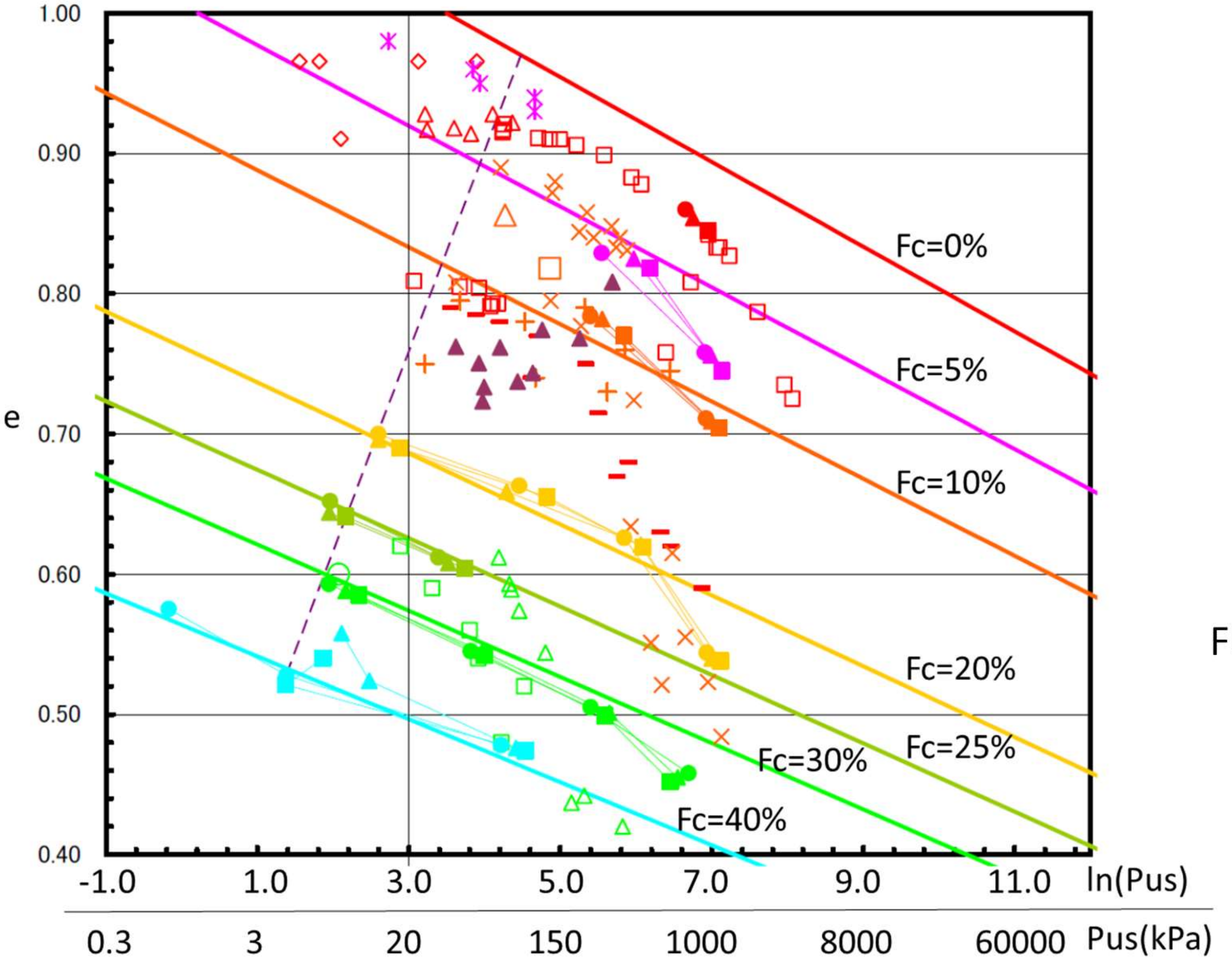
Stress path
undrained monotonic shear



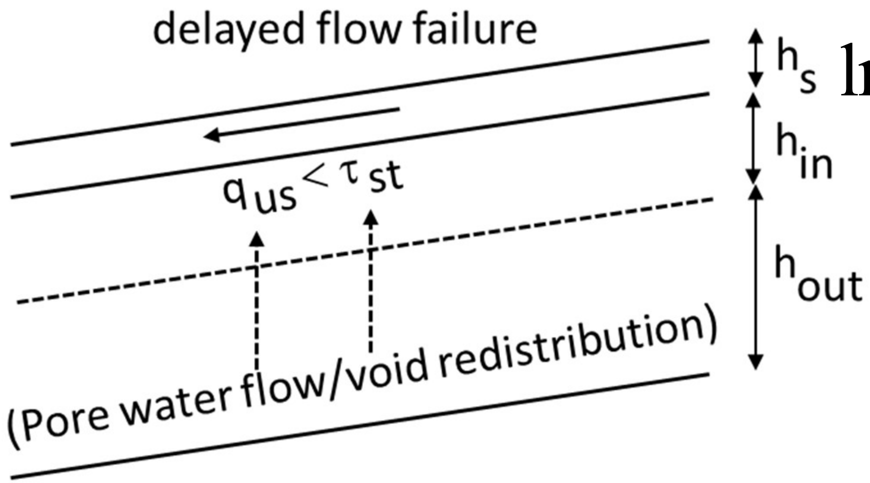


Yoshimine et al (1998), Iai et al (2011)

$$\ln\left(\frac{p_{us}}{p_a}\right) = -\left(\frac{e-e_a}{1+e_a}\right) / \varepsilon_{mus} = -\frac{\varepsilon_{in}}{\varepsilon_{mus}}$$

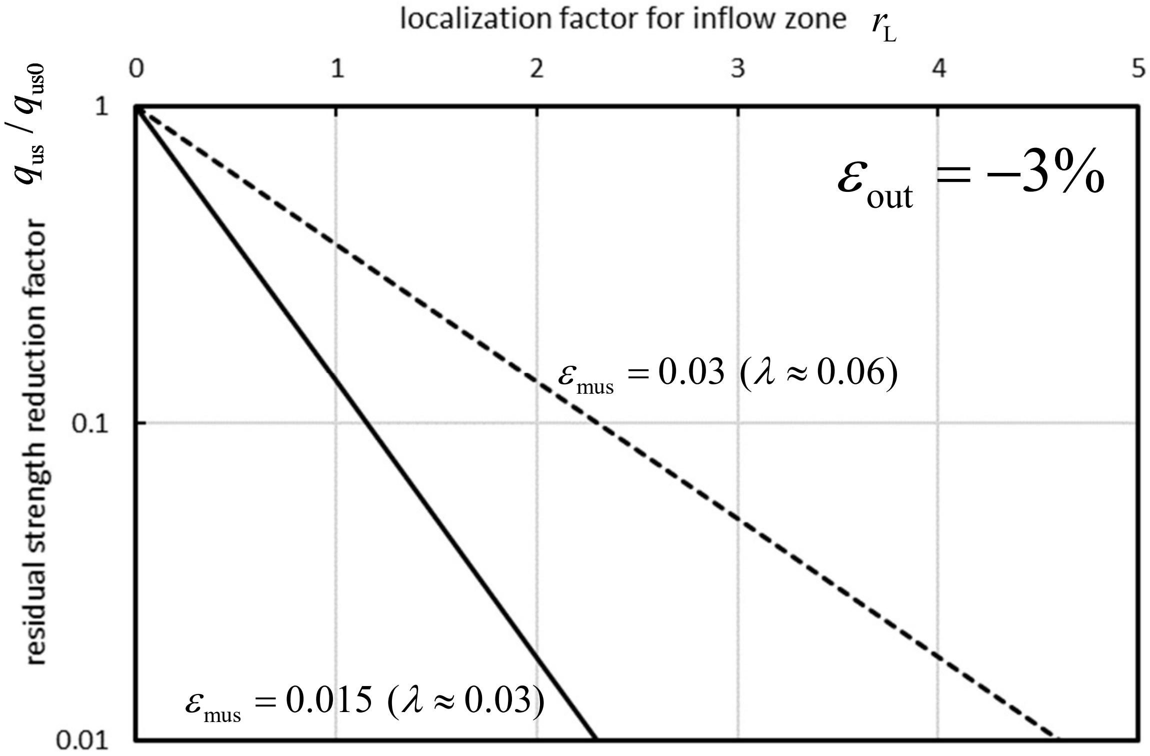


FLIP consortium (2011)

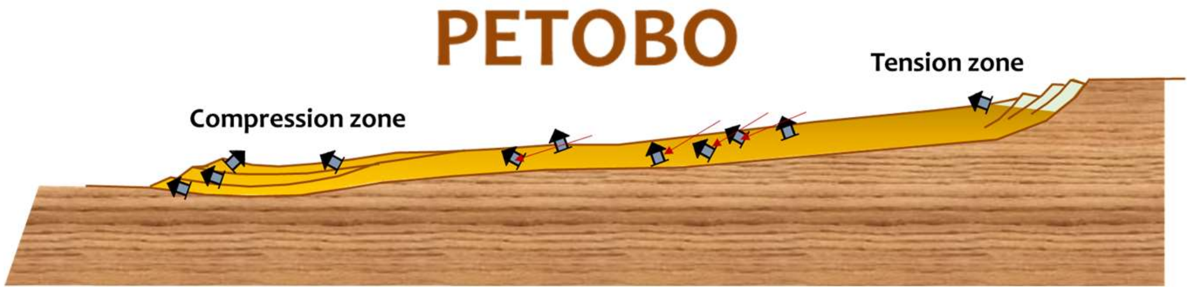


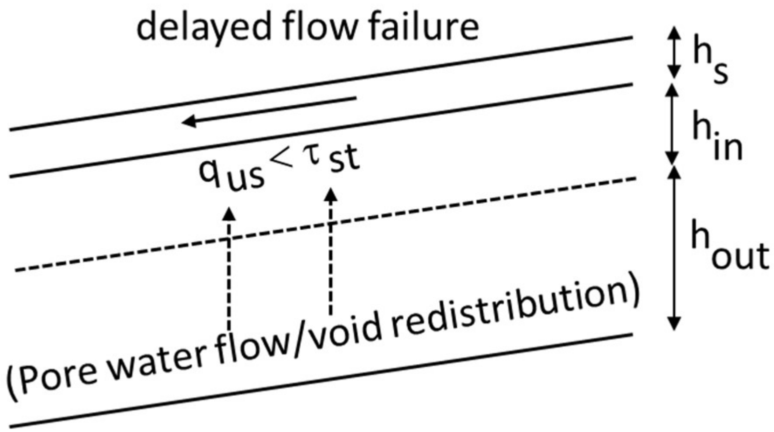
$$\ln\left(\frac{q_{us}}{q_{us0}}\right) = -\left(\frac{\varepsilon_{in}}{\varepsilon_{mus}}\right) = -r_L\left(\frac{\varepsilon_{out}}{\varepsilon_{mus}}\right)$$

$$r_L = r_{\Delta\varepsilon}\left(\frac{h_{out}}{h_{in}}\right)$$



Example

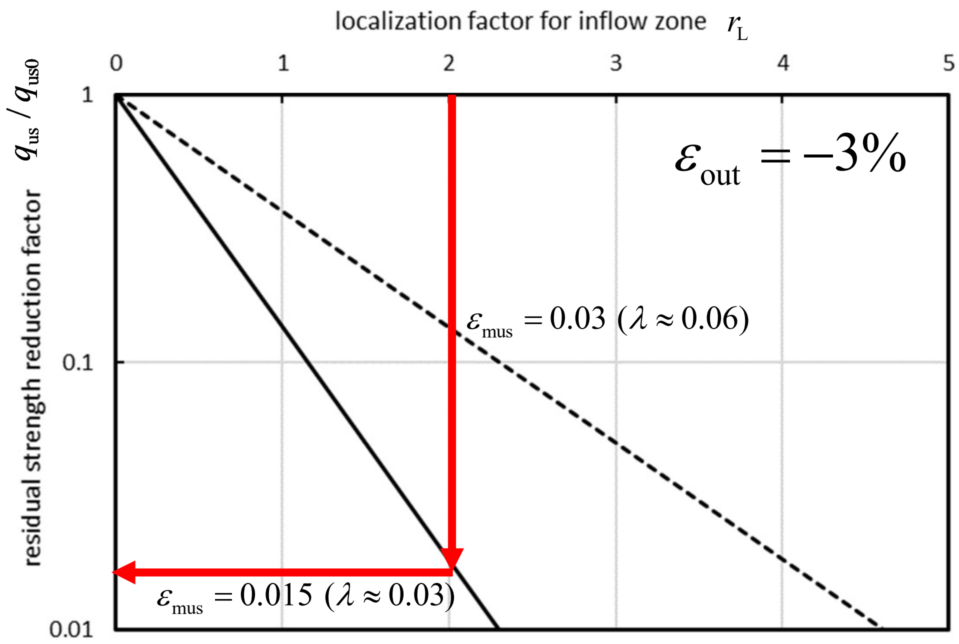




$$\ln\left(\frac{q_{us}}{q_{us0}}\right) = -\left(\frac{\varepsilon_{in}}{\varepsilon_{mus}}\right) = -r_L\left(\frac{\varepsilon_{out}}{\varepsilon_{mus}}\right)$$

$$r_L = r_{\Delta\varepsilon}\left(\frac{h_{out}}{h_{in}}\right)$$

$h_{in} = 2$ m	$q_{us0} = 50$ kPa
$h_{out} = 8$ m	$h_s = 2$ m
$r_{\Delta\varepsilon} = 0.5$	



$$r_L = 0.5 \times \left(\frac{8}{2}\right) = 2$$

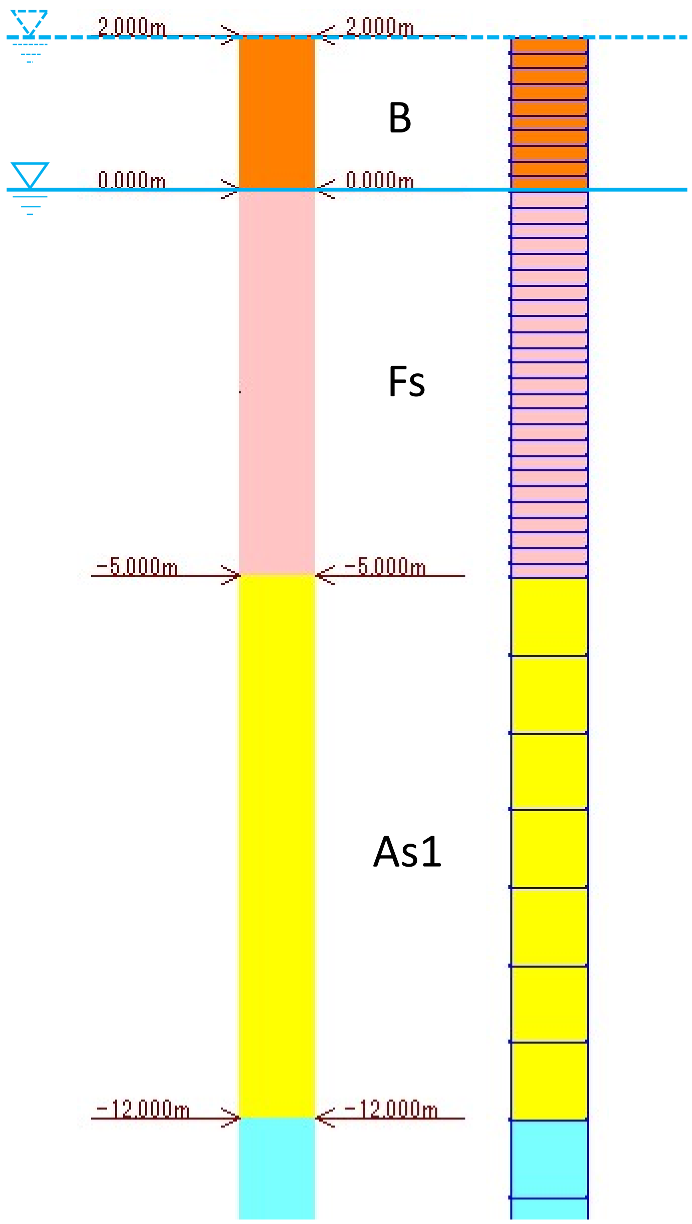
$$\left(\frac{q_{us}}{q_{us0}}\right) = 0.02$$

$$q_{us} = 1.0 \text{ kPa}$$

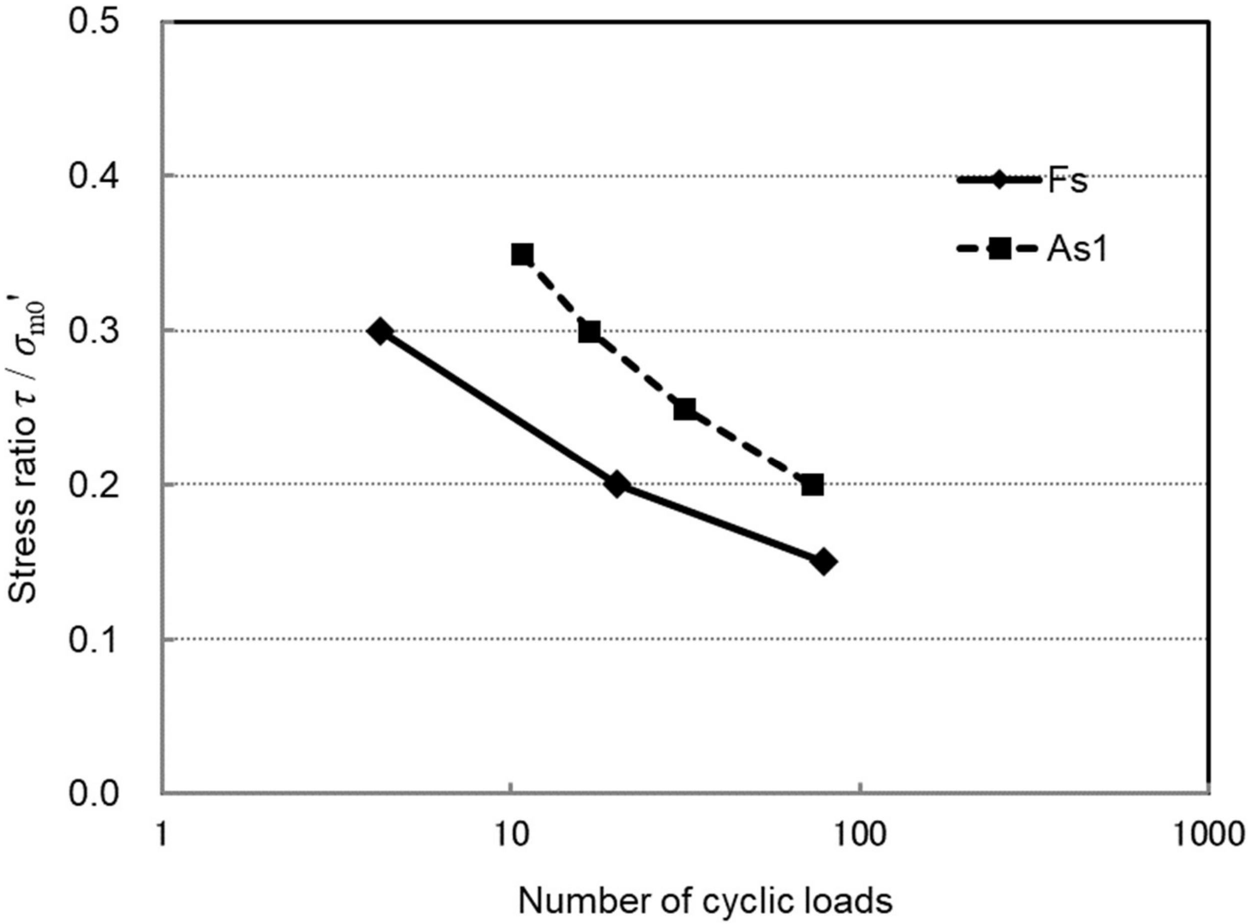
$$\tau_{st} = \rho h_s \sin\theta = 1.8 \times 2 \times \sin(2°) \approx 1.2 \text{ kPa}$$

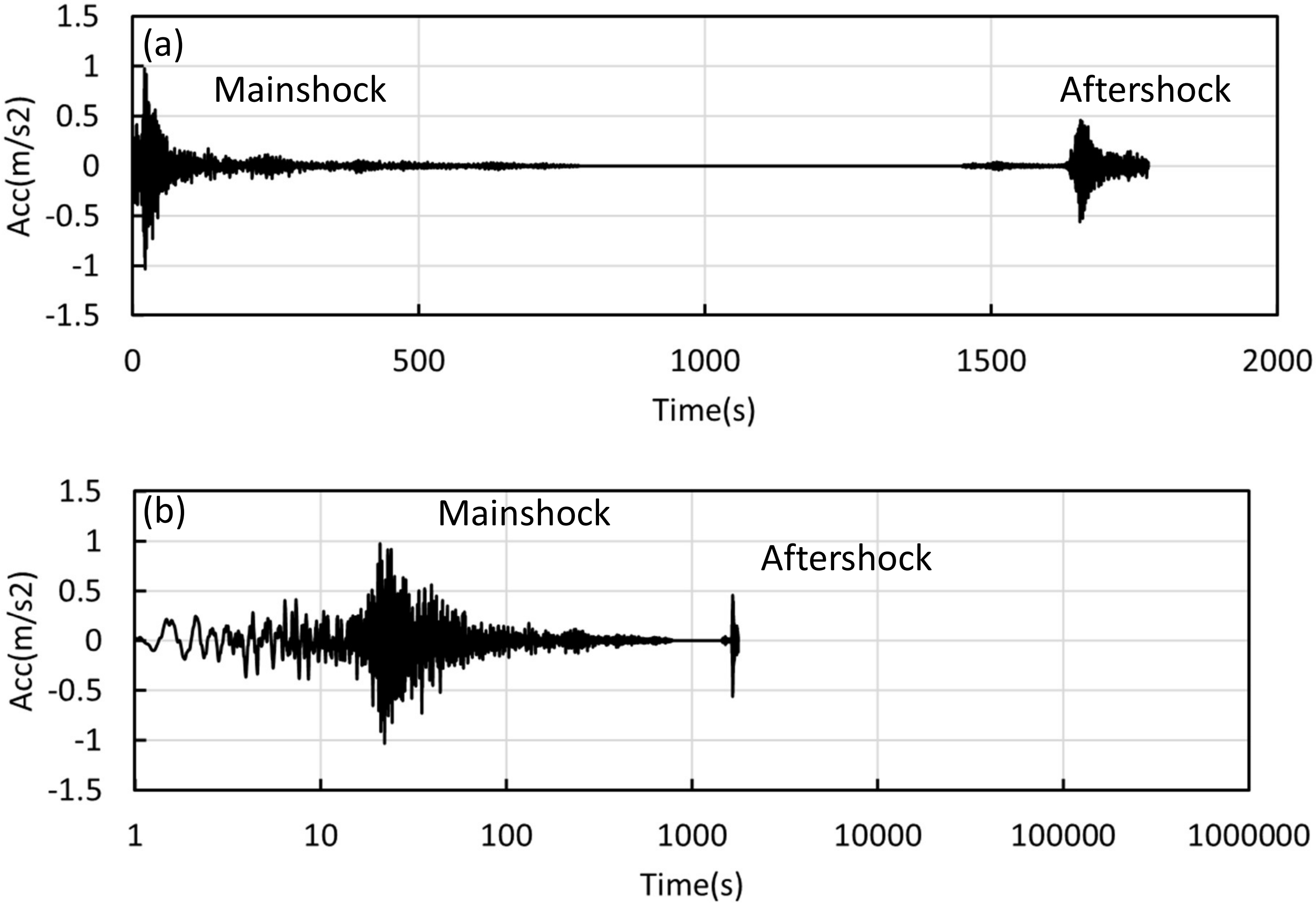
$q_{us} < \tau_{st}$ Flow

Delayed sand boil – 2011 East Japan Earthquake


2.000m
2.000m
B
0.000m
0.000m
Fs
-5.000m
-5.000m
As1
-12.000m
-12.000m

Liquefaction resistance



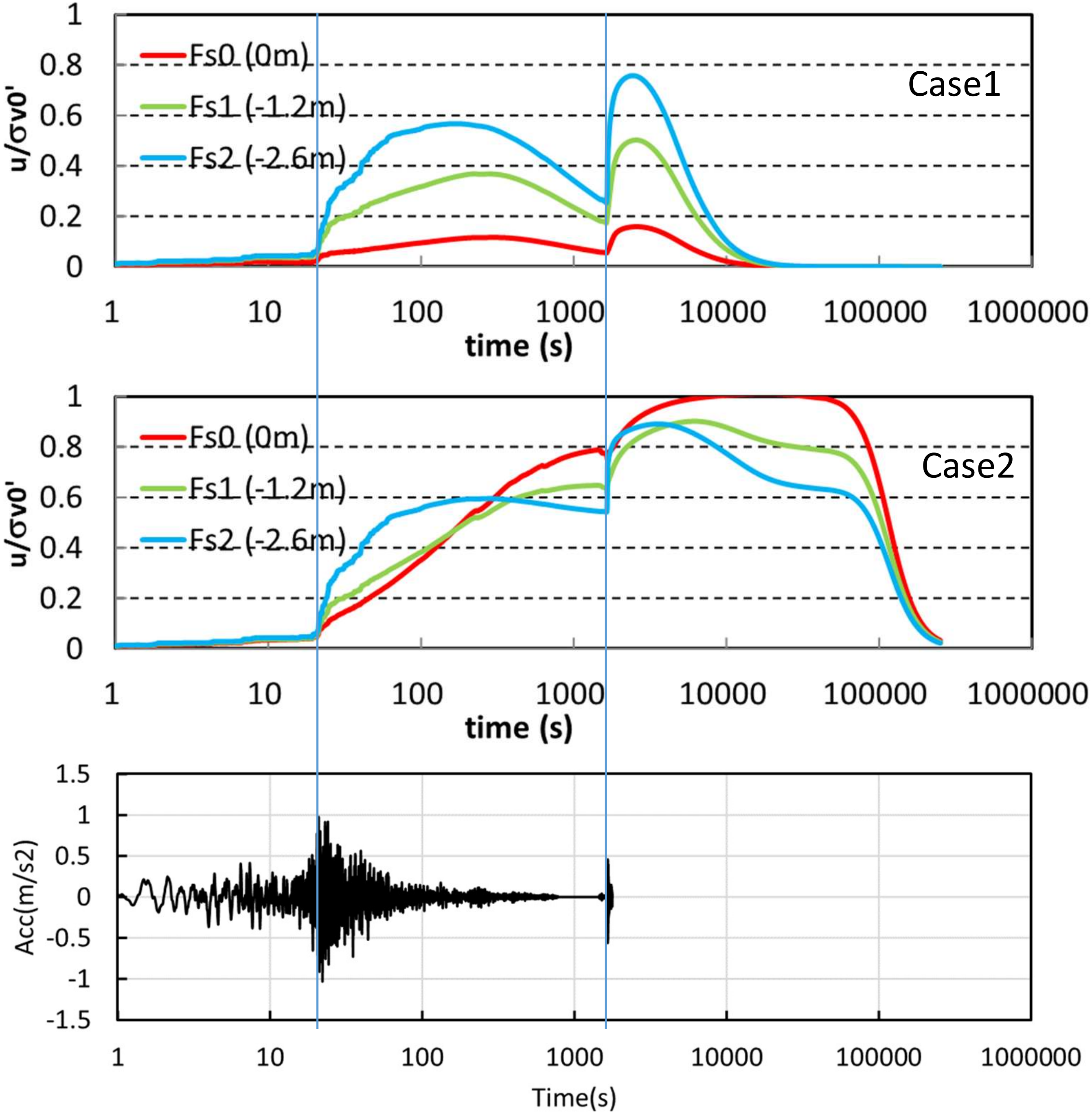

1.5
1
0.5
0
-0.5
-1
-1.5
Acc(m/s2)
(a)
Mainshock
Aftershock
0
500
1000
1500
2000
Time(s)
1.5
1
0.5
0
-0.5
-1
-1.5
Acc(m/s2)
(b)
Mainshock
Aftershock
1
10
100
1000
10000
100000
1000000
Time(s)

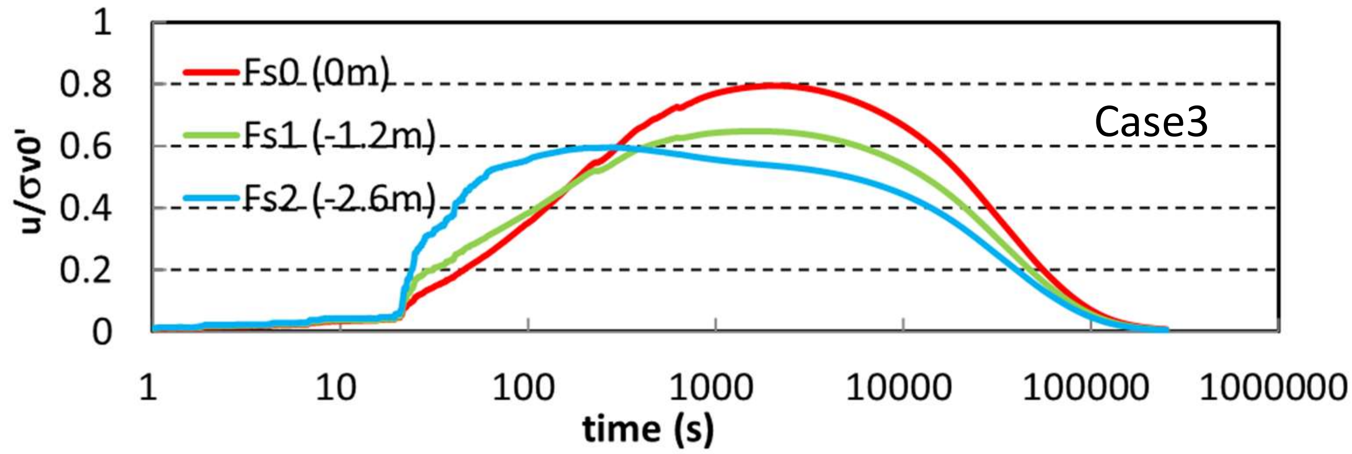
Analyses cases

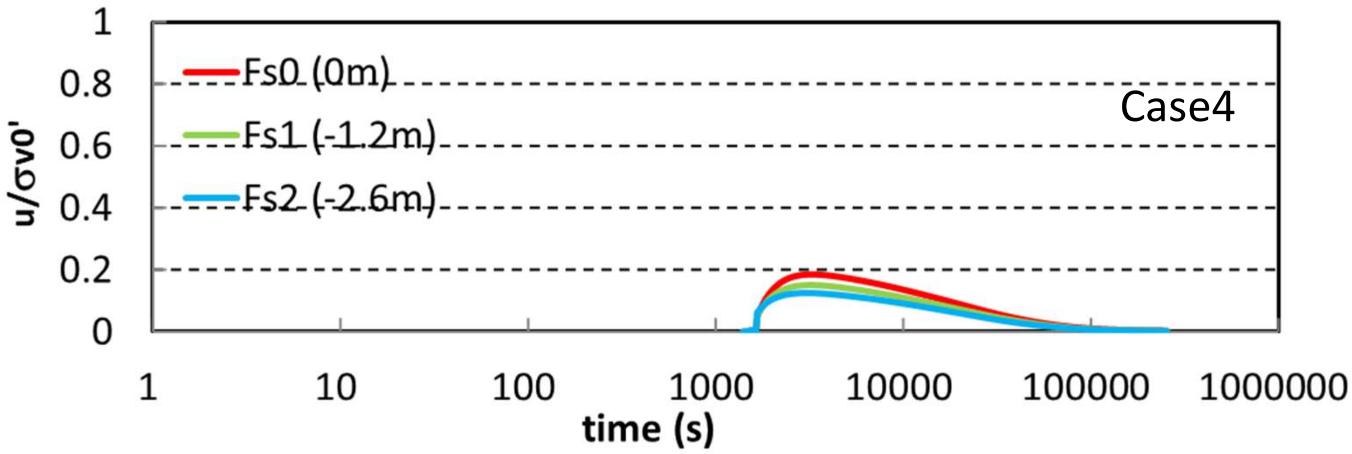
	Case1	Case2	Case3	Case4
k_{Bs}/k_{Fs}	5	0.05	0.05	0.05
Input motion	Main & after	Main & after	Main	After

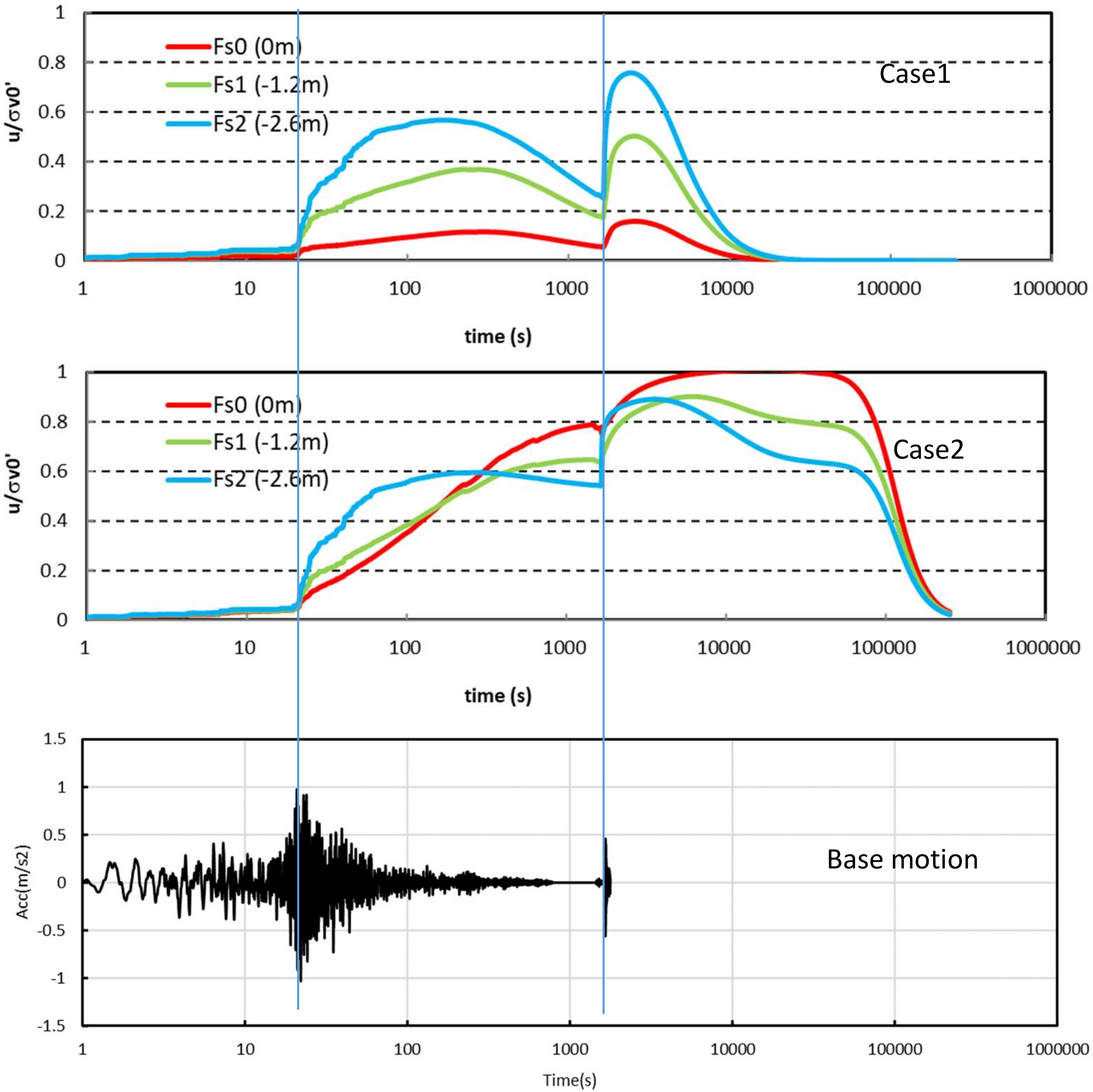
k_{Fs}=1xE-5m/s

k_{As1}/k_{Fs}=10

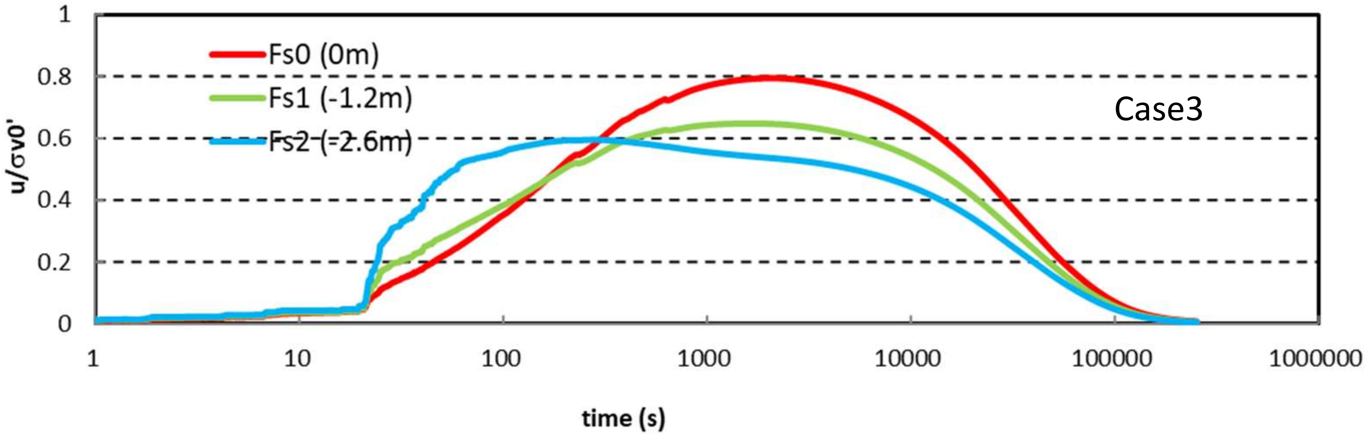

Fs0 (0m)
Fs1 (-1.2m)
Fs2 (-2.6m)
Case1
u/σv0'
time (s)
Case2
Acc(m/s2)
Time(s)

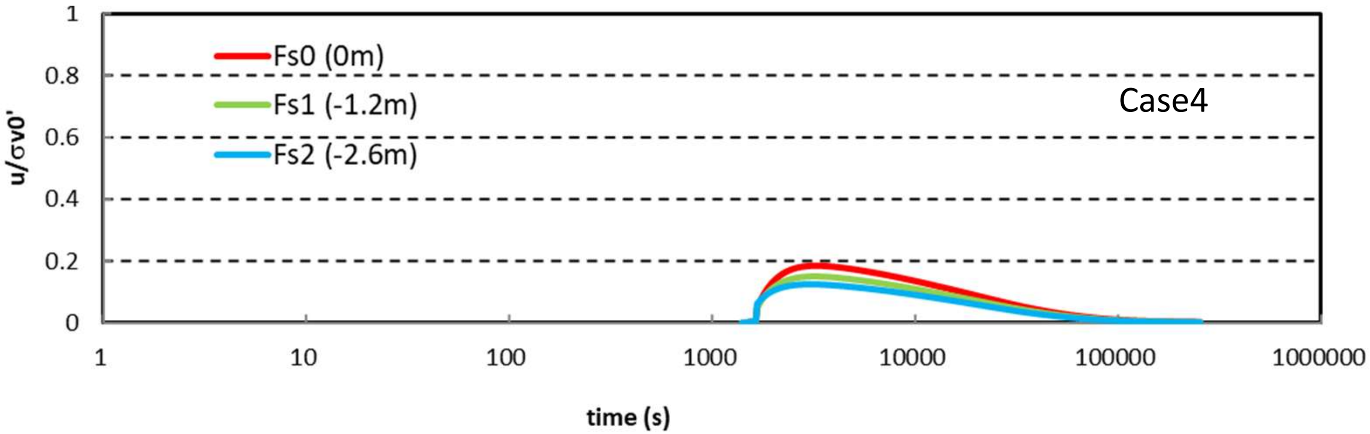

1
0.8
0.6
0.4
0.2
0
u/σv0'
Fs0 (0m)
Fs1 (-1.2m)
Fs2 (-2.6m)
Case3
1
10
100
1000
10000
100000
1000000
time (s)

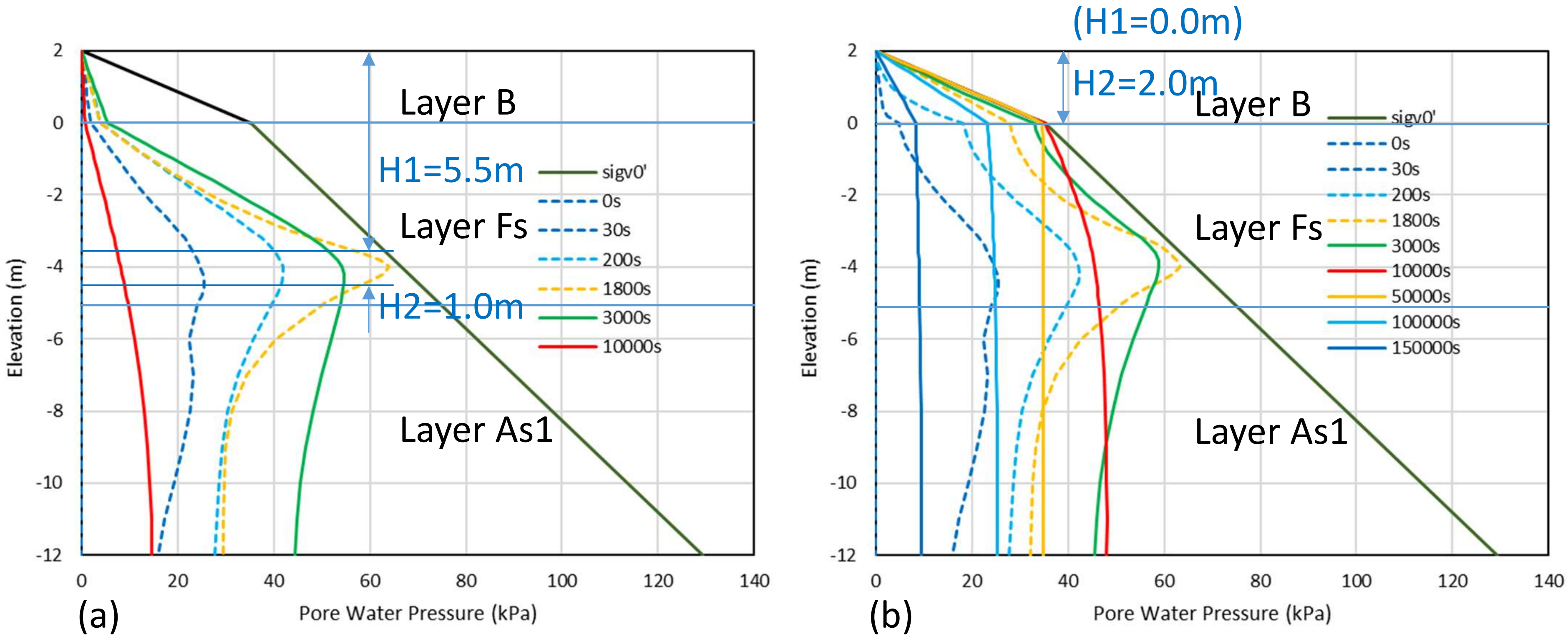

1
0.8
0.6
0.4
0.2
0
u/σv0'
Fs0 (0m)
Fs1 (-1.2m)
Fs2 (-2.6m)
Case4
1
10
100
1000
10000
100000
1000000
time (s)

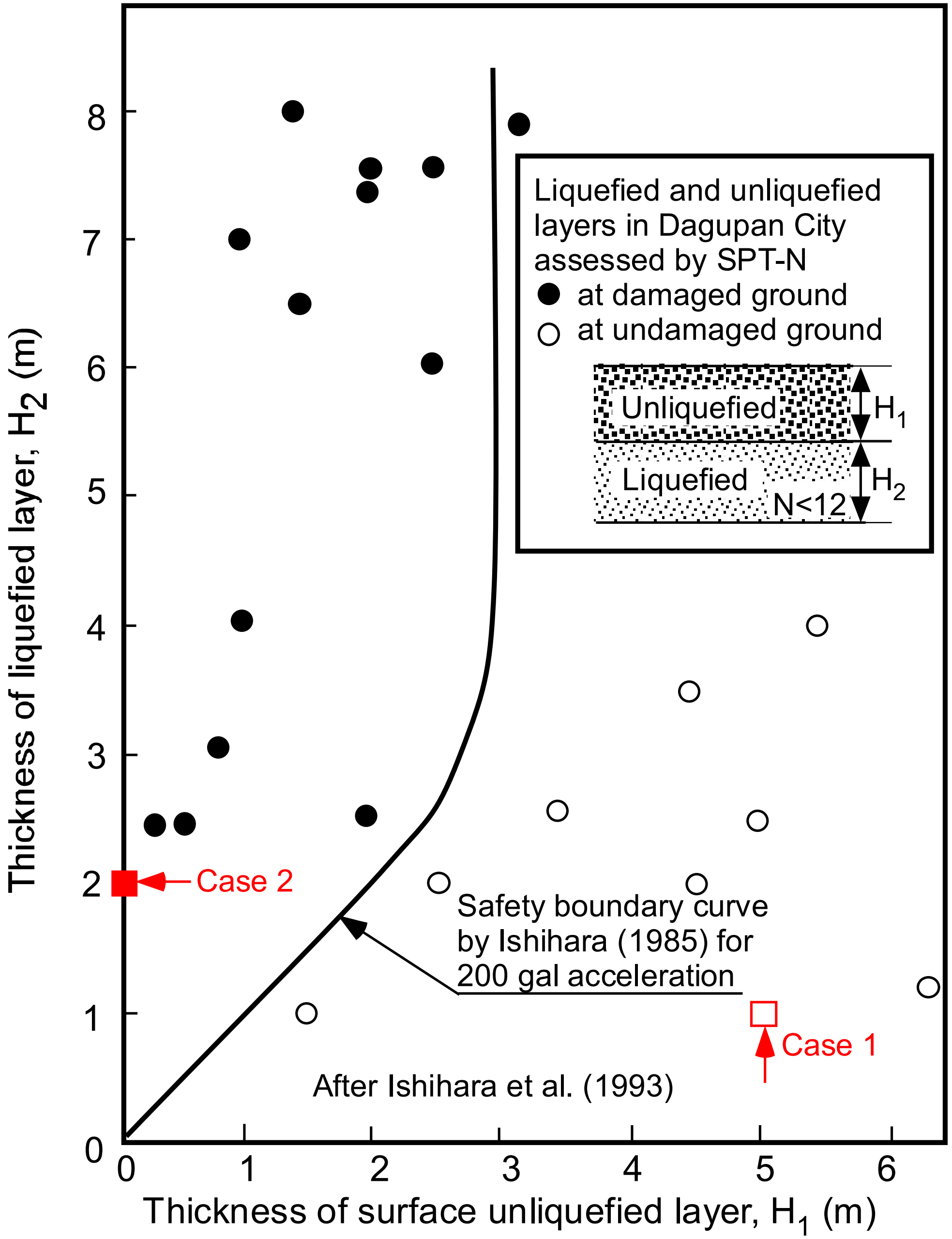


u/σv0'
Fs0 (0m)
Fs1 (-1.2m)
Fs2 (-2.6m)
Case1
time (s)
Case2
Acc(m/s2)
Base motion
Time(s)

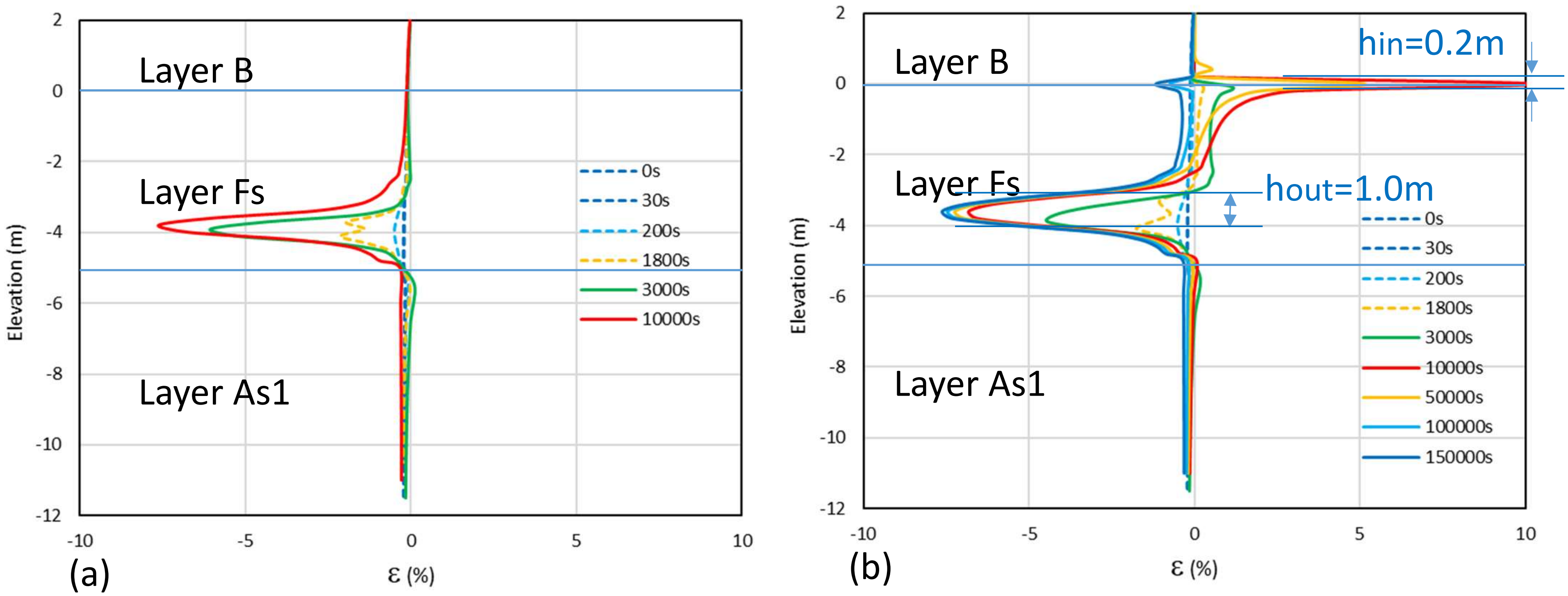

1
0.8
0.6
0.4
0.2
0
u/σv0'
Fs0 (0m)
Fs1 (-1.2m)
Fs2 (-2.6m)
Case3
1
10
100
1000
10000
100000
1000000
time (s)


1
0.8
0.6
0.4
0.2
0
u/σv0'
Fs0 (0m)
Fs1 (-1.2m)
Fs2 (-2.6m)
Case4
1
10
100
1000
10000
100000
1000000
time (s)


(H1=0.0m)
Layer B
H1=5.5m
Layer Fs
H2=1.0m
Layer As1
H2=2.0m
sigv0'
0s
30s
200s
1800s
3000s
10000s
50000s
100000s
150000s
Elevation (m)
Pore Water Pressure (kPa)
(a)
(b)

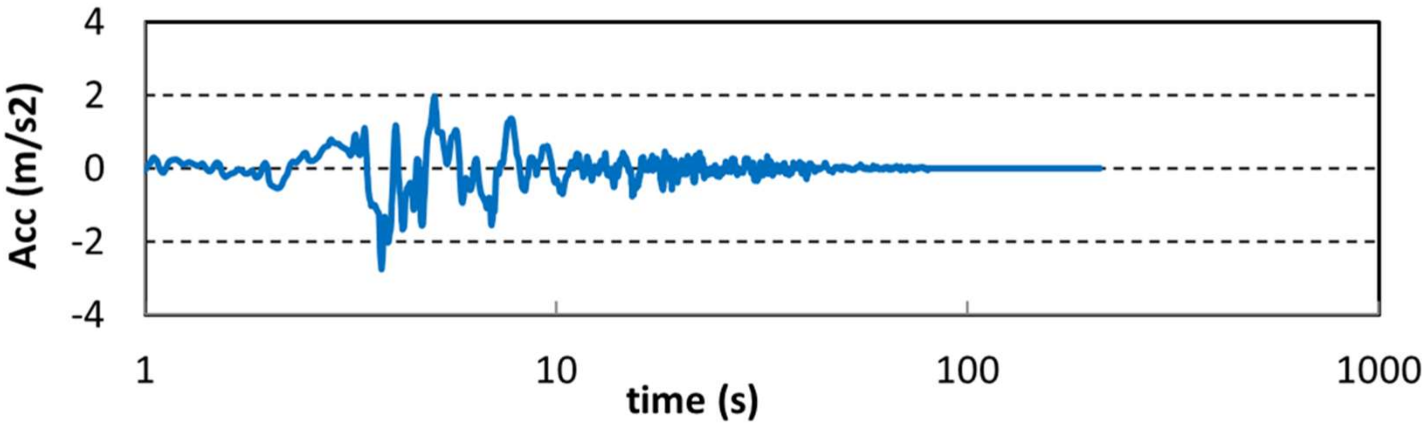


Liquefied and unliquefied layers in Dagupan City assessed by SPT-N
at damaged ground
at undamaged ground
Unliquefied
Liquefied
N<12
H_1
H_2
Case 2
Case 1
Safety boundary curve by Ishihara (1985) for 200 gal acceleration
After Ishihara et al. (1993)
Thickness of liquefied layer, H_2 (m)
Thickness of surface unliquefied layer, H_1 (m)
0
1
2
3
4
5
6
7
8



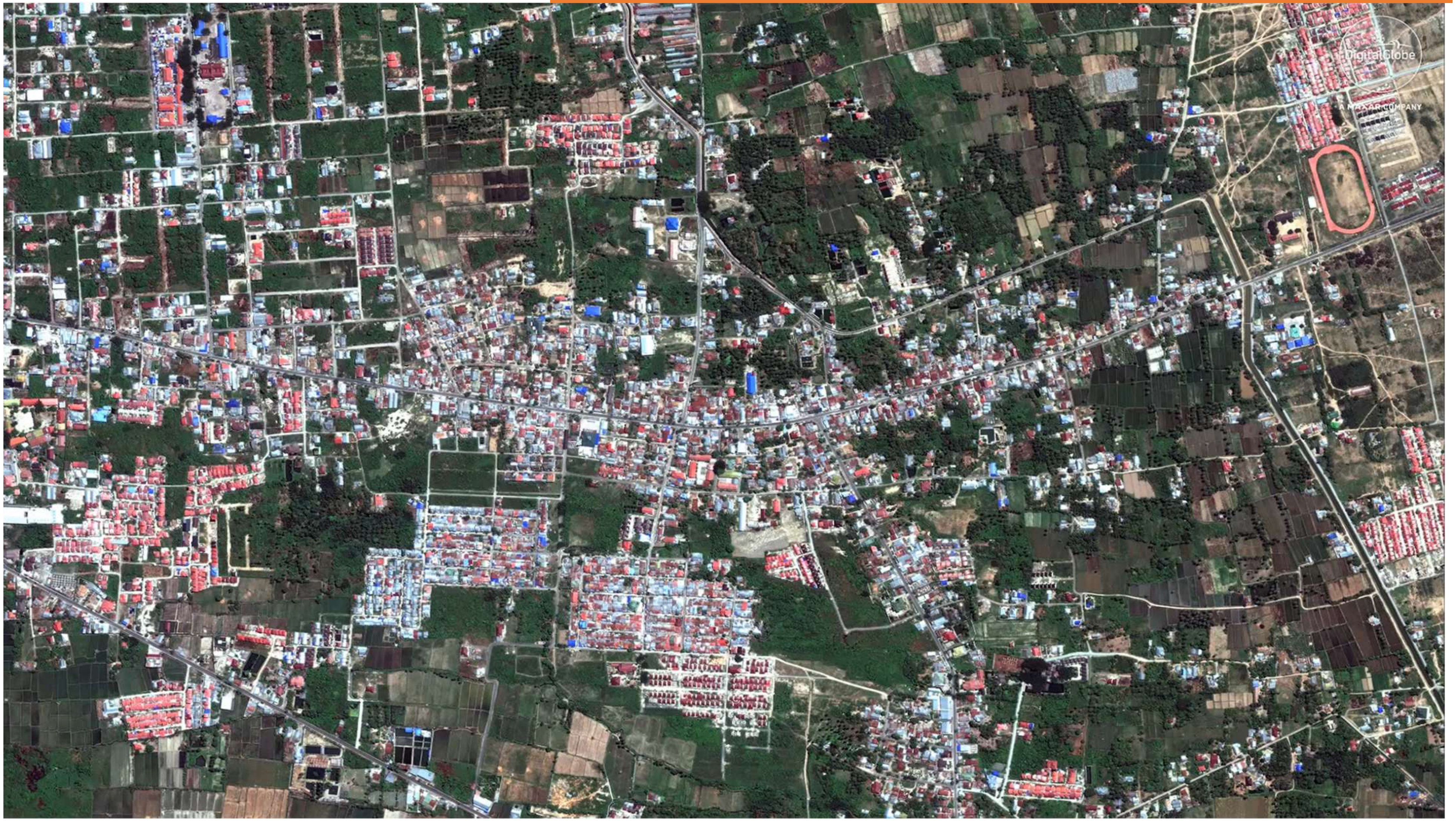
Layer B
Layer Fs
Layer As1
Elevation (m)
ε (%)
0s
30s
200s
1800s
3000s
10000s
(a)
Layer B
Layer Fs
Layer As1
hin=0.2m
hout=1.0m
Elevation (m)
ε (%)
0s
30s
200s
1800s
3000s
10000s
50000s
100000s
150000s
(b)

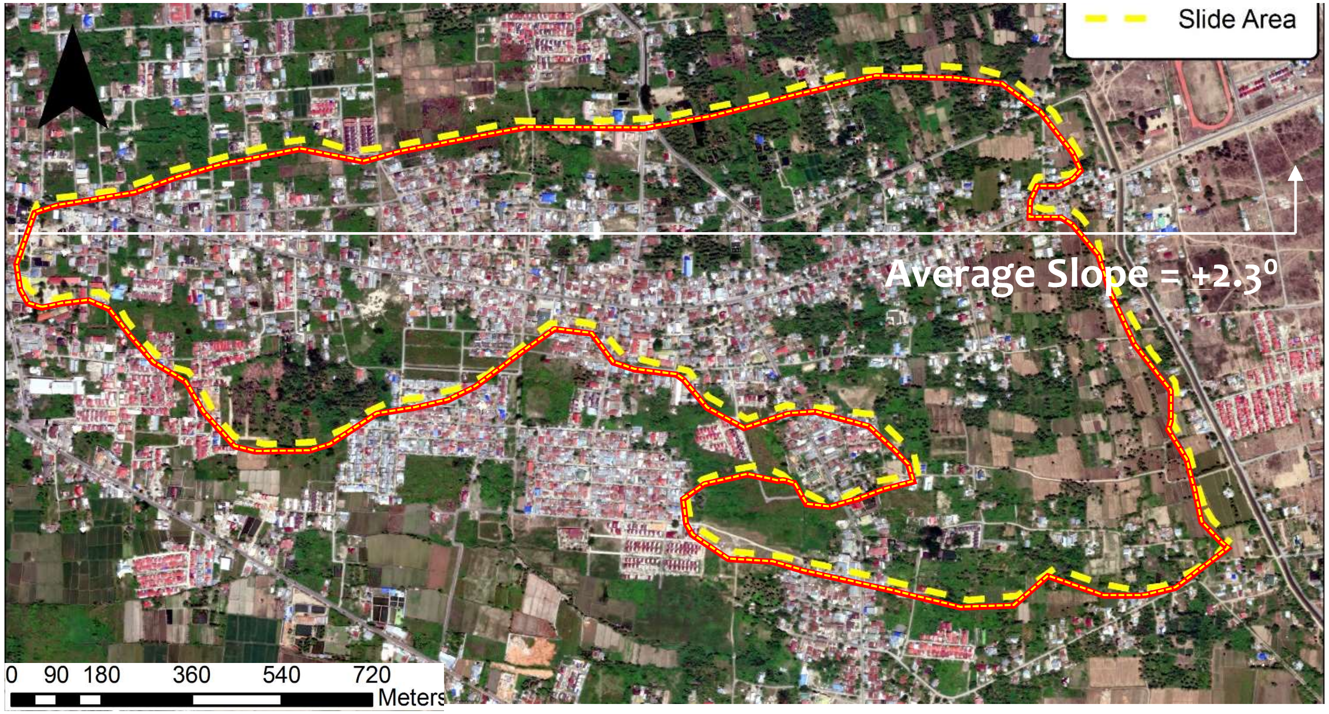
2018 PALU earthquake, Indonesia (after Irsyam et al, 2019)

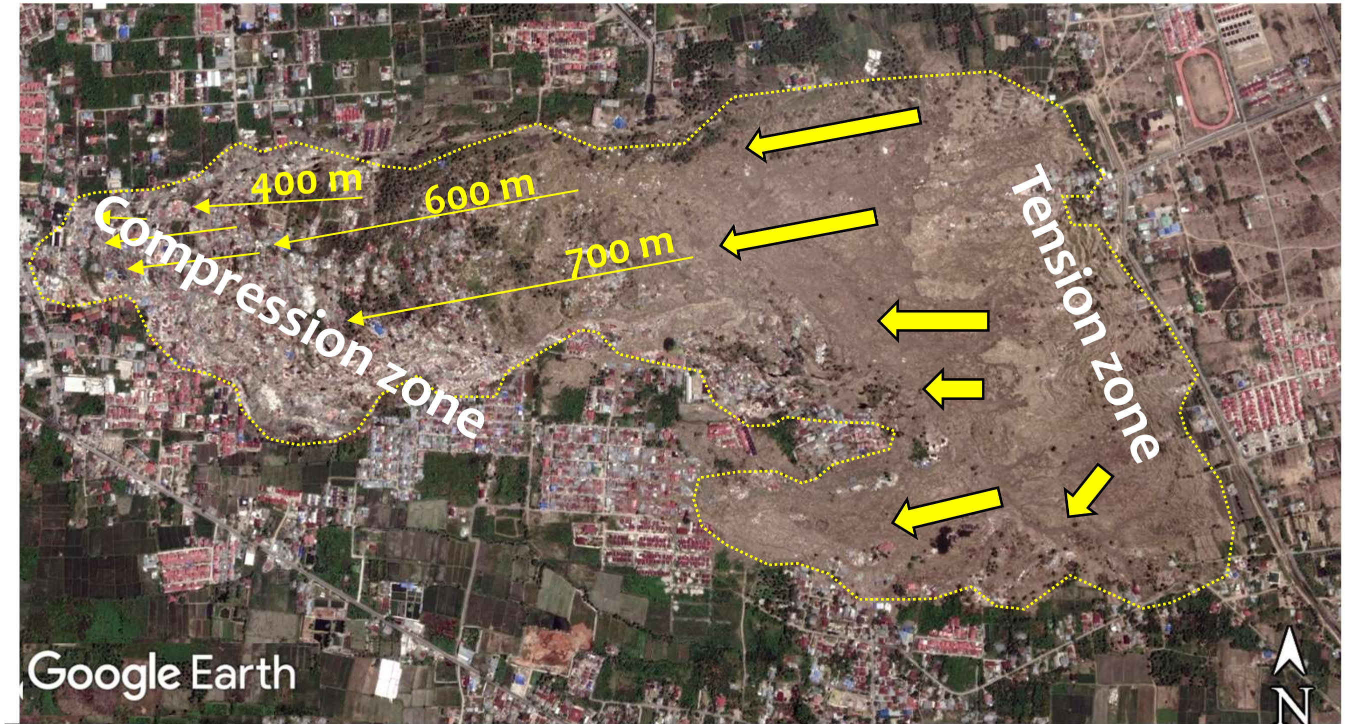


Petobo

(Process of soil liquefaction in Petobo Housing Complex www.Instagram.com/p/BokdLnxDx27/?utm_source=jg_embed)



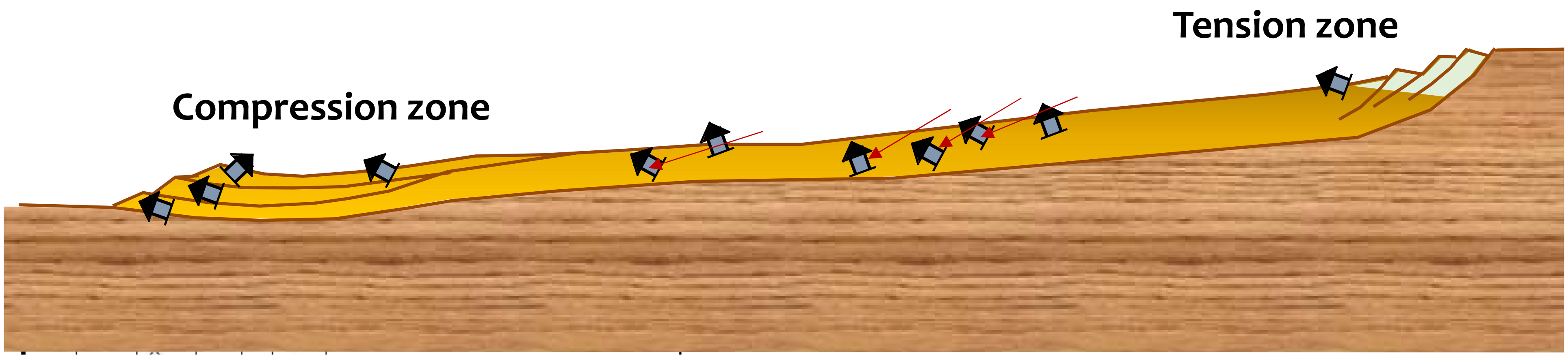




Flow slide and movement direction (modified from Mason et al, 2019)

Ground movement (Bessette-Kirton at al, 2018)

PETOBO

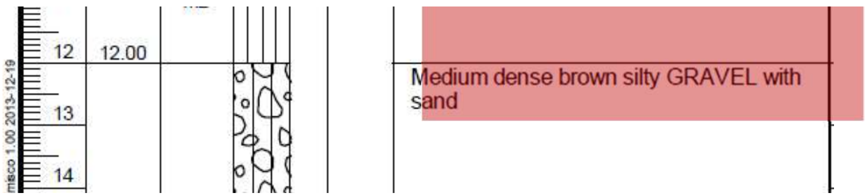


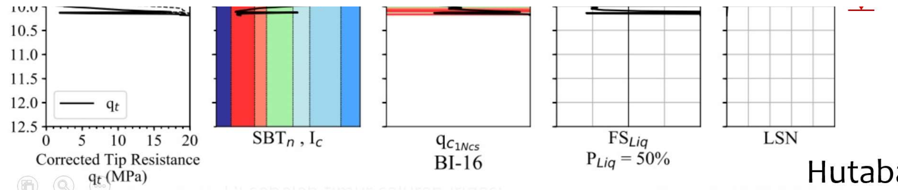
Ground shaking at saturated loose alluvium fan deposit → Pore pressure generation →

Redistribution stress due possibility pore pressure dissipation/ water film →

Shear stresses > residual strength → Flow slide

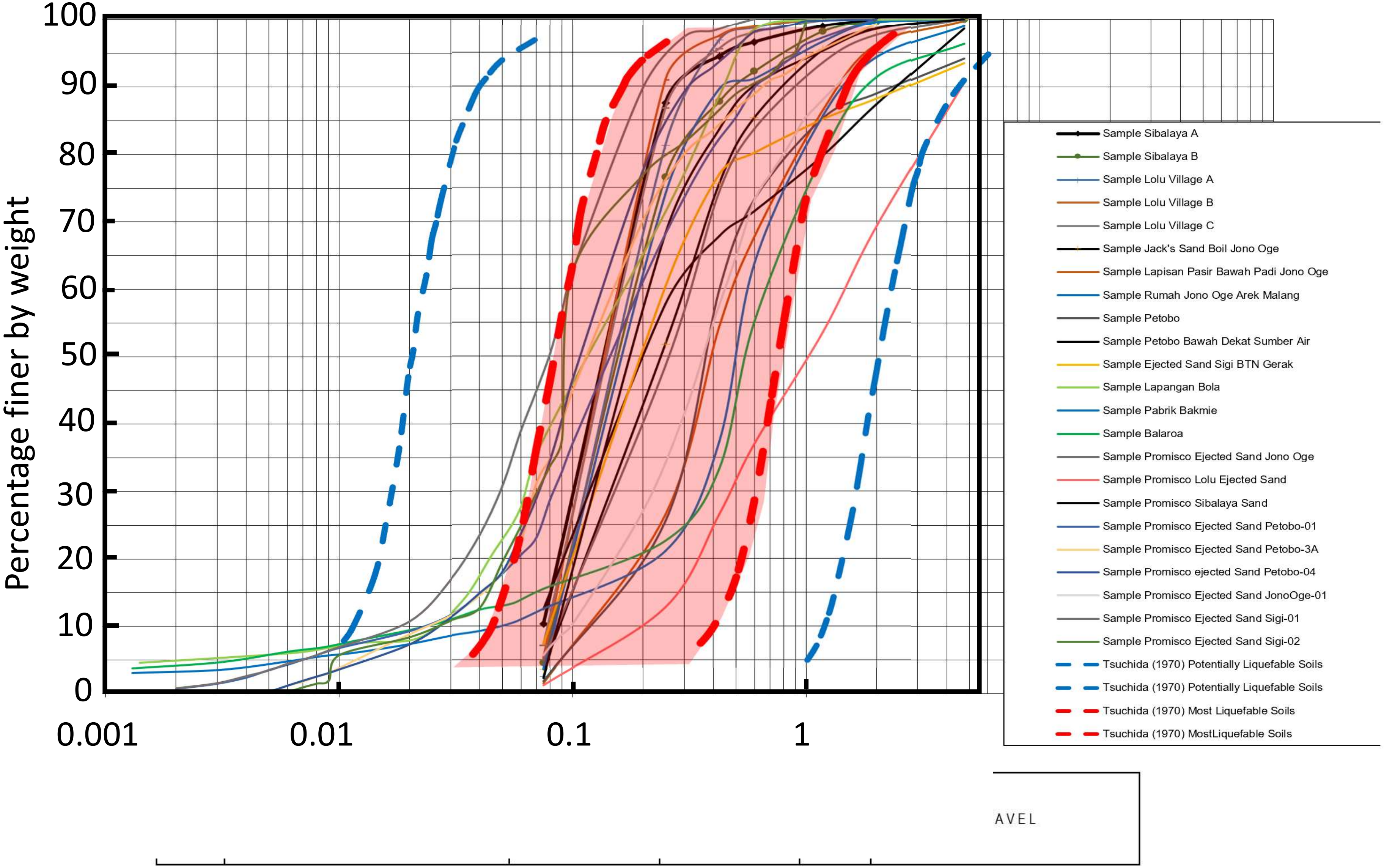
Is there any possibility of breakage of aquifer that contribute to massive ground displacement?

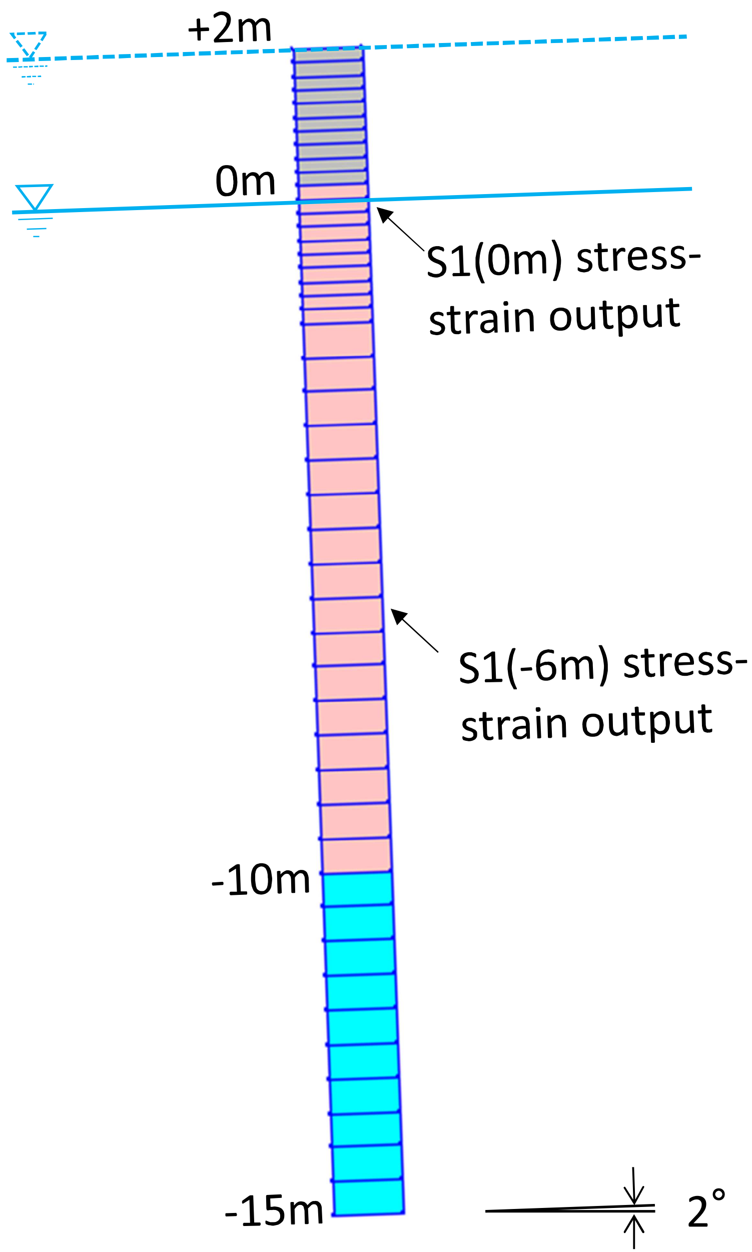




Hutab

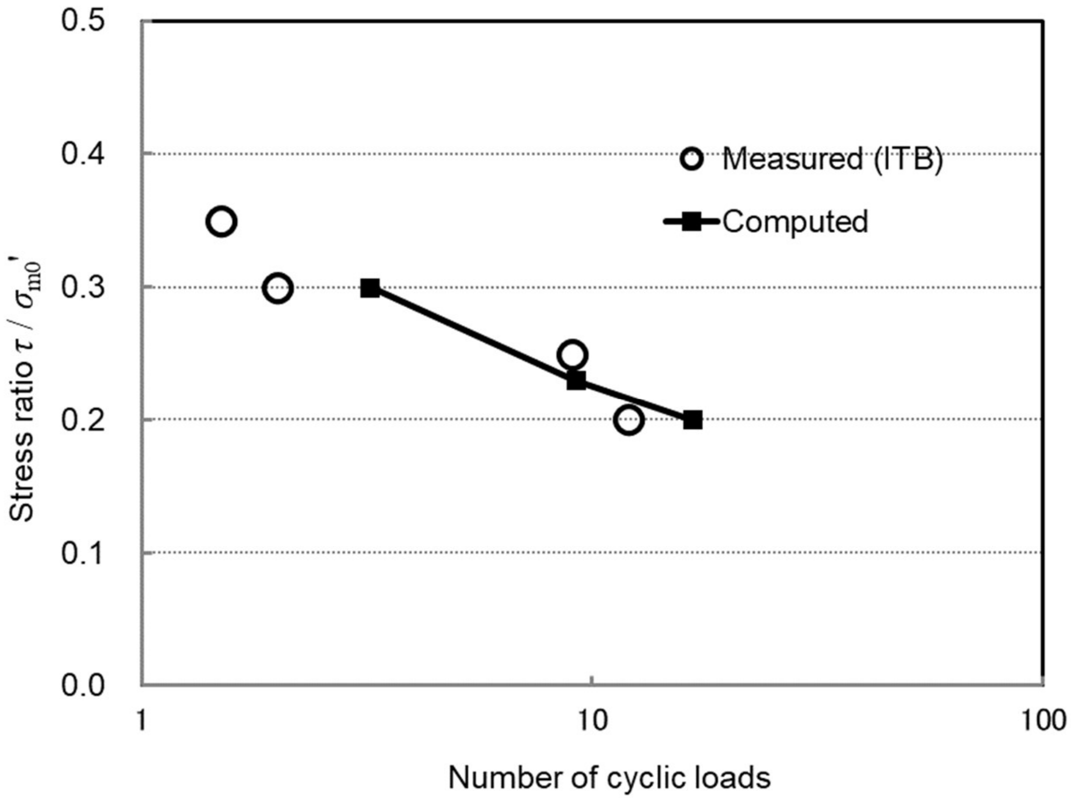
Grain Size Distribution of Ejected Soil Samples




+2m
0m
S1(0m) stress-strain output
S1(-6m) stress-strain output
-10m
-15m
2°

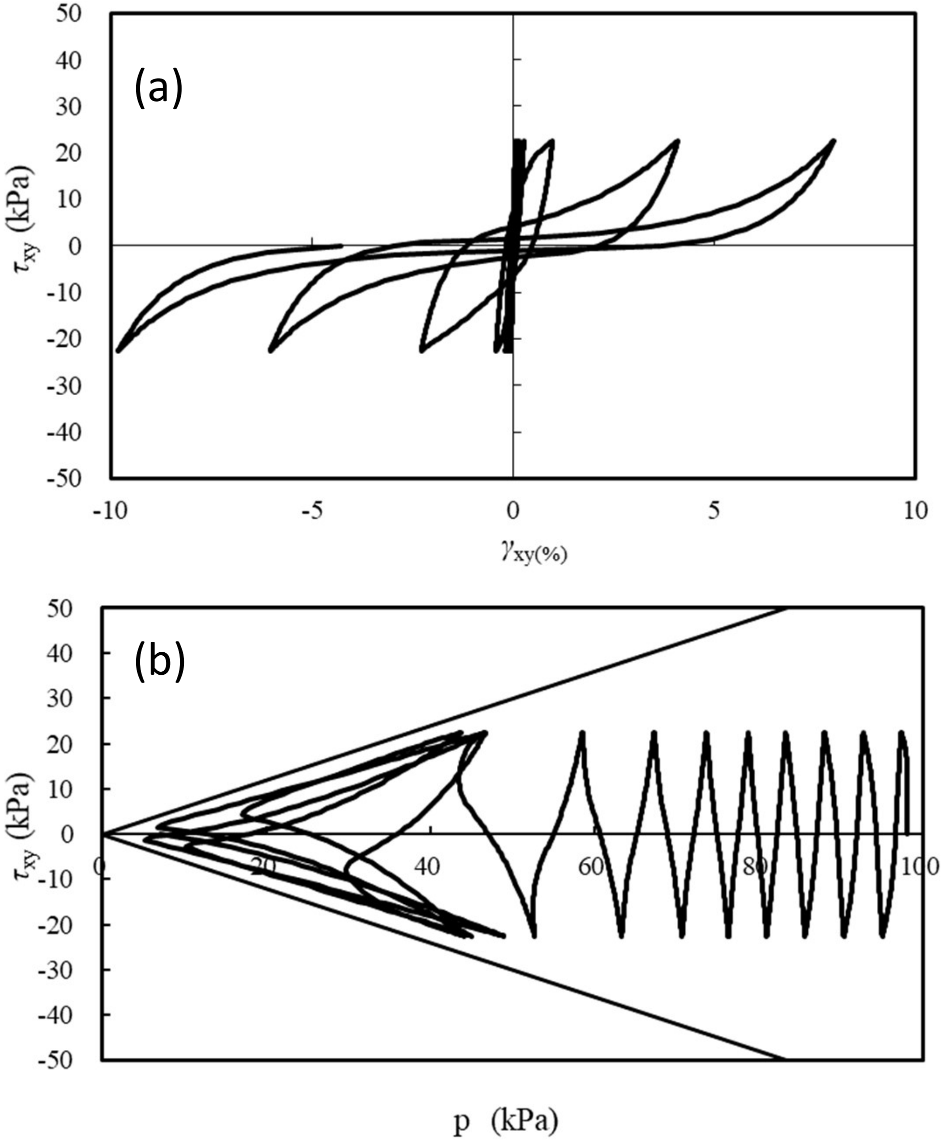
Analyses cases

		CaseI	CaseII	CaseIII	CaseIV
k_{S0}/k_{S1}		5	0.005	0.05	0.005
S1	k_{S1} (1E-4m/s)	1	1	0.1	1
	q_{us0}(kPa)	20	20	20	50

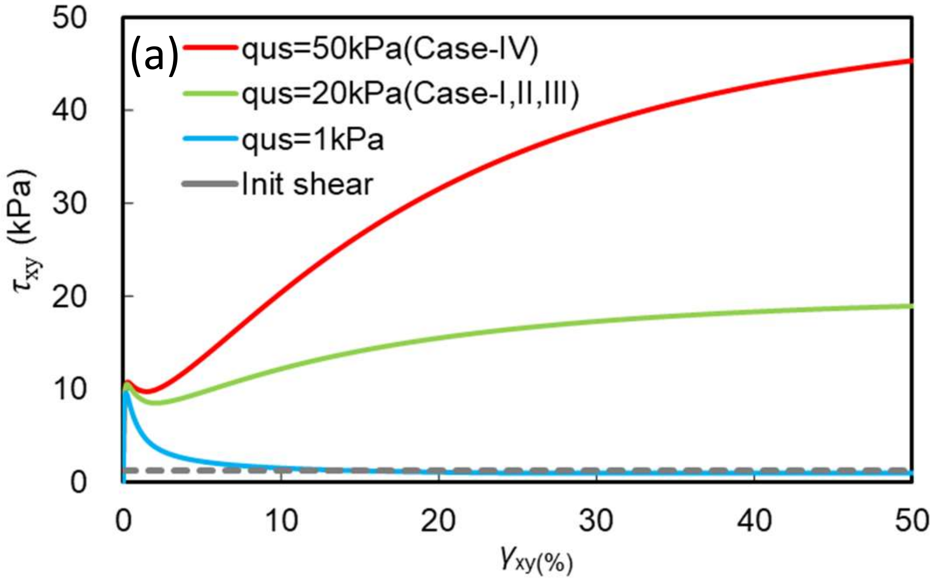


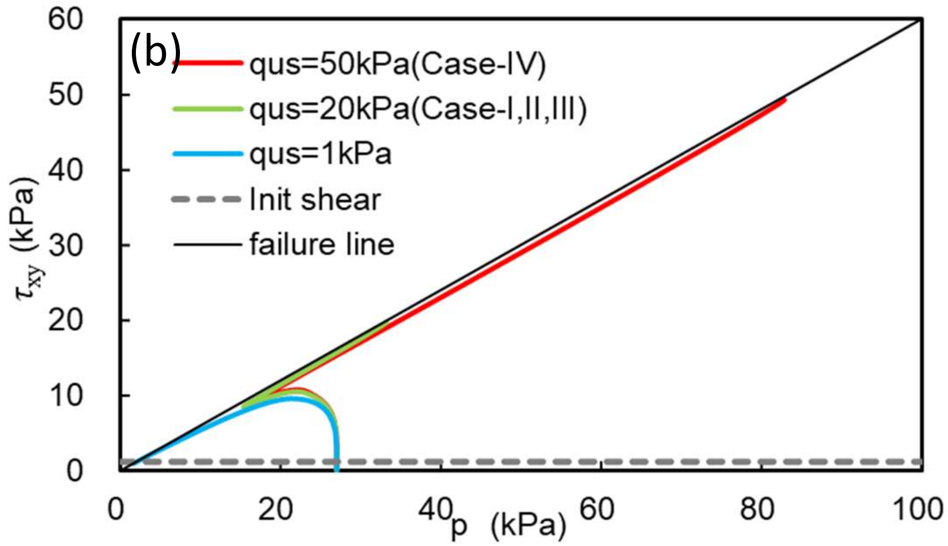
0.5
0.4
0.3
0.2
0.1
0.0
Stress ratio τ / σm0'
Measured (ITB)
Computed
1
10
100
Number of cyclic loads

Undrained cyclic loading

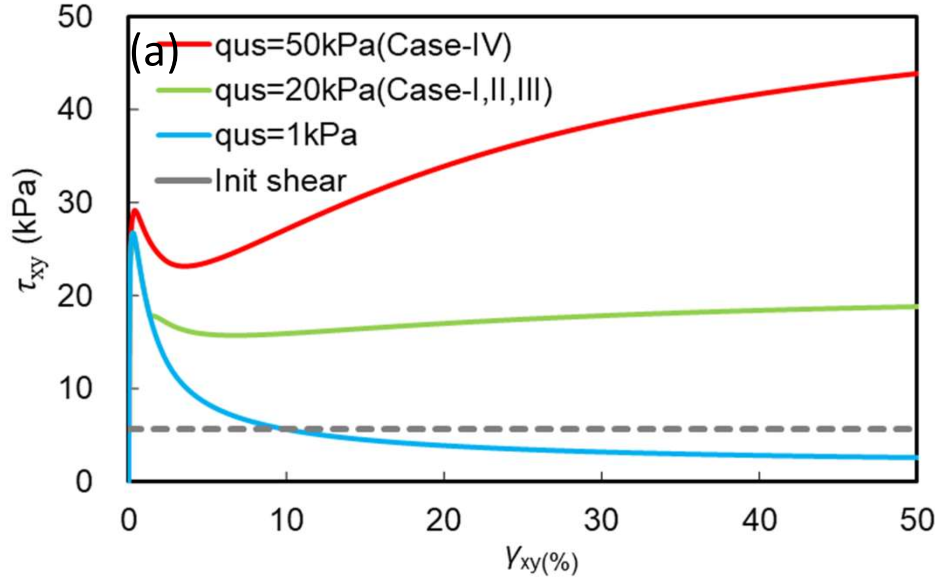


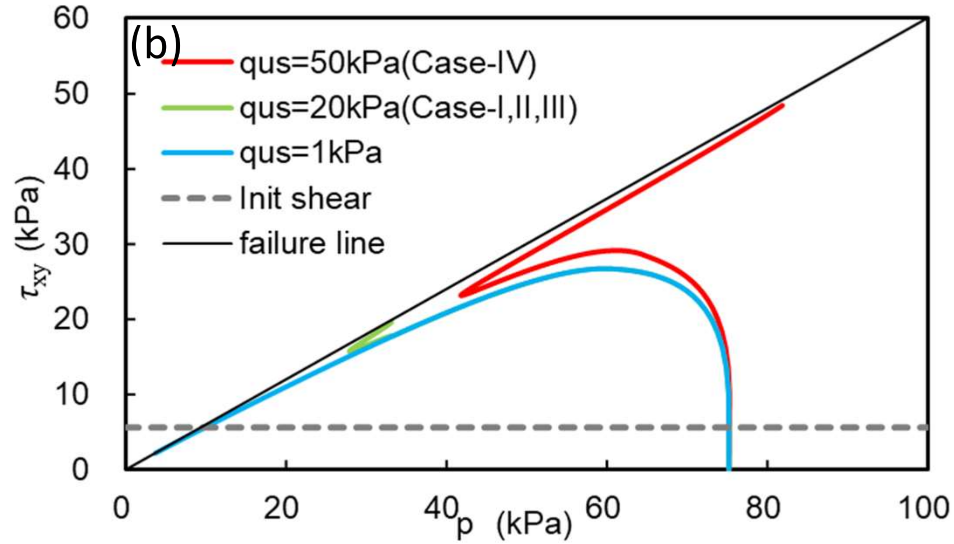
Undrained monotonic loading S1 (0m)



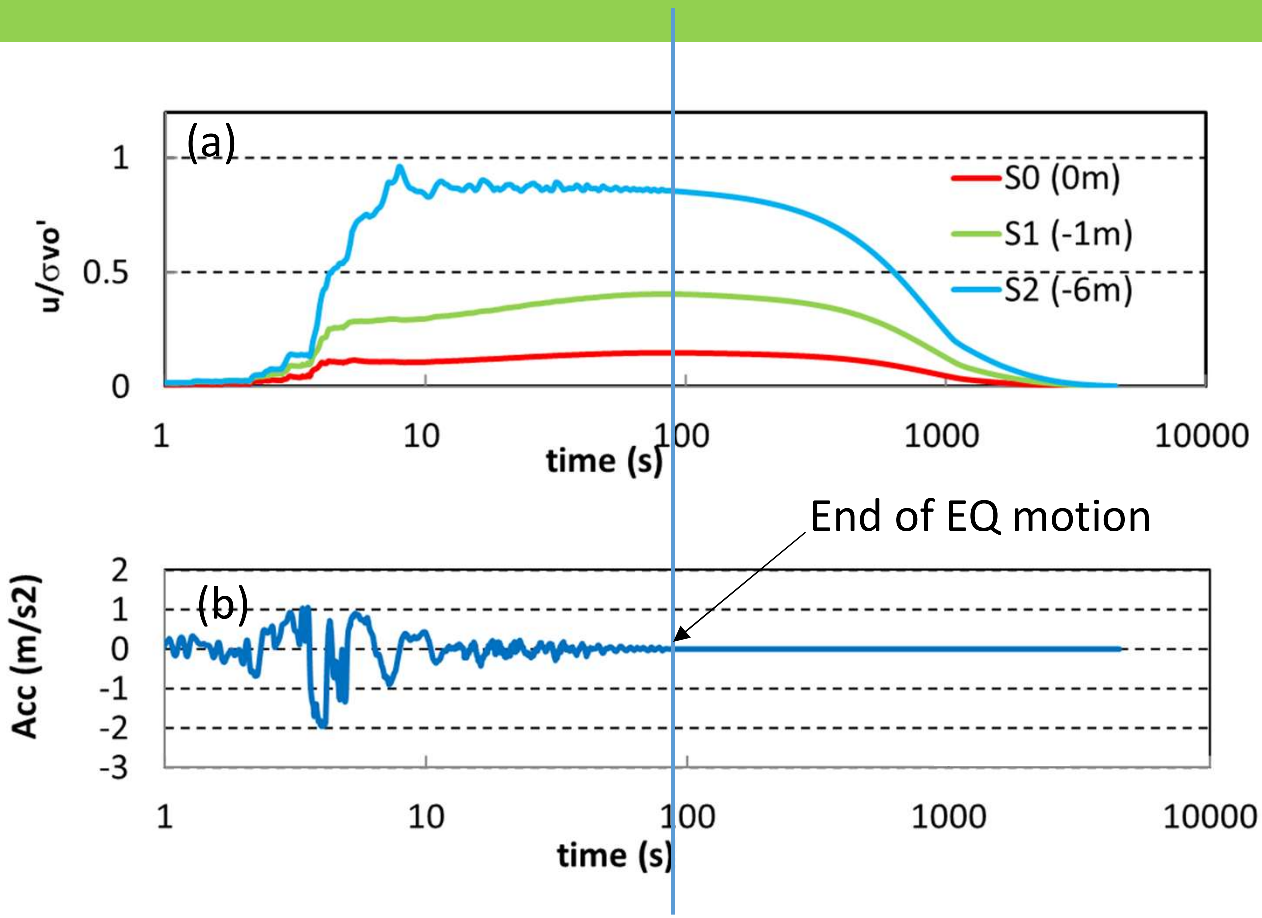


Undrained monotonic loading S1 (-6m)

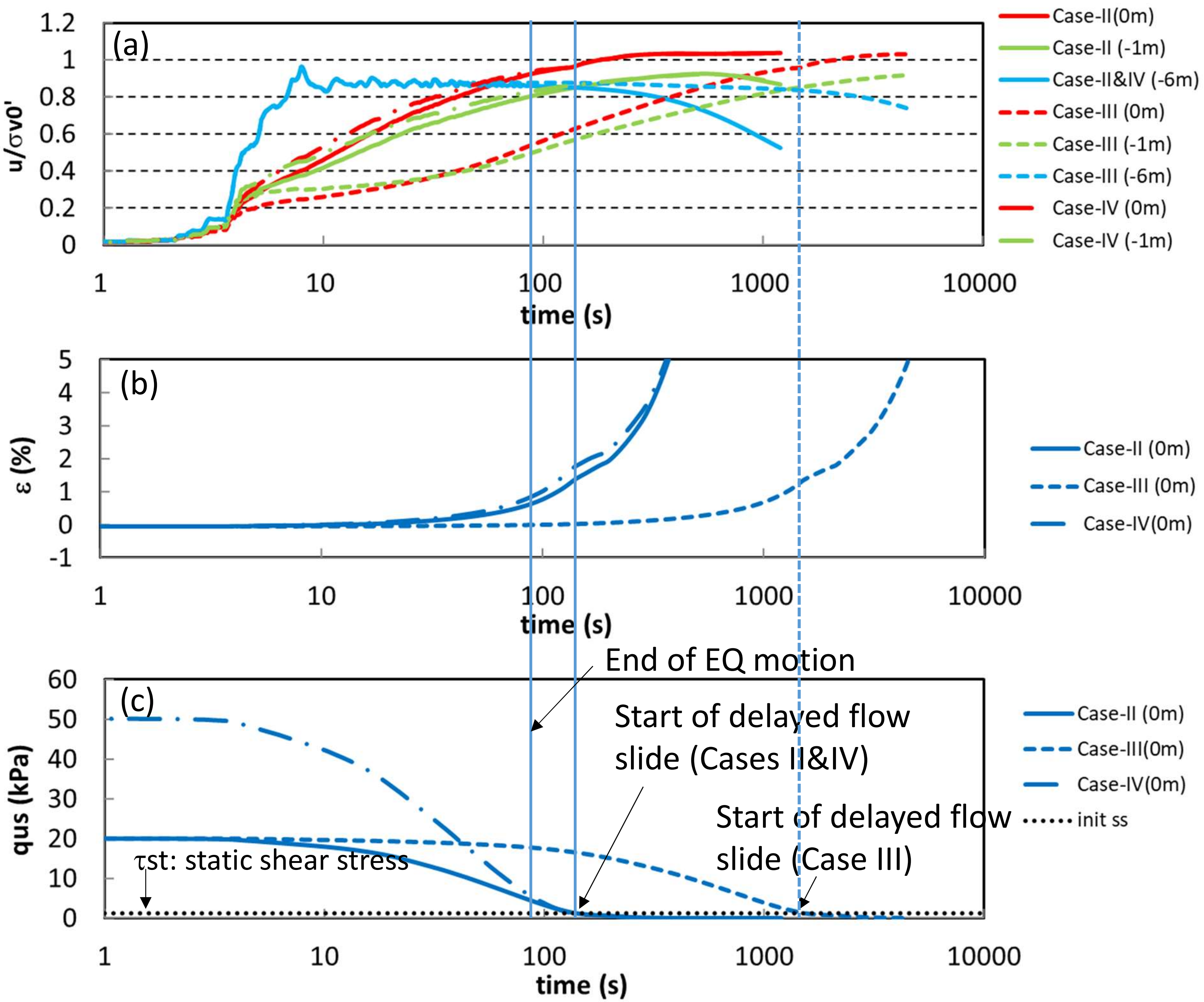


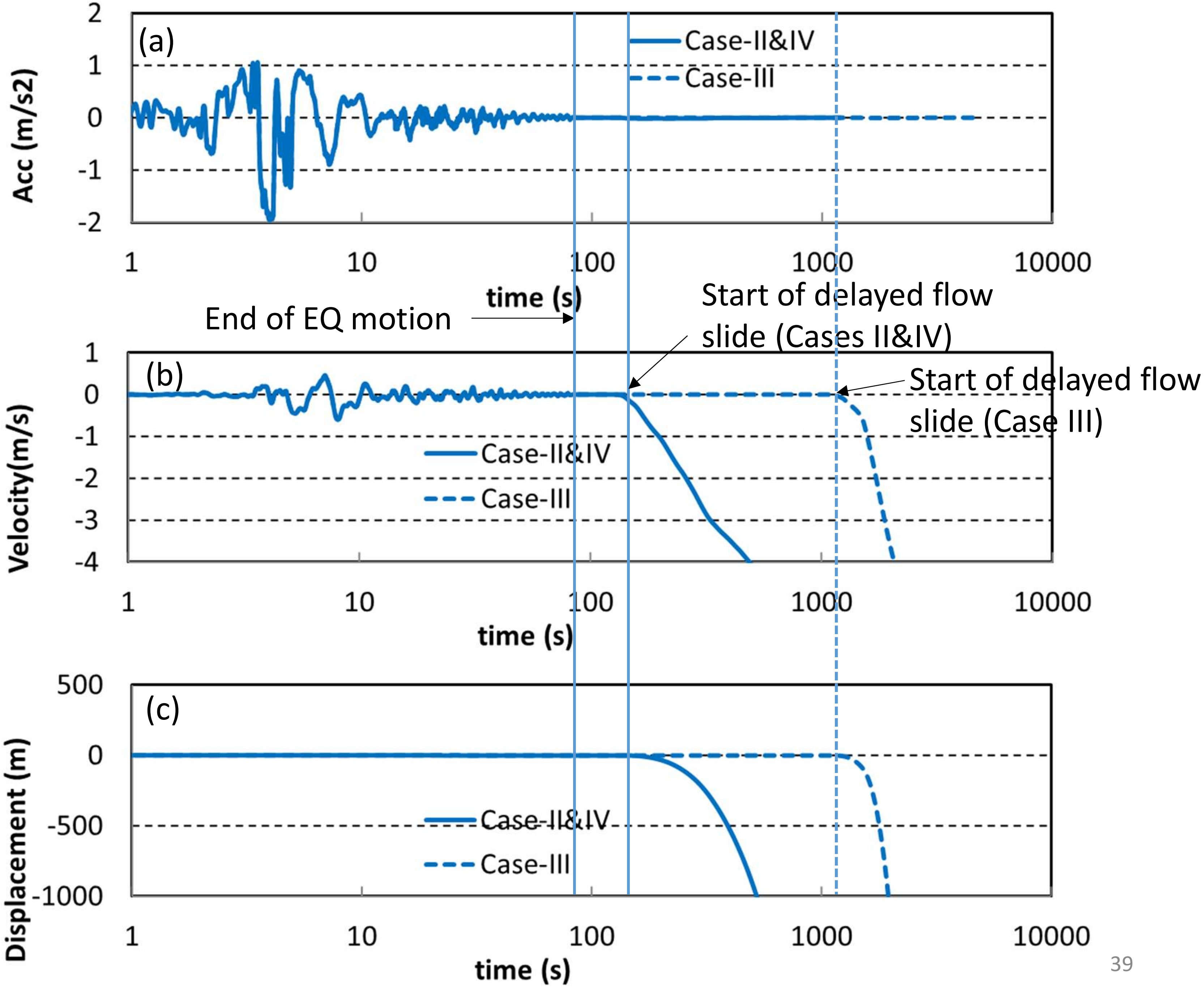


Time histories CaseI



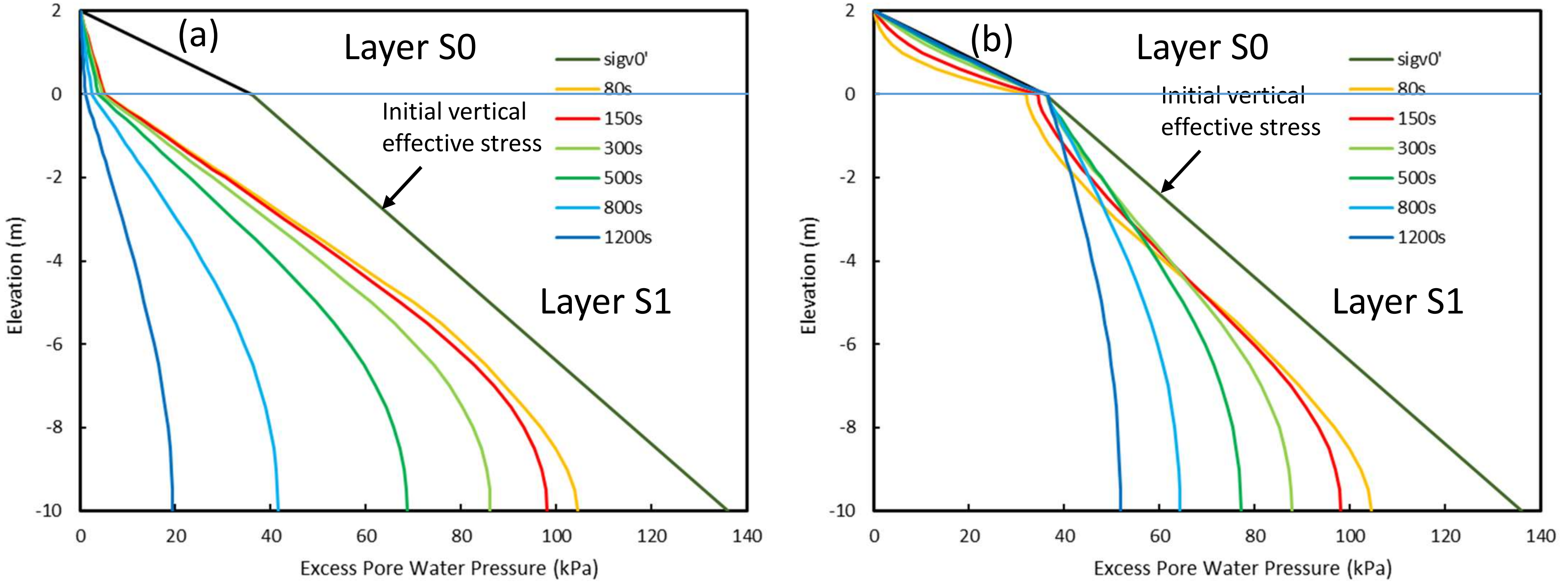
Time histories Cases II,III,& IV


(a)
u/σv0'
time (s)
Case-II(0m)
Case-II (-1m)
Case-II&IV (-6m)
Case-III (0m)
Case-III (-1m)
Case-III (-6m)
Case-IV (0m)
Case-IV (-1m)
(b)
ε (%)
time (s)
Case-II (0m)
Case-III (0m)
Case-IV(0m)
(c)
qus (kPa)
time (s)
End of EQ motion
Start of delayed flow slide (Cases II&IV)
Start of delayed flow slide (Case III)
τst: static shear stress
Case-II (0m)
Case-III(0m)
Case-IV(0m)
init ss



(a)
Case-II&IV
Case-III
Acc (m/s2)
2
1
0
-1
-2
1
10
100
1000
10000
time (s)
End of EQ motion
Start of delayed flow slide (Cases II&IV)
Start of delayed flow slide (Case III)
(b)
Velocity(m/s)
1
0
-1
-2
-3
-4
Case-II&IV
Case-III
1
10
100
1000
10000
time (s)
(c)
Displacement (m)
500
0
-500
-1000
Case-II&IV
Case-III
1
10
100
1000
10000
time (s)

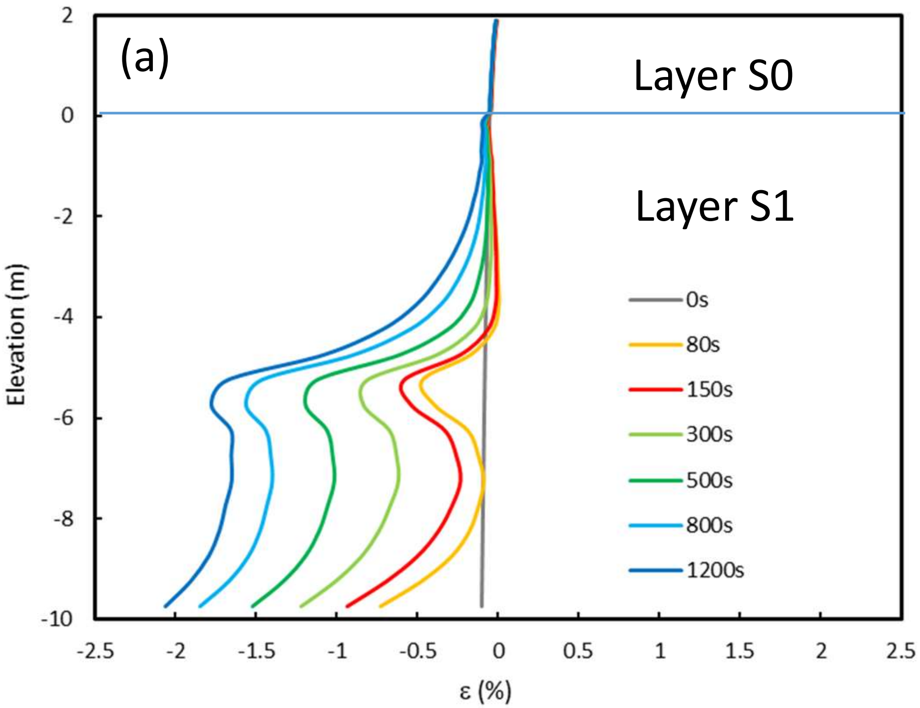
Distribution of PP



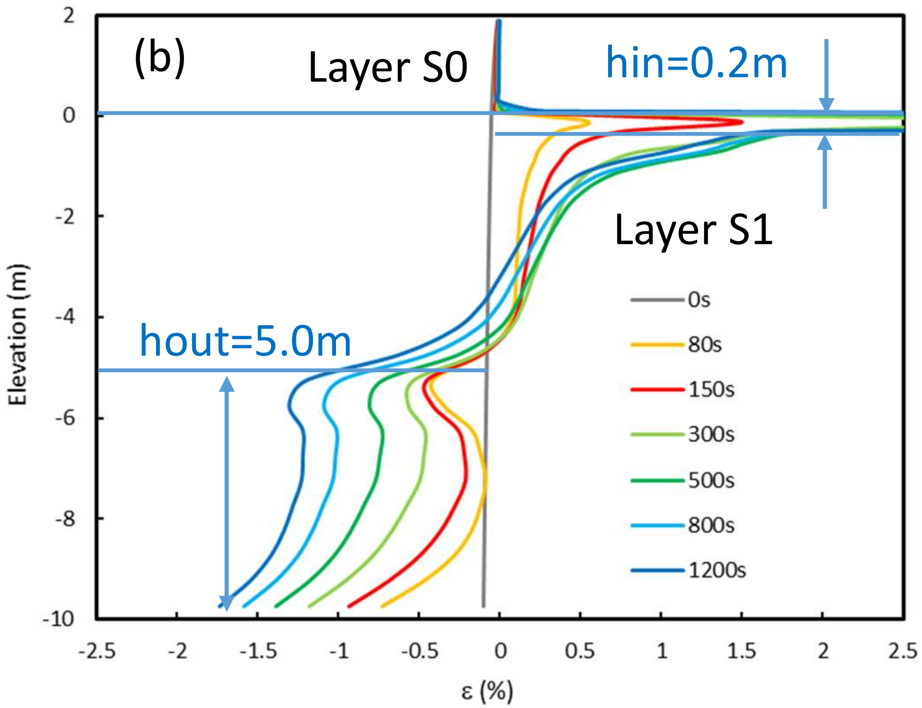
CaseI

CaseII&IV

Volumetric strain distribution

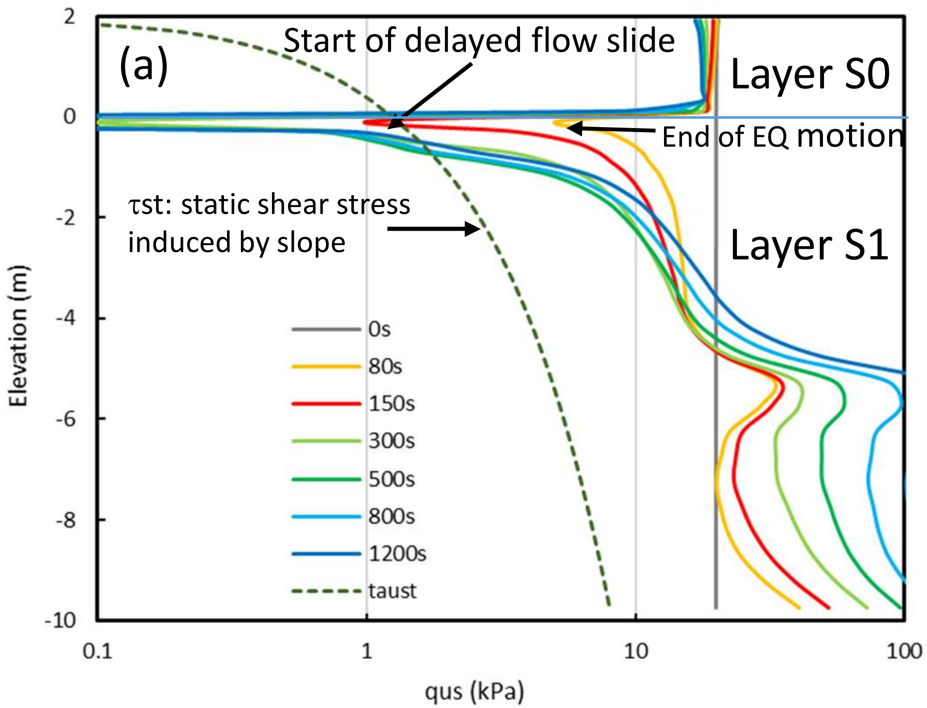


CaseI

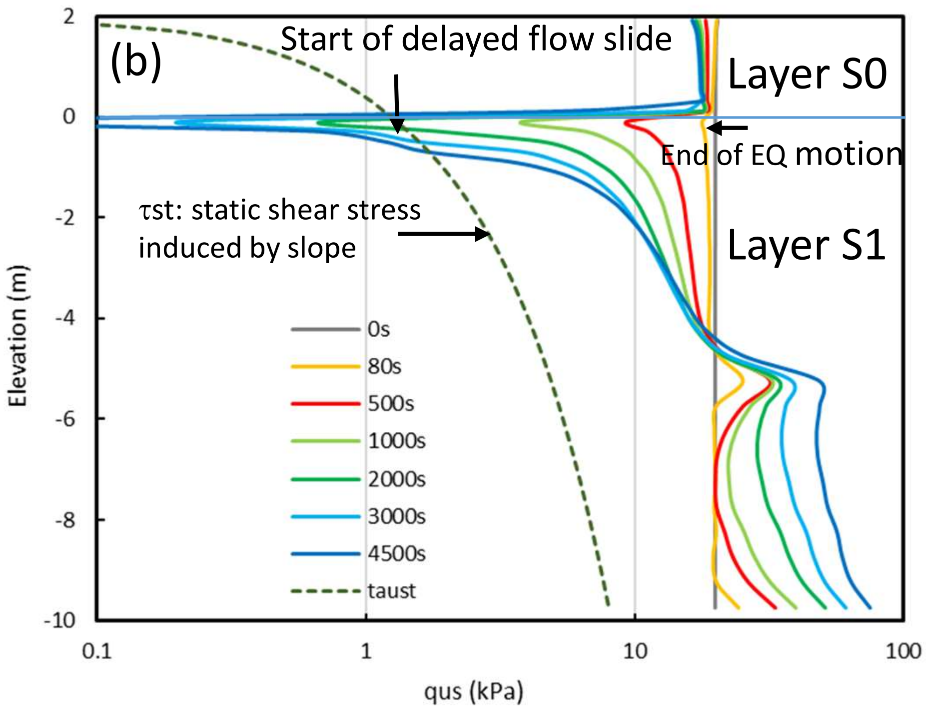


CaseII&IV

qus distribution

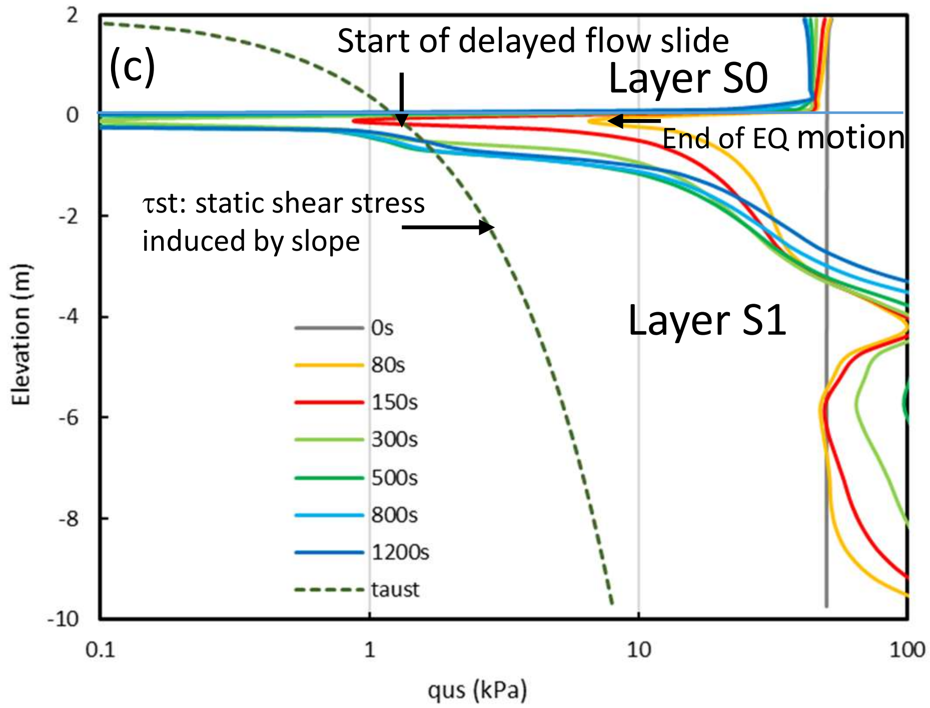


Case II



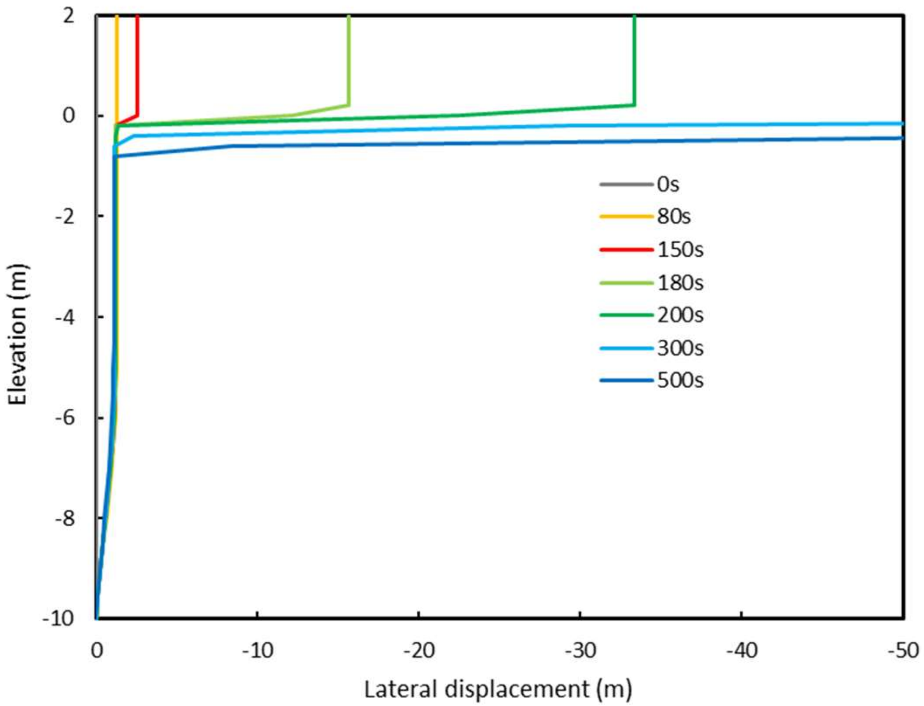
Case III

Volumetric strain and qus distribution



Case IV

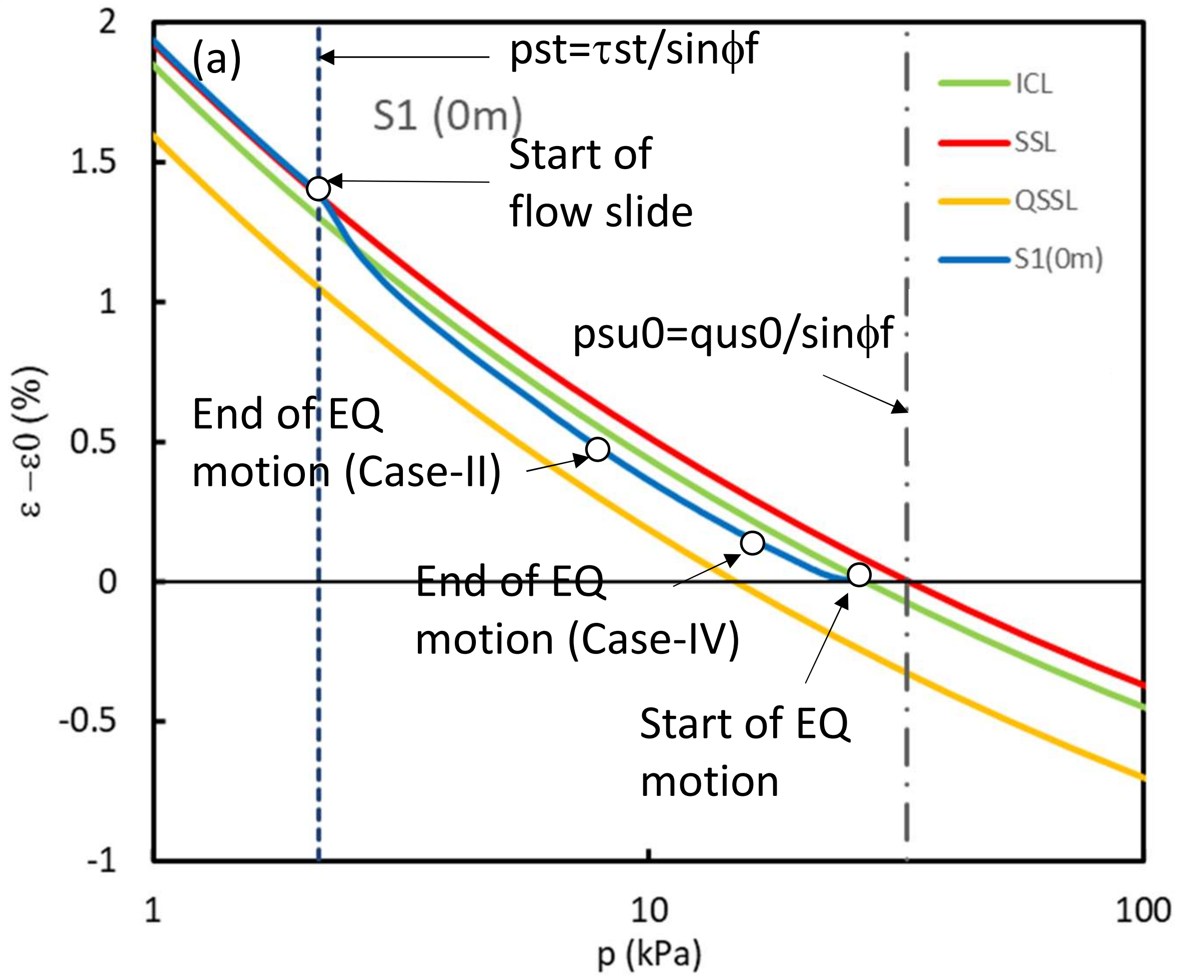
DSP



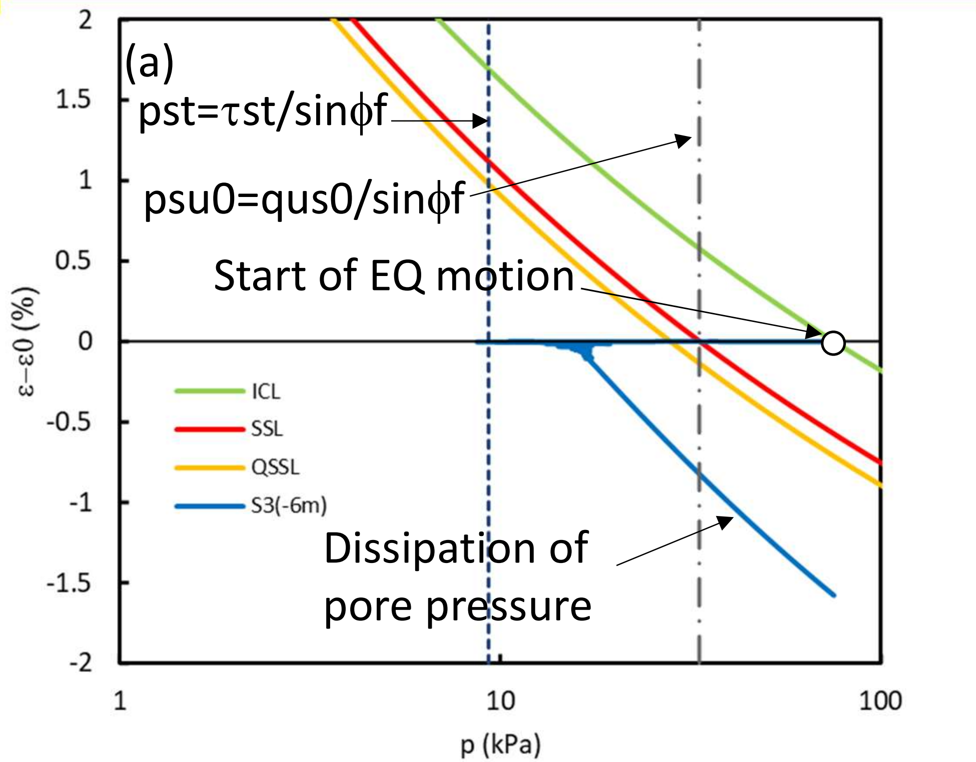
2
0
-2
-4
-6
-8
-10
Elevation (m)
0
-10
-20
-30
-40
-50
Lateral displacement (m)
0s
80s
150s
180s
200s
300s
500s

Case II

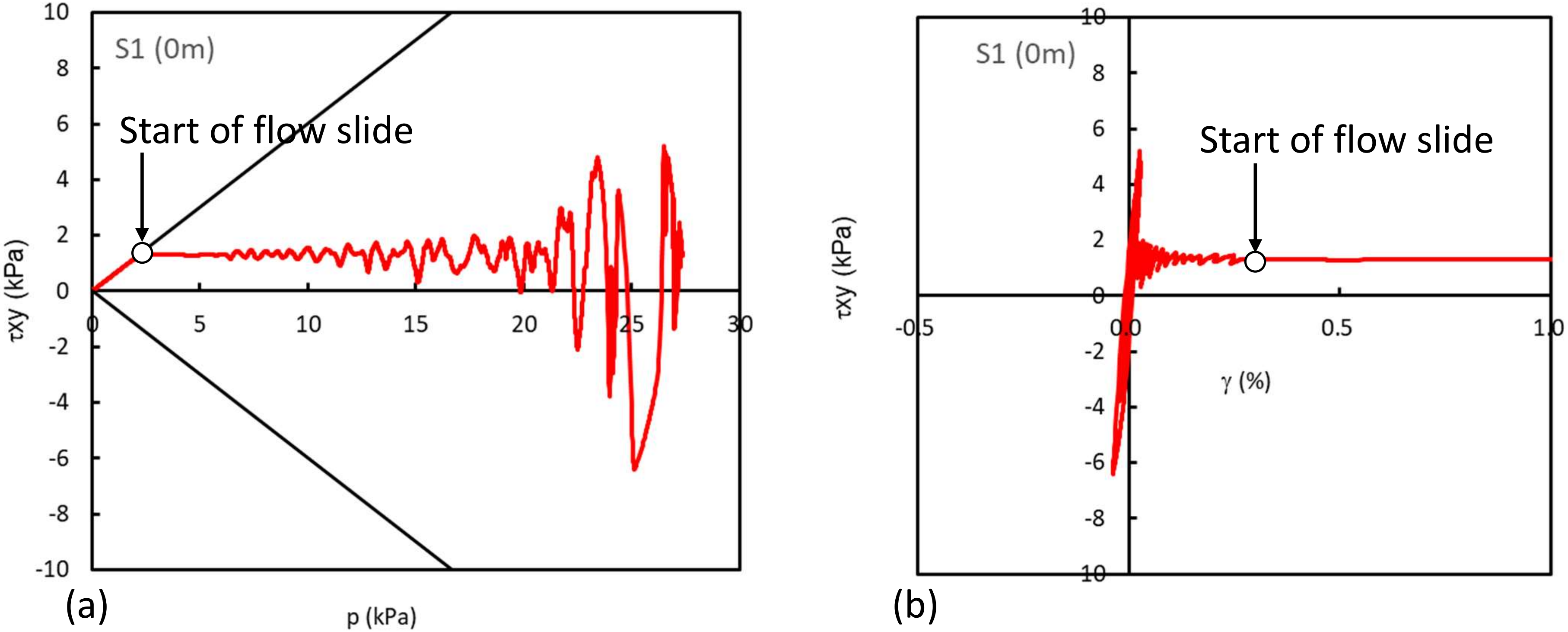
Inflow zone: Case-II & IV



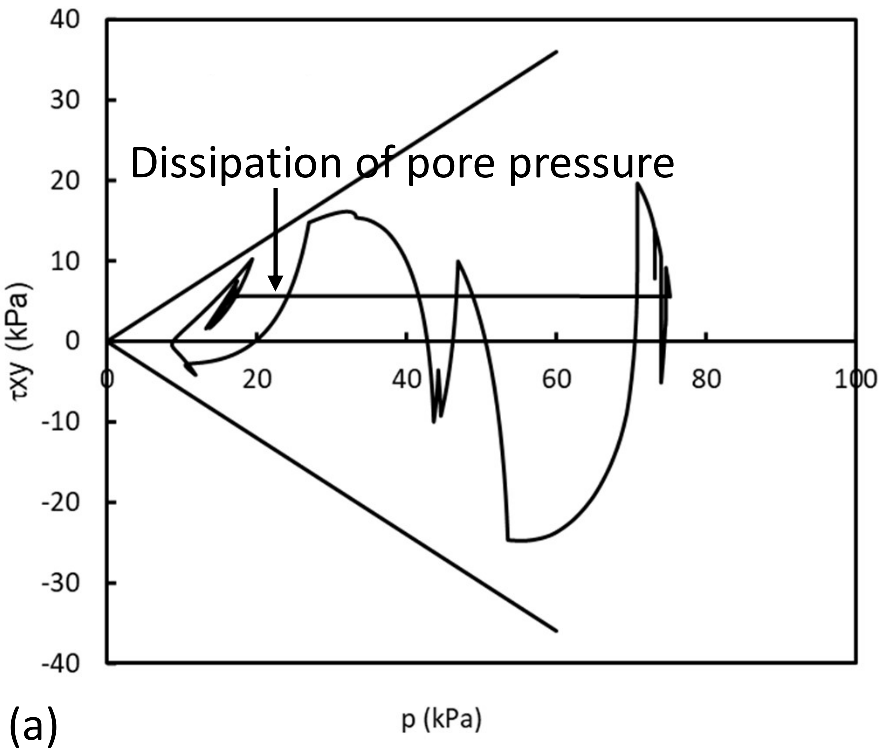
Outflow zone: Cases-I,II,IV



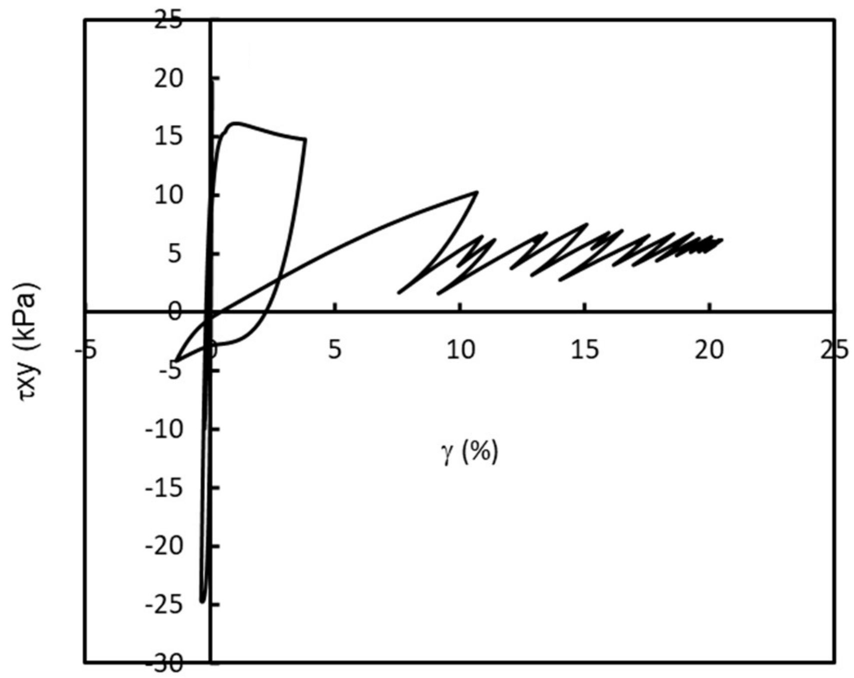
Inflow zone: Cases-II & IV



Outflow zone: Cases-I through IV

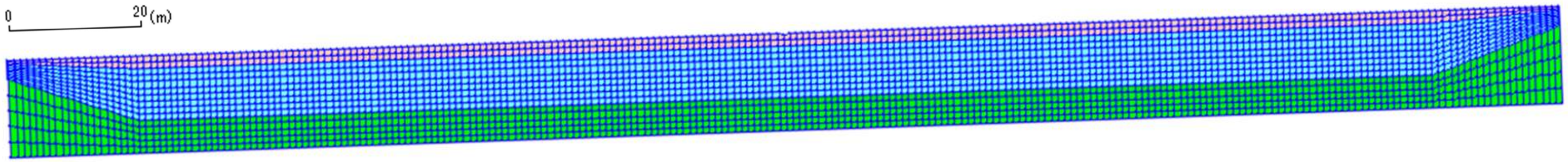


(a)



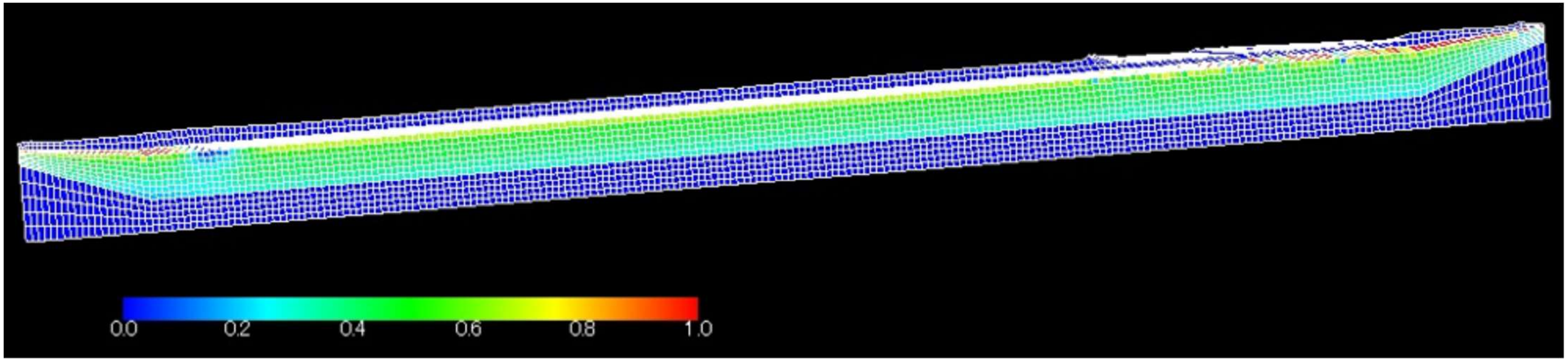
(b)

Simplified/generalized 2D model analysis of delayed flow failure

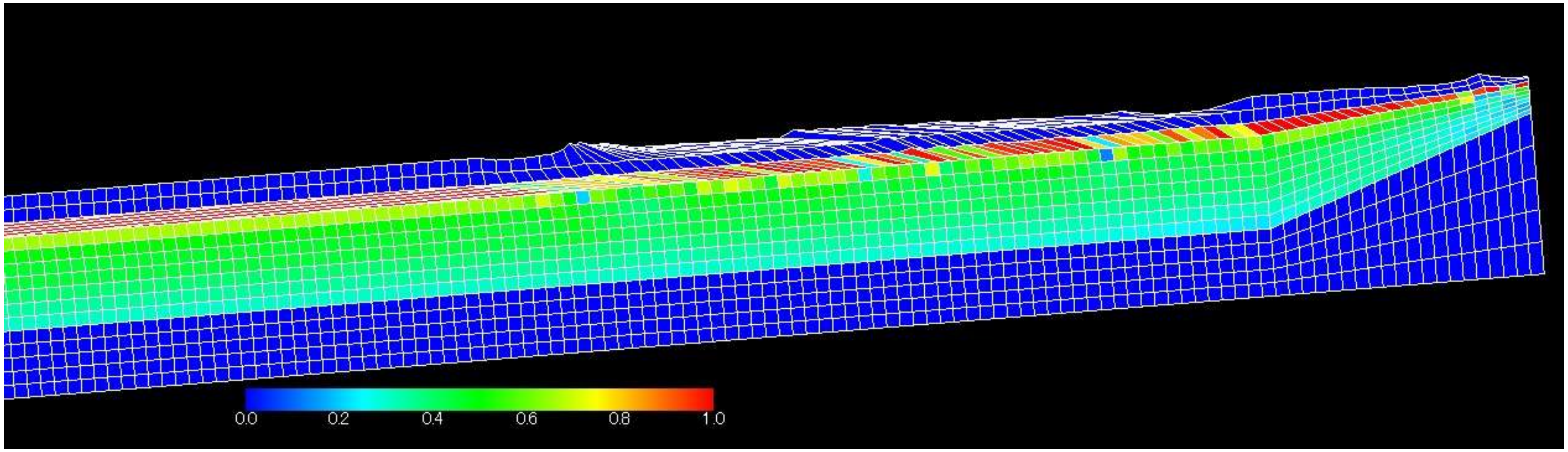


Surface crust layer: undrained condition

Global failure mode (at the instance of 5m slide in mid zone)

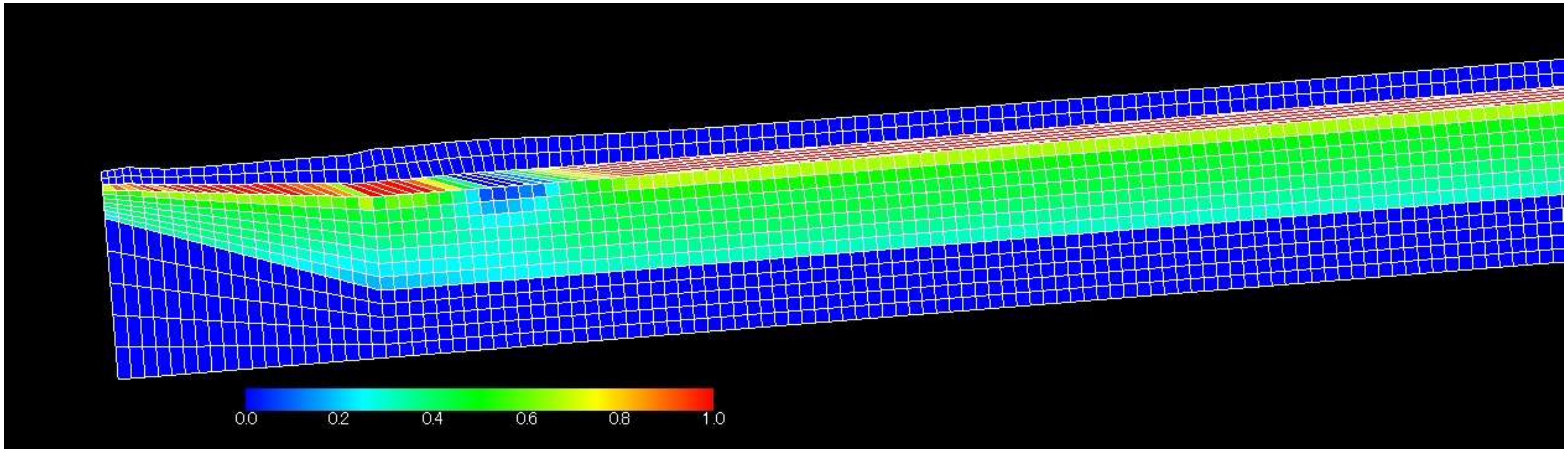


Failure mode in tension zone

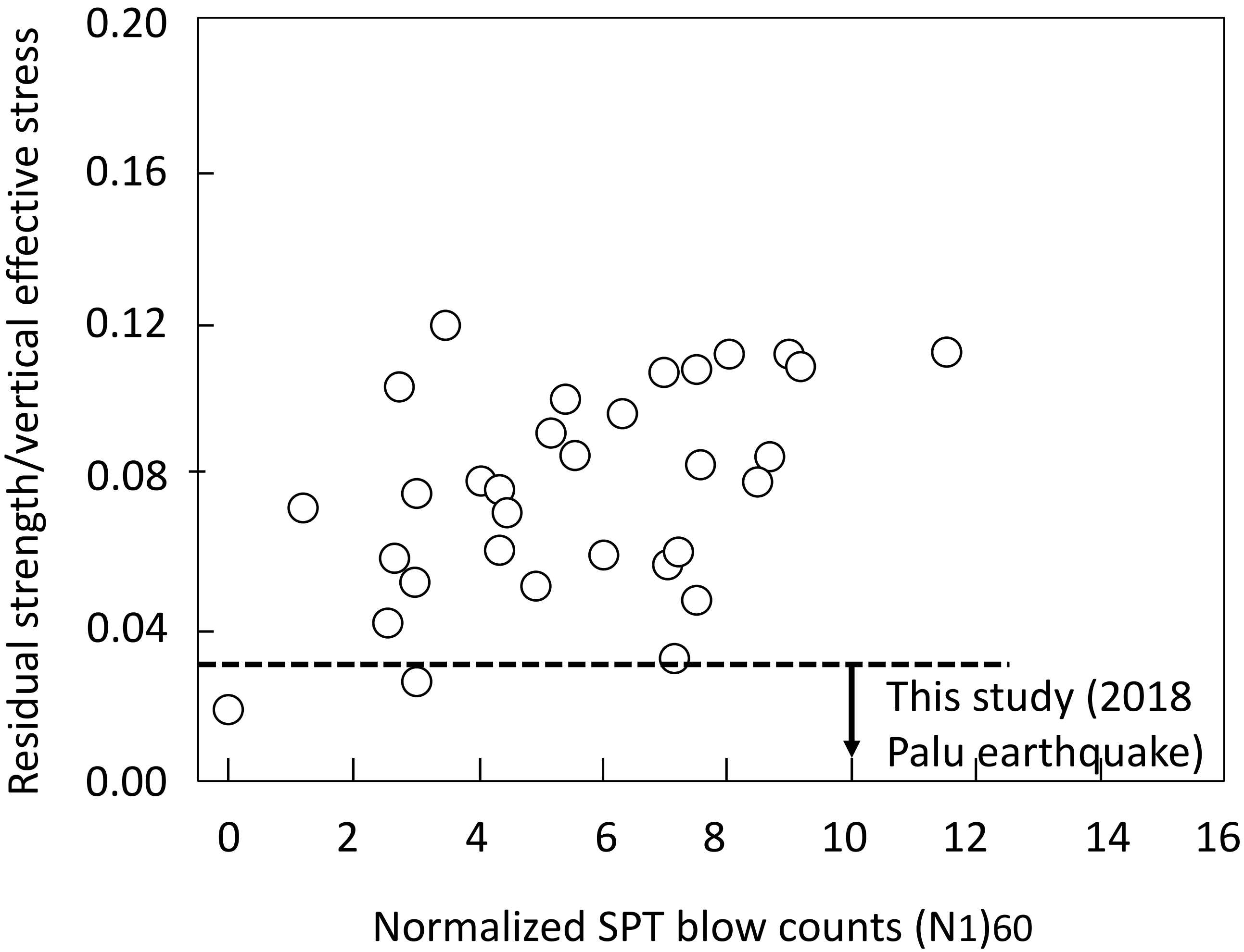


Tension fracture mode of complex random deformation gradually spreading from the edge toward the mid zone of slope

Failure mode in compression zone



more or less orderly deformation
mode of compressive shear



Residual strength/vertical effective stress
0.20
0.16
0.12
0.08
0.04
0.00
0
2
4
6
8
10
12
14
16
This study (2018
Palu earthquake)
Normalized SPT blow counts (N1)60

Remark on “Water film”

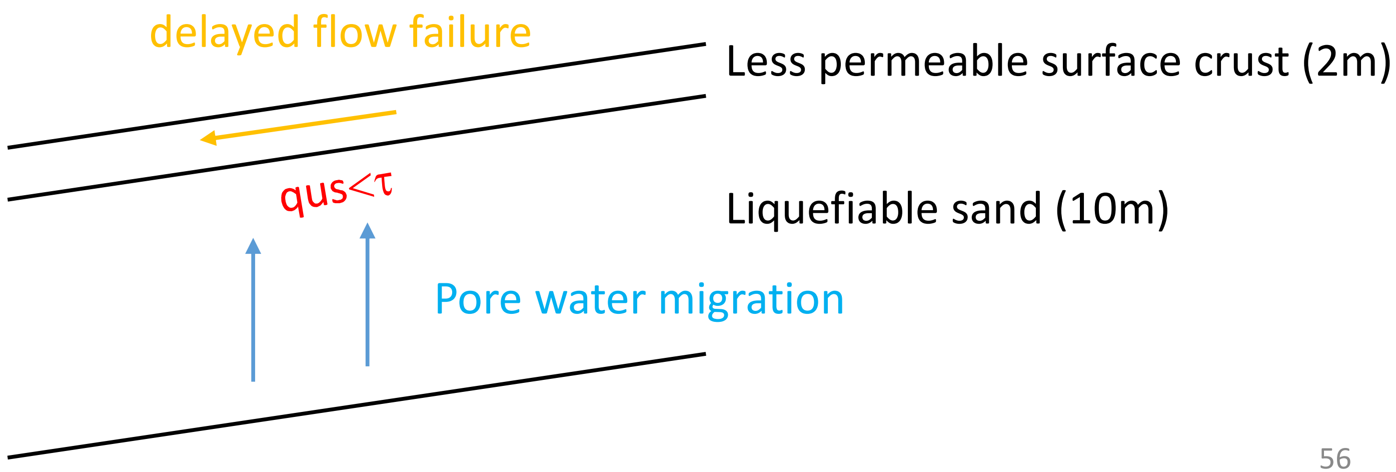
- In this study, the effect of water film often observed beneath the less permeable surface crust was not explicitly discussed. To quote Whitman (1985), “If, during or after shaking, the disturbed sand … leaving a liquid film at the interface, an unstable situation occurs. Actually, it is only necessary for a thin layer atop the sand to loosen enough that its steady state resistance becomes less than the static shear stress.” The nonlinear dynamic analysis performed in this study supports Whitman’s perspective.

Summary of the earthquake response analysis by FLIP

- Delayed failure: Some time after the earthquake motion, the less permeable capping surface crust layer (2m thick with 2 degree slope with static shear stress of τst=1.2kPa) begins to slide downward with a steady motion at the top of the liquefiable layer having steady state (undrained) shear strength ranging from qus=20 to 50kPa at the initial state.
- Sliding tends to localize just below the capping surface crust layer.
- Tension zone shows tension fracture of the capping surface crust layer
- Compression zone shows deformation of the capping surface crust layer in compression shear mode
- All the above results are consistent with those observed

Mechanism in delayed flow failure

- Pore water migration into the sand just below the capping clay layer⇒volume expansion of the sand⇒reduction in qus
- When qus< τ, delayed flow failure is triggered.



Suggestions for practice

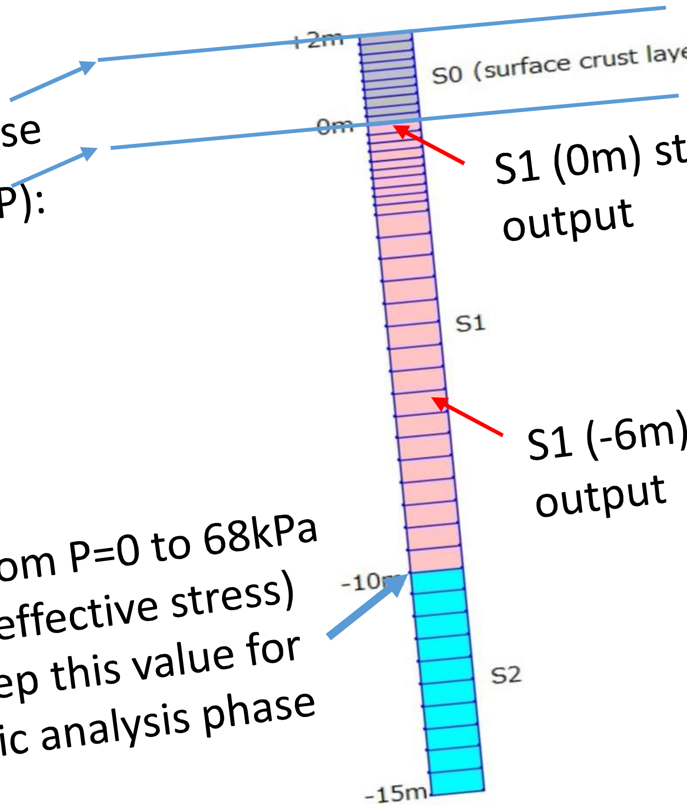
- Permeabilities of surface crust layer and liquefiable soil layer are the key parameters that govern the occurrence of delayed flow failure and delay time.
- Permeable surface crust having higher permeability than that of liquefiable soil does not develop delayed flow failure. This fact should be beneficial in engineering practice of risk assessment and mitigation of delayed flow failure.

Imposed inflow analysis (aquifer)

- Excess pore water pressure of 68kPa at a depth of 10m without earthquake shaking

B.C. P=0 kPa (EPWP): dynamic analysis phase

B.C. P=0 kPa (stat PWP): initial gravity analysis phase



S1 (0m) stress strain output

S1 (-6m) stress strain output

B.C. EPWP increased from P=0 to 68kPa (50% of initial vertical effective stress) for 10 seconds and keep this value for the rest of the dynamic analysis phase

Coefficient of permeability (m/s)

qus=20kPa	Case-1C	Case-2C	Case-3C
Layer S0	5E-7	5E-7	5E-5
Layer S1	1E-4	1E-5	1E-5
Layer S2	1E-7	1E-7	1E-7

qus=50kPa	Case-1D	Case-2D	Case-3D
Layer S0	5E-7	5E-7	5E-5
Layer S1	1E-4	1E-5	1E-5
Layer S2	1E-7	1E-7	1E-7

Case-1C: less permeable surface crust (high permeability contrast) qus=20kPa