Investigating the Influences of Various Complexity of Hydrogeological Models on Pore Water Pressure Buildup Triggered by Seismic Wave Propagation

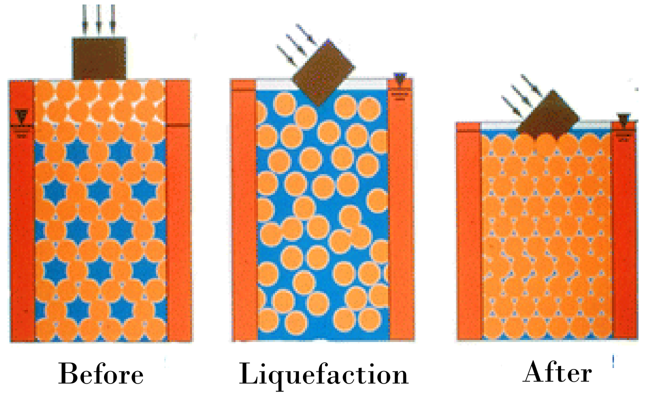
Name: Agustina Shinta Marginingsih

Advisor: Prof. Shih-Jung Wang

Date:2022/10/07

Introduction

Pore Water Pressure and Soil Liquefaction



Ground failure or loss of strength that causes soil to behave temporarily as a viscous liquid.
The phenomenon occurs in water-saturated unconsolidated soils affected by seismic which cause ground vibrations during earthquakes.

Source: https://www.britannica.com/science/soil-liquefaction

This mechanism can be stated by the principle of effective stress, introduced by Van Terzaghi (1936):

$$\sigma' = \sigma - p$$

When the pore water pressure increase the effective stress is decrease and full liquefaction occurs when the effective stress is equal to 0, where,

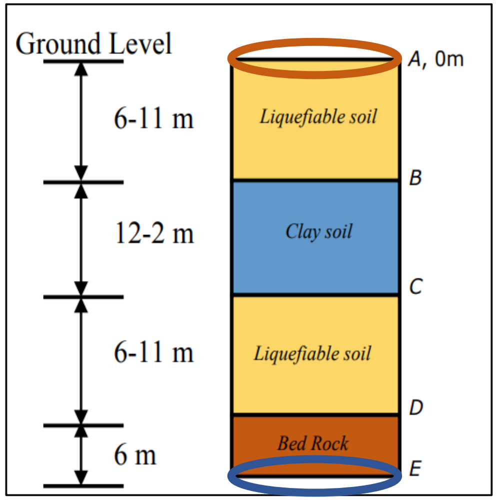
$$\sigma = p$$

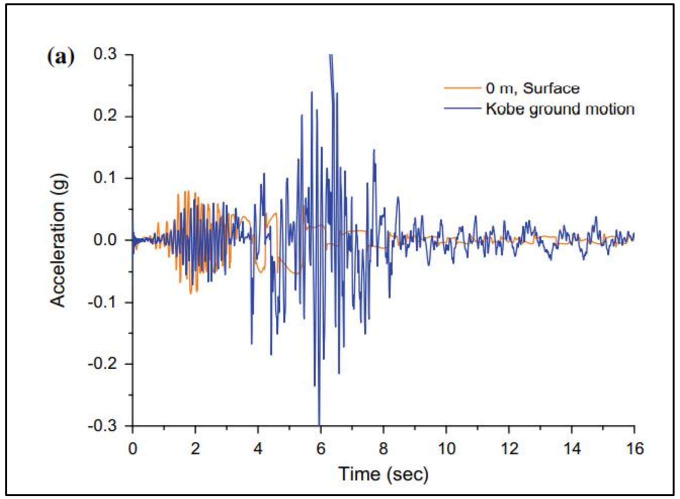
σ ‘: Effective stresses
σ : Total stress
p : Pore-water pressures

Seismic Wave Propagation in Soil Layer

The seismic waves propagate from bedrock are modified by the presence of layered soil. Recent studies have shown that the presence of a liquefiable soil layer can significantly reduce inertial load. Liquefaction of soil layer prevents the transmission of seismic waves acting as shield protecting the above layers (Huded et al. 2020).

Example:
(Huded et al. 2020)





Traditional Study:

Homogeneous system

Perfect layer system

How about various hydrogeological models?

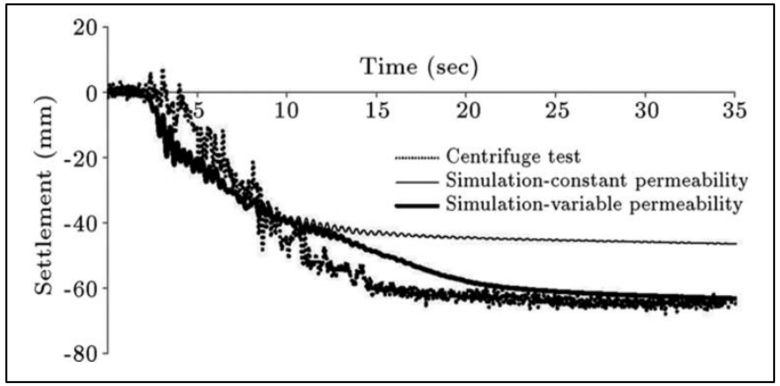
Do you see the difference between the input acceleration (Kobe Earthquake of 1995) and the acceleration measured on the ground surface?

This study shows how seismic waves modified by the presence of liquefiable soil layers.

Vertical Displacement (Ground Settlement)

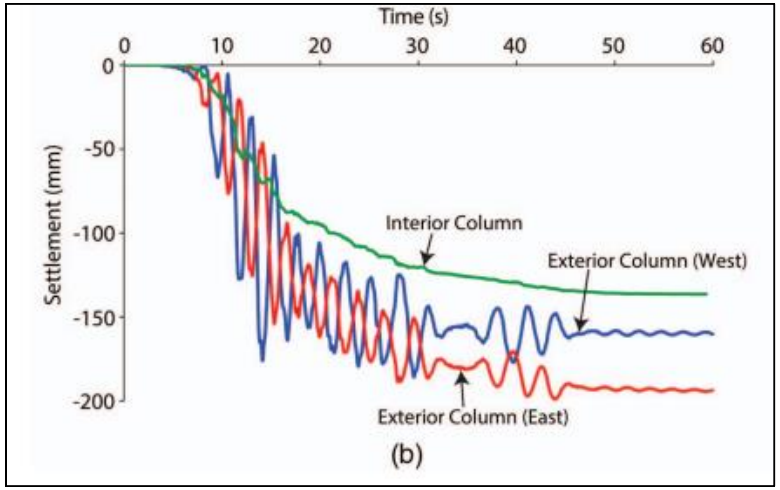
The generation of excess pore water pressure takes the main role in the ground settlement mechanisms which is excess pore water pressure dissipation will induce the ground settlement. In the undrained saturated sand, the volume condition is maintained because there is no drainage to let the excess pore water pressure dissipate, and vice versa (Bray and Seed, yrs)

Example 1:



Rahmani et al. (2012) try to compare the experiment (centrifuge test) and the numerical analysis for the ground settlement.

Example 2:



Luque, R., & Bray, J. D. (2017) try to analyze non-uniform ground settlement in area under the structure (Interior Column) and 'free field' area (Exterior Column).

Finite Element Method

The basic equation for the time-dependent movement of a volume under the influence of a dynamic load is described by (Galavi, 2013):

$$\boldsymbol{M} \cdot \ddot{\boldsymbol{u}} + \boldsymbol{C} \cdot \dot{\boldsymbol{u}} + \boldsymbol{K} \cdot \boldsymbol{u} = \boldsymbol{F}$$

Where:

M = Mass matrix

u = Displacement vector

C = Damping matrix

K = Stiffness matrix

F = Dynamic force vector

UBC-Sand Model

The UBC-SAND model is a simple elastoplastic stress/strain model for simulating the liquefaction phenomenon of sand with a relative density less than 80%.

Elastic Response

Assumed to be isotropic and specified by elastic shear modulus (G^e) and bulk modulus (B^e):

$$G^e = K_G^e P_{ref} \left[\frac{P' + P_t}{P_{ref}}\right]^{ne}$$

$$B^e = \frac{2(1+\nu)}{3(1-2\nu)} G^e$$

Where:

K_G^e = Elastic shear modulus number

ne = Elastic shear modulus index

P_{ref} = Reference pressure (atmospheric pressure)

P' = Effective confining pressure

P_t = Maximum shear stress

ν = Poisson's ratio

Plastic Response

Plastic shear modulus (G^p):

$$G^P = G_i^P \,.\, \left(1 - \frac{\tau}{\tau_f} \,.\, R_f\right)^{np}$$

Where:

τ = Current shear stress

τ_f = Failure shear stress

R_f = Failure ratio

np = Elastic shear modulus index

G_i^P = αG^e and α depends on relative density

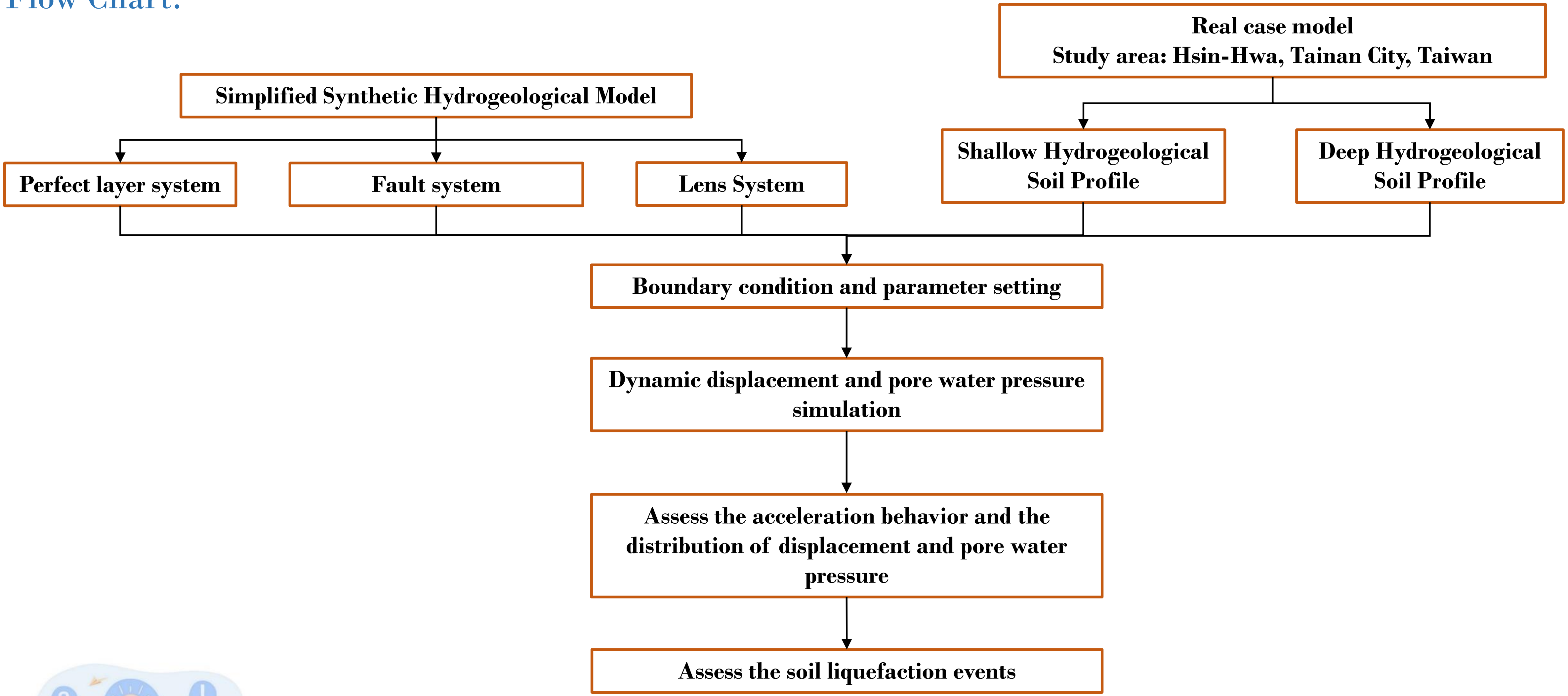
Study Area

Objectives

- Identify the wave propagation in various hydrogeological models
- Assess the dynamic distribution of displacement and pore water pressure
- Discuss the liquefaction events based on the assessment result

Methodology

Flow Chart:



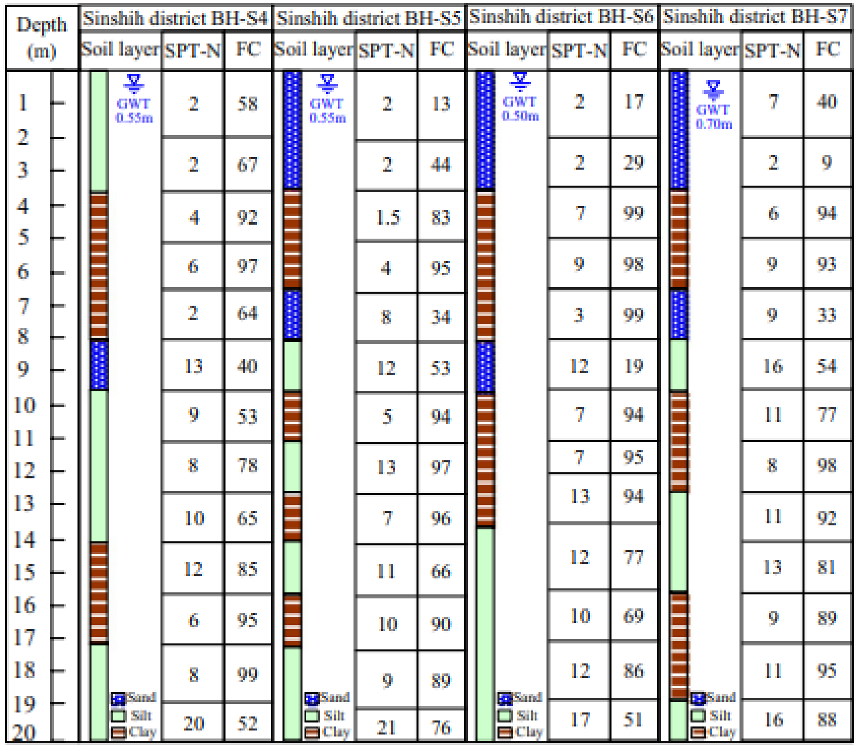
Model Set up

Simplified Synthetic Hydrogeological Model

Soil Parameter

Input and Boundary condition

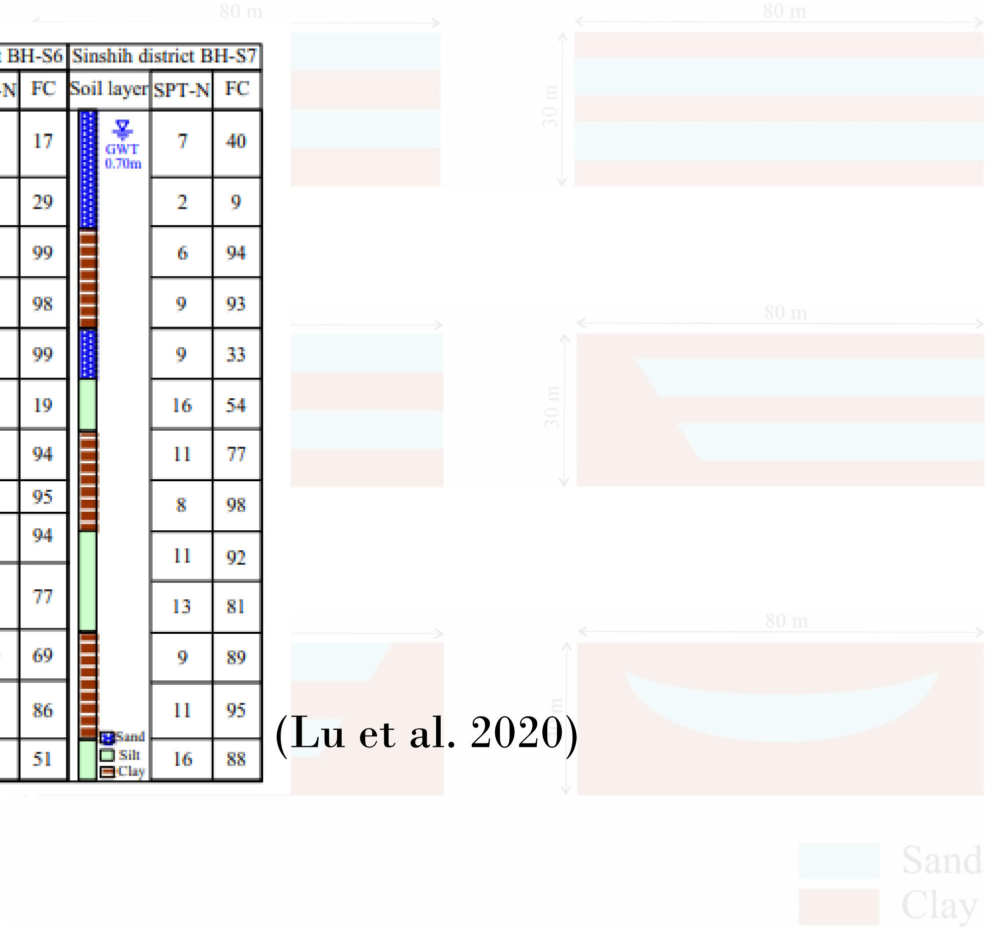
Cross Section



Sinshih district BH-S4		Sinshih district BH-S5		Sinshih district BH-S6		Sinshih district BH-S7	
SPT-N	FC	SPT-N	FC	SPT-N	FC	SPT-N	FC
2	58	2	13	2	17	7	40
2	67	2	44	2	29	2	9
4	92	1.5	83	7	99	6	94
6	97	4	95	9	98	9	93
2	64	8	34	3	99	9	33
13	40	12	53	12	19	16	54
9	53	5	94	7	94	11	77
8	78	13	97	7	95	8	98
10	65	7	96	13	94	11	92
12	85	11	66	12	77	13	81
6	95	10	90	10	69	9	89
8	99	9	89	12	86	11	95
20	52	21	76	17	51	16	88

(Lu et al. 2020)

Simplified



Model Set up

Simplified Synthetic Hydrogeological Model

Soil Parameters

Input and Boundary condition

Sand Layer:

Modulus of elasticity (E)	877 kN/m^2
Elastic shear modulus number (K_G^e)	1,100
Elastic shear modulus index (ne)	0.5
Plastic shear modulus number (K_G^p)	310
Plastic shear modulus index (np)	0.4
Poisson's ratio	0.1
Undrained Poisson's ratio	0.495
Unit weight (γ_{unsat})	18 kN/m^3
Unit weight (γ_{sat})	20 kN/m^3
Cohesion (c)	0 kPa
Peak friction angle ($\emptyset_p$)	33.8
Constant volume friction angle ($\emptyset_{cv}$)	33
Earth pressure coefficient (K_0)	1
Post liquefaction calibration	0.6
Reference pressure (P_{ref})	100 kN/m^2
Failure ratio (R_f)	0.9

(Huded et al. 2020)

Model Set up

Simplified Synthetic Hydrogeological Model

Soil Parameters

Input and Boundary condition

Clay Layer:

Modulus of elasticity (E)	8500 kN/m^2
Poisson's ratio	0.3
Undrained Poisson's ratio	0.495
Unit weight (γ_{unsat})	16 kN/m^3
Unit weight (γ_{sat})	20 kN/m^3
Cohesion (c)	10 kN/m^2
Frictional angle ($\emptyset$)	20
Dilatancy angle (ψ)	0
Earth pressure coefficient (K_0)	1

Rock:

Modulus of elasticity (E)	8,011.000 kN/m^2
Poisson's ratio	0.3
Undrained Poisson's ratio	0.495
Unit weight (γ_{unsat})	22 kN/m^3
Unit weight (γ_{sat})	22 kN/m^3
Cohesion (c)	10 kN/m^2
Frictional angle ($\emptyset$)	20
Dilatancy angle (ψ)	0
Earth pressure coefficient (K_0)	1

(Huded et al. 2020)

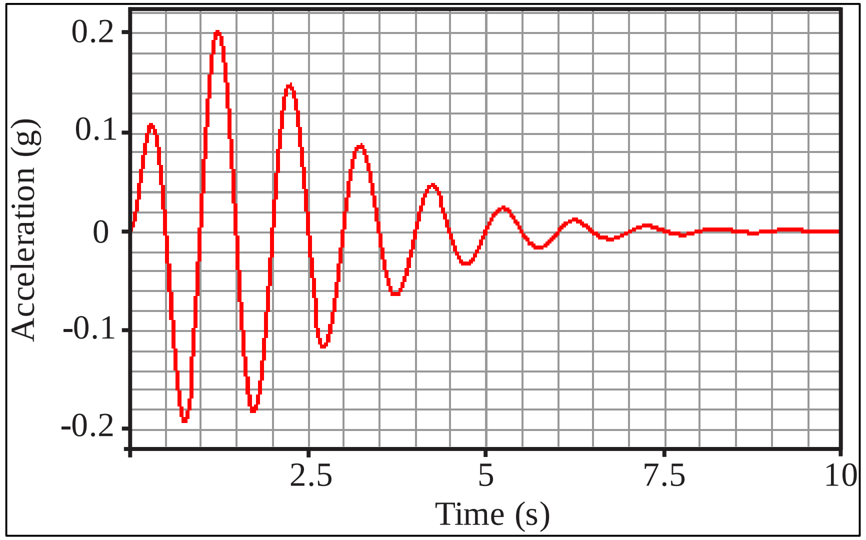
Model Set up

Simplified Synthetic Hydrogeological Model

Soil Parameter

Input and Boundary Condition

Driving Seismic Wave



- The wave simulation will use the sinusoidal (a max: 0.2 g) wave as input.
- The sinusoidal wave will be generated 20 s at the bottom of the domain horizontally.

Model Set up

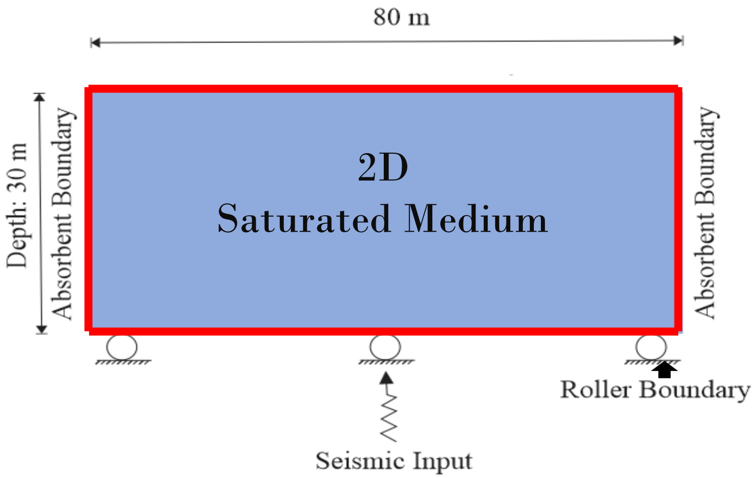
Simplified Synthetic Hydrogeological Model

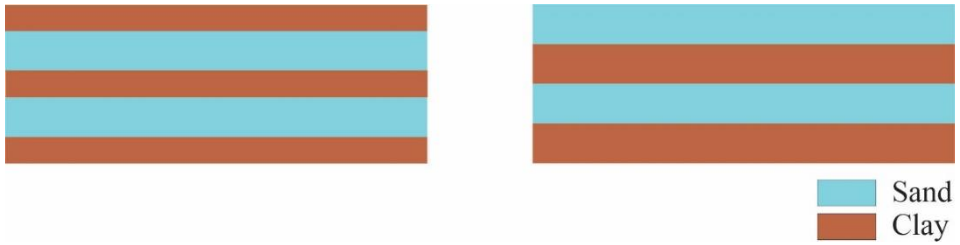
Soil Parameter

Input and Boundary Condition

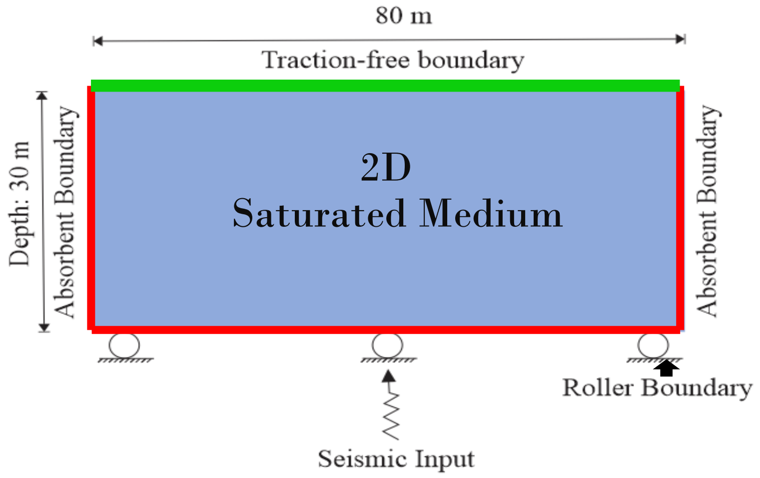
Boundary Condition Sketch

Undrained Condition





Drained Condition



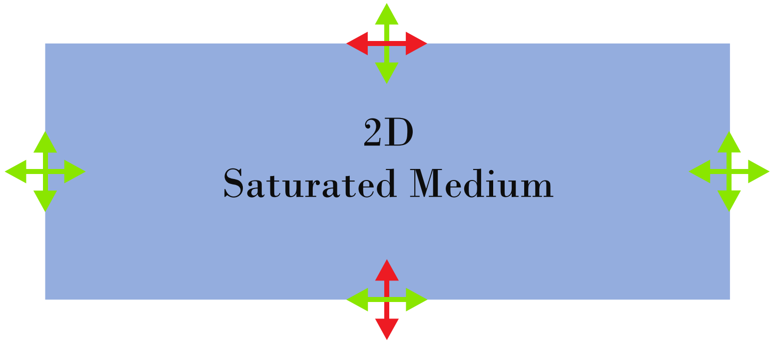
Model Set up

Simplified Synthetic Hydrogeological Model

Soil Parameter

Input and Boundary Condition

Boundary Condition for Displacement



- Surface: soil and water free to move in y direction
- Side: soil and water are free to move in x and y directions
- Base: free to move to the x direction, the vertical displacement is fixed

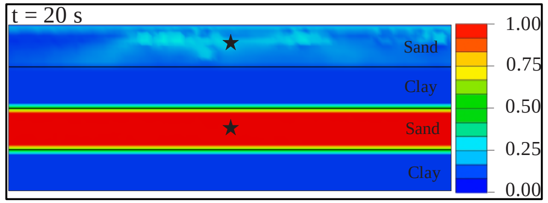
(Taiebat,2020)

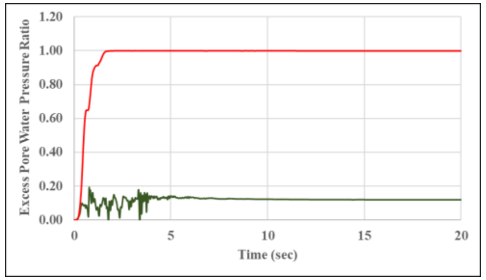
Excess Pre Water Pressure

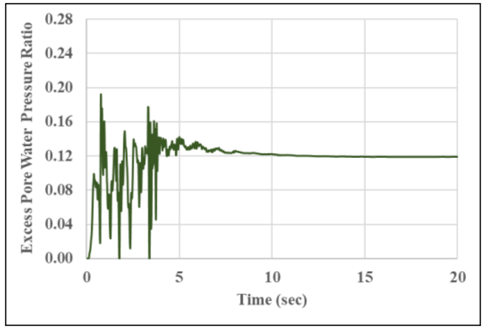
Perfect Layer System

Drained

Sand
Clay





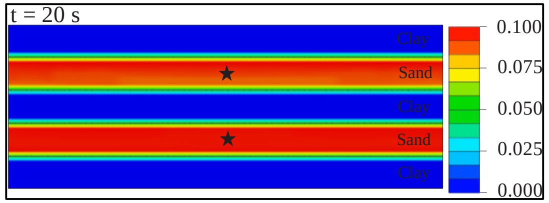


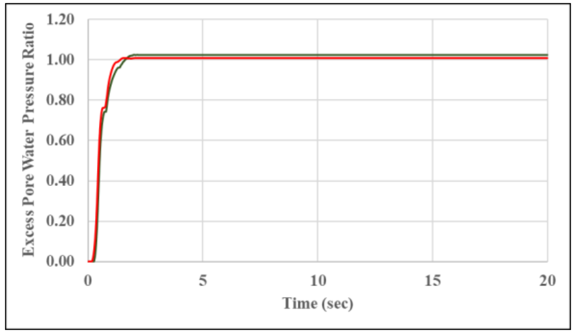
: Top Sand Layer

: Bottom Sand Layer

Undrained

Sand
Clay





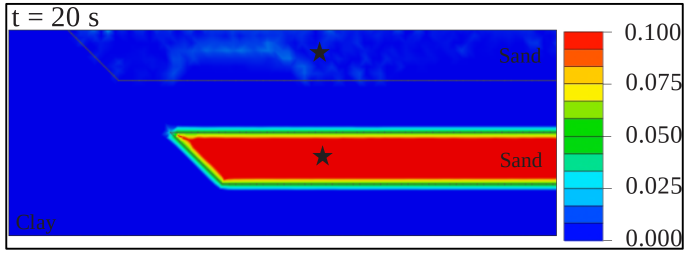
: Top Sand Layer

: Bottom Sand Layer

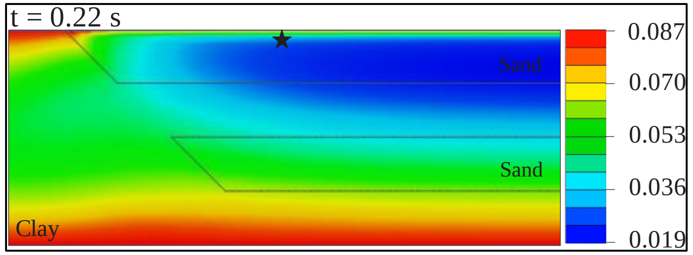
★ =Analysis Point

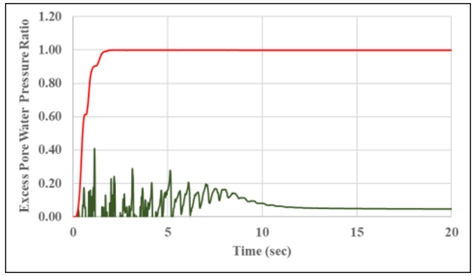
Drained Pinch-out (Fault Dislocation) System

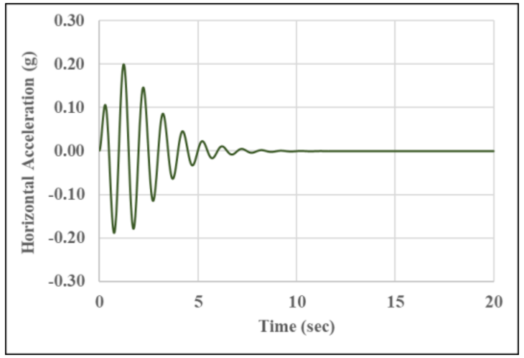
Excess Pore Water Pressure Ratio

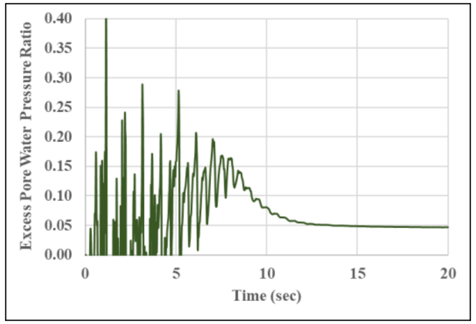


Horizontal Acceleration









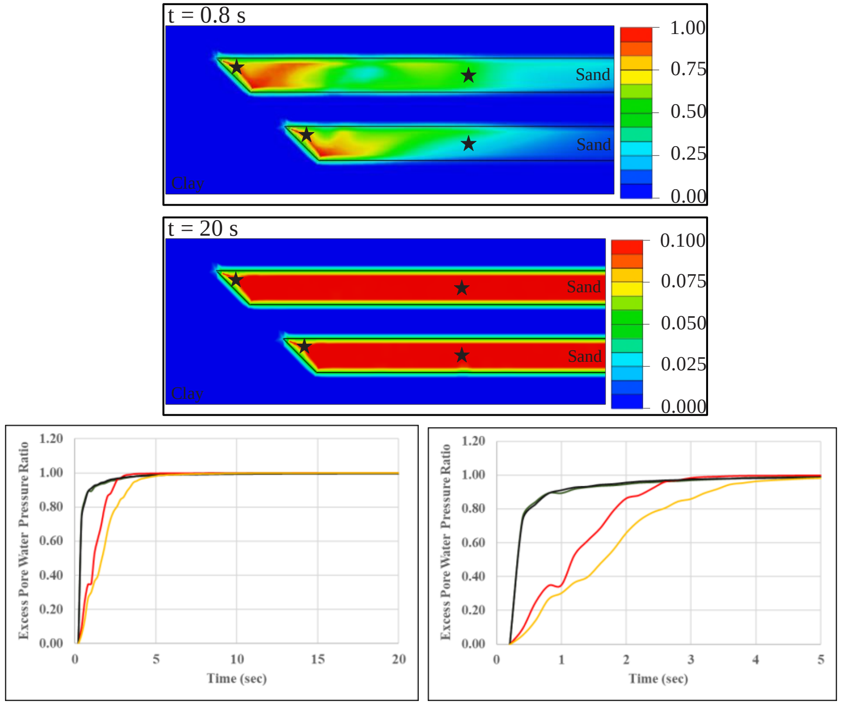
: Top Sand Layer

: Bottom Sand Layer

★ =Analysis Point

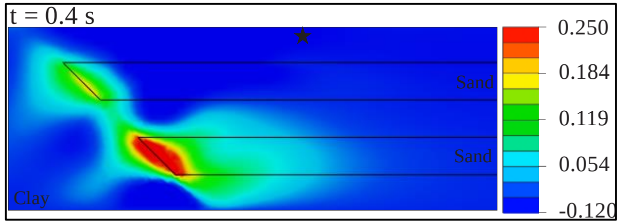
Undrained Pinch-out (Fault Dislocation) System

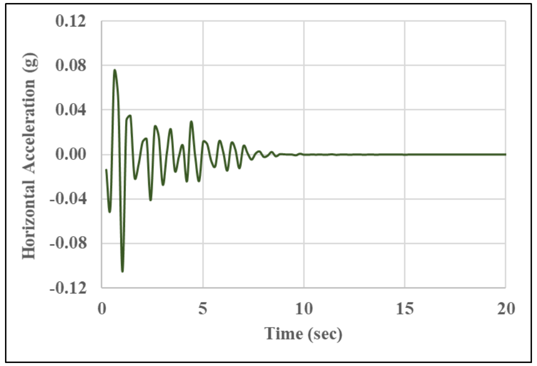
Excess Pore Water Pressure Ratio



: Top Left
: Top Right
: Bottom Left
: Bottom Right

Horizontal Acceleration

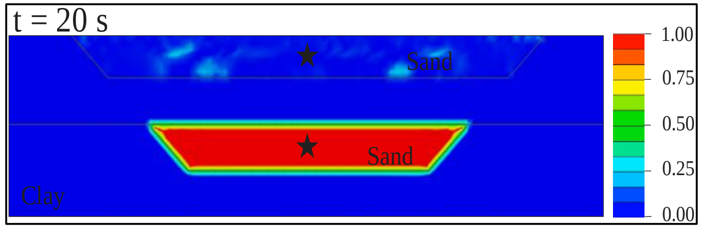


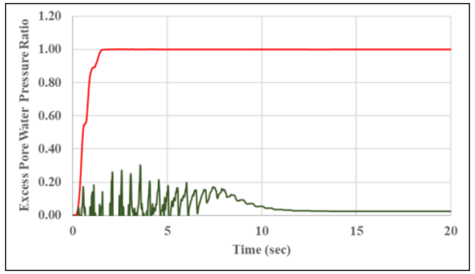


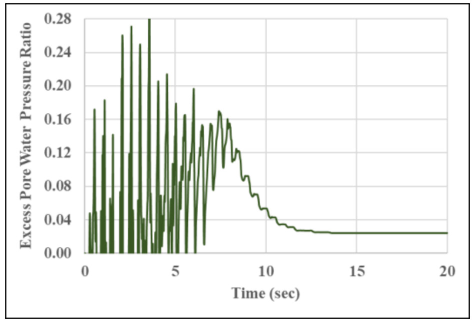
★ =Analysis Point

Drained Lens (Riverbed Deposit) System

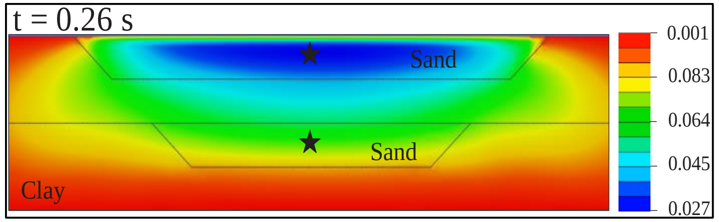
Excess Pore Water Pressure Ratio

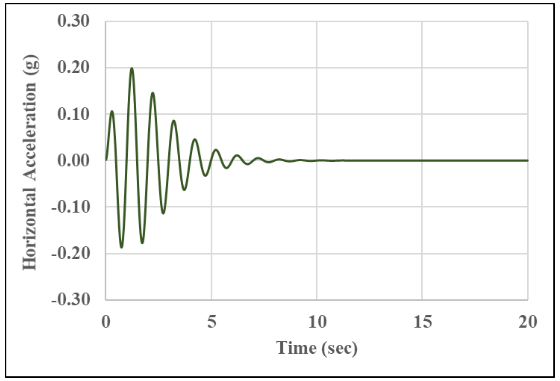






Horizontal Acceleration



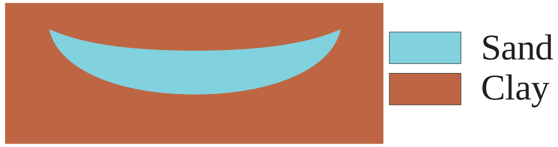


: Top Sand Layer

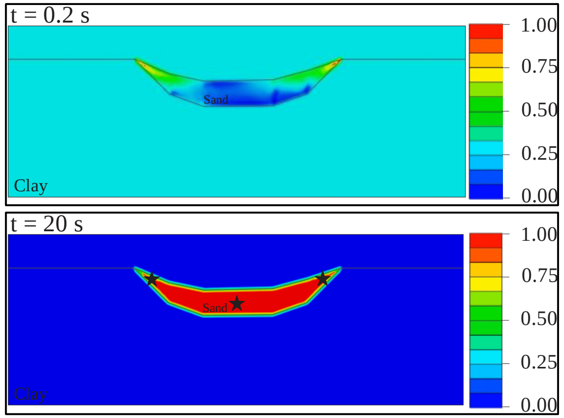
: Bottom Sand Layer

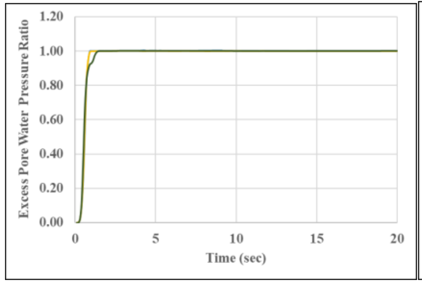
★ =Analysis Point

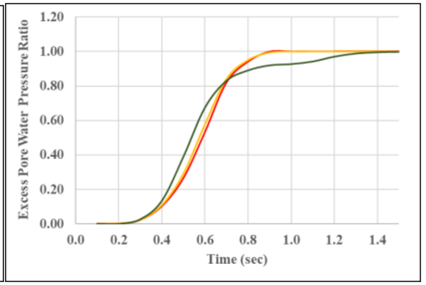
Undrained Lens (Riverbed Deposit) System



Excess Pore Water Pressure Ratio





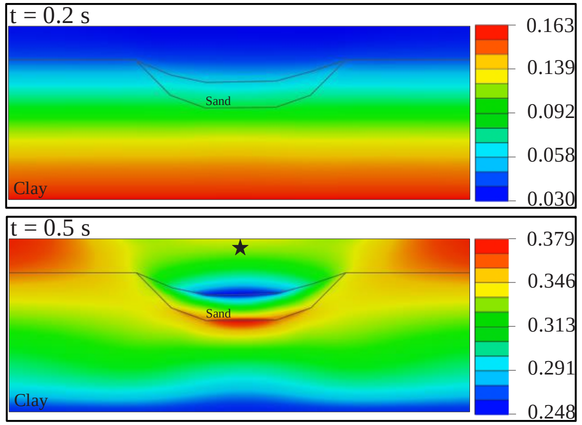


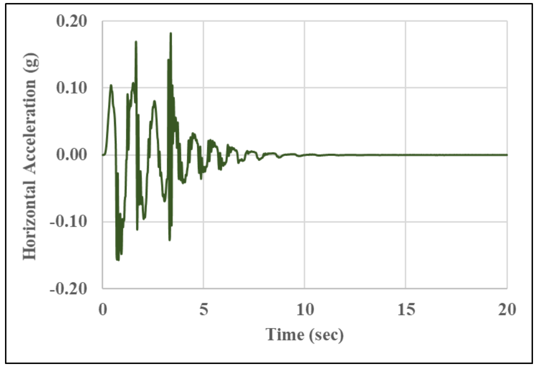
: Left Corner

: Middle

: Right Corner

Horizontal Acceleration

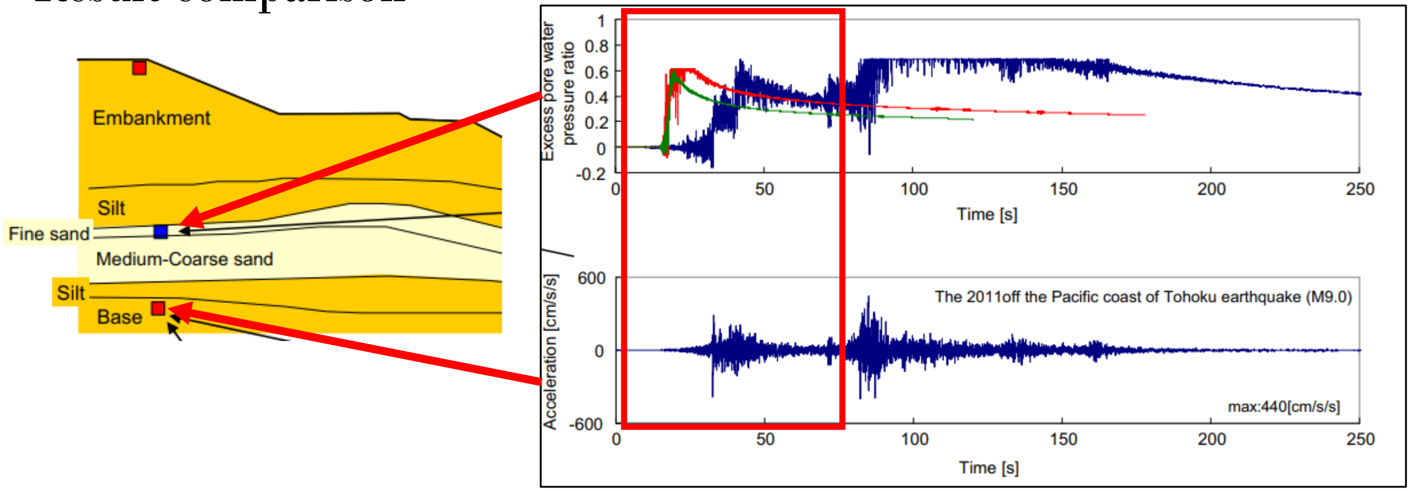




★ =Analysis Point

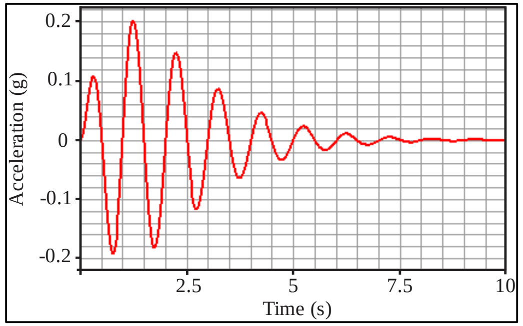
Drained Excess Pore Water Pressure Ratio

Result comparison

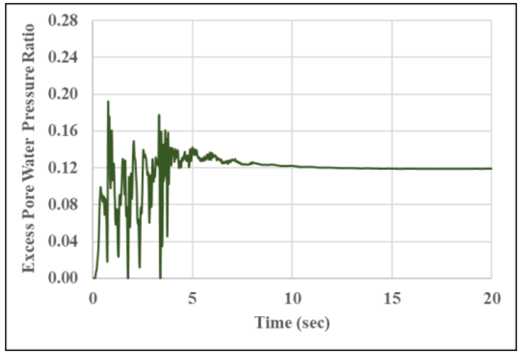


(Unjoh, 2012)

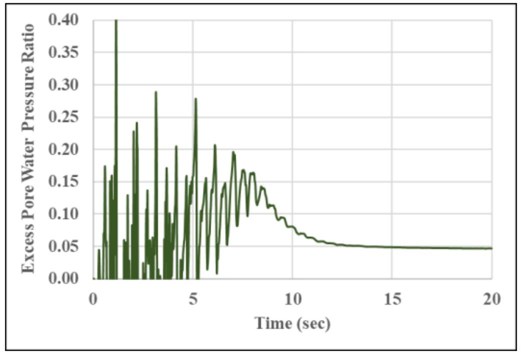
Input Acceleration



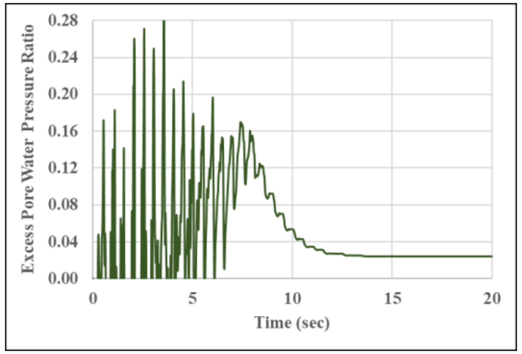
Perfect Layer System



Pinch-out (Fault Dislocation) System



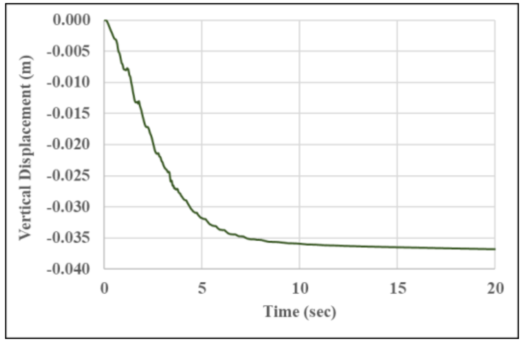
Lens (Riverbed Deposit) System

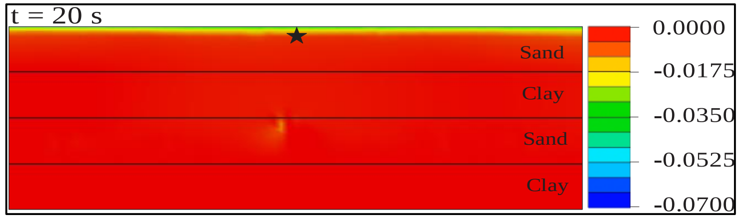


Vertical Displacement and Drained Simplify Hydrogeological Model

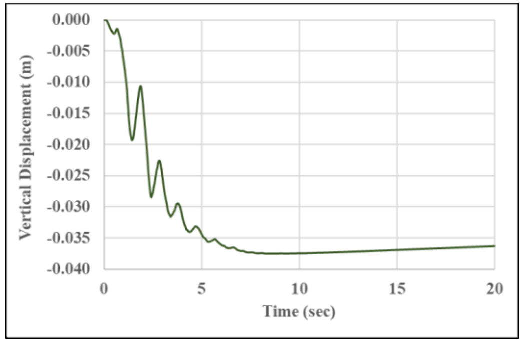
Result comparison

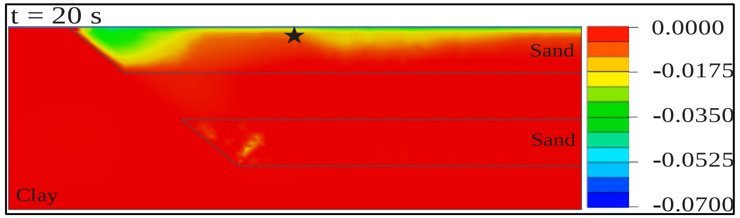
Perfect Layer System



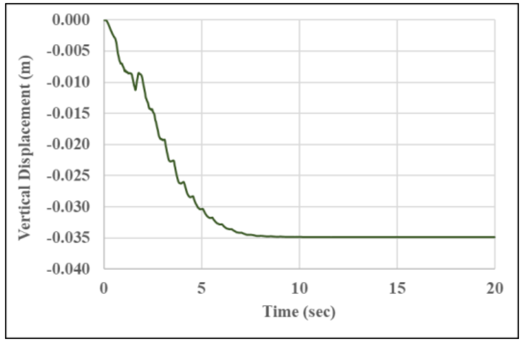


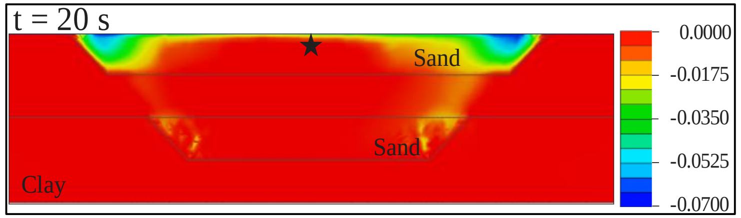
Pinch-out (Fault Dislocation) System





Lens (Riverbed Deposit) System





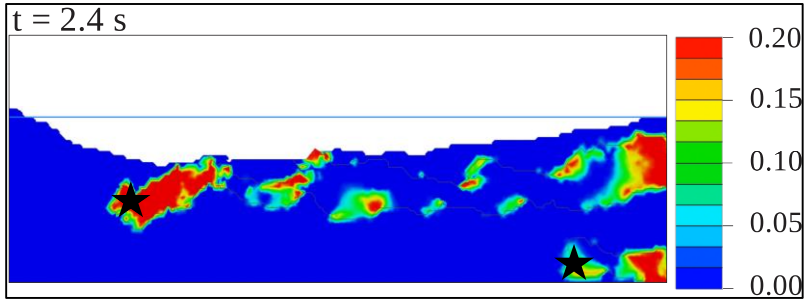
The accumulation of pore water pressure at the corner sand layer leads to the higher ground settlement.

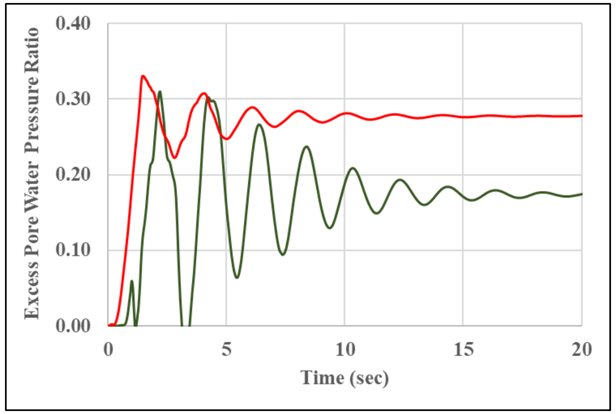
Real Case 1: Shallow Hydrogeological Soil Profile

Boundary Condition Set-up

- Surface: soil and water free to move in the y direction
- Side: soil and water are free to move in x and y directions (No absorbent boundary)
- Base: free to move to the x direction, the vertical displacement is fixed (roller boundary)

Excess Pore Water Pressure Ratio

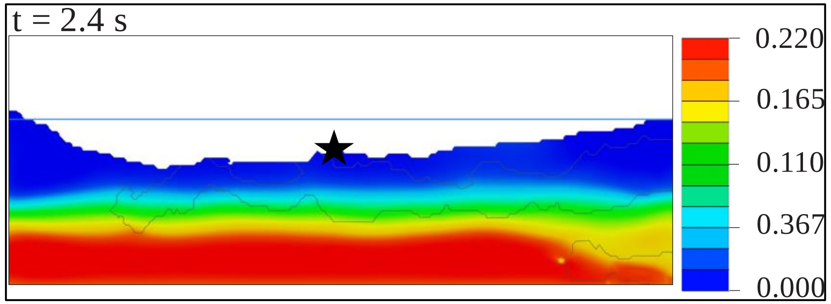


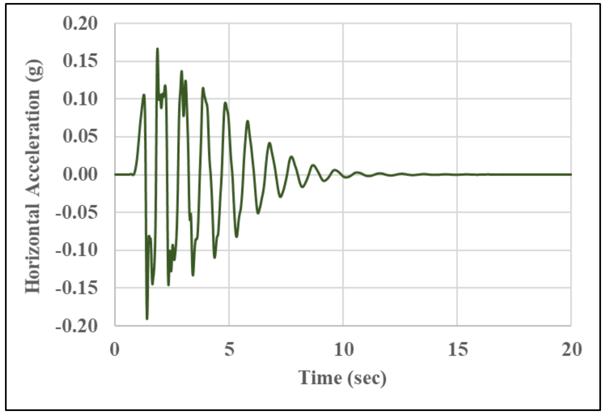


: Top Sand Layer

: Bottom Sand Layer

Acceleration

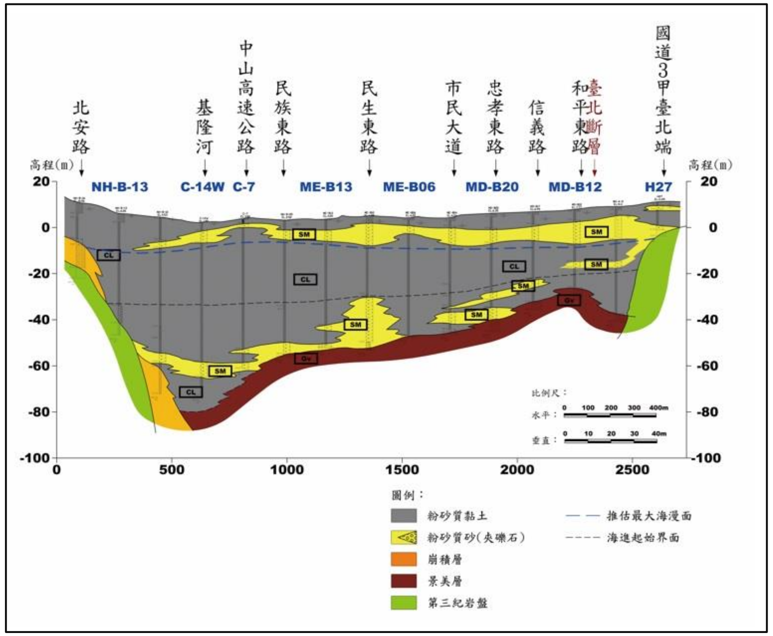




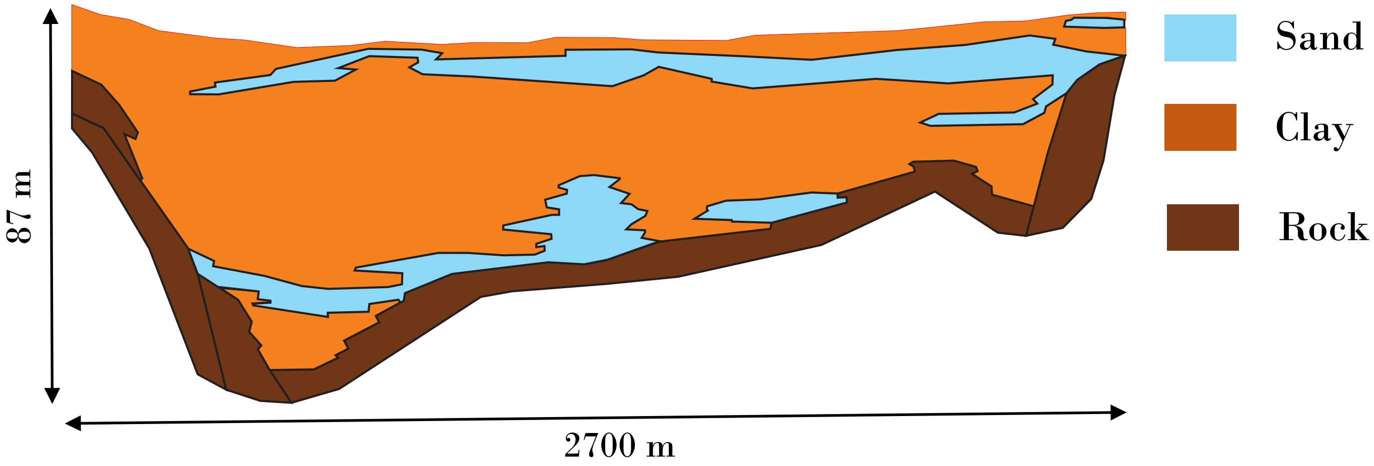
★ =Analysis Point

Real Case 2: Deep Hydrogeological Soil Profile

Original Cross Section



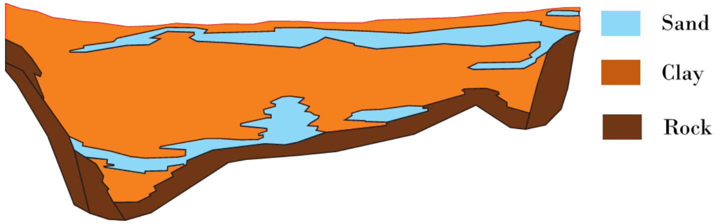
Simplified Cross Section



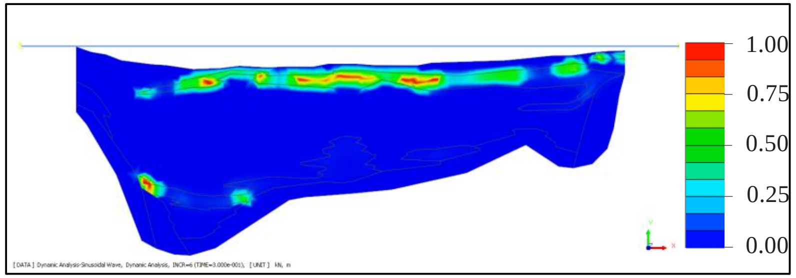
Boundary Condition Set-up

- Surface: soil and water free to move in the y direction
- Side: soil and water are free to move in x and y directions (No absorbent boundary)
- Base: free to move to the x direction, the vertical displacement is fixed (roller boundary)

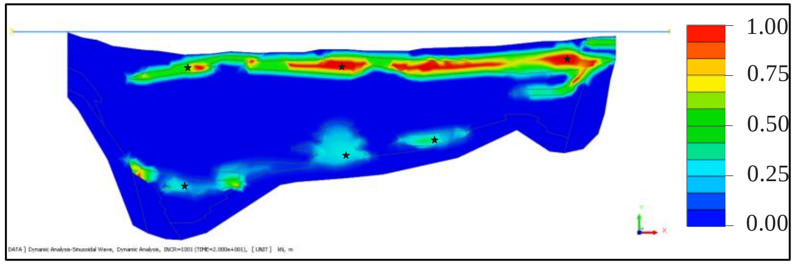
Excess Pore Water Pressure Ratio

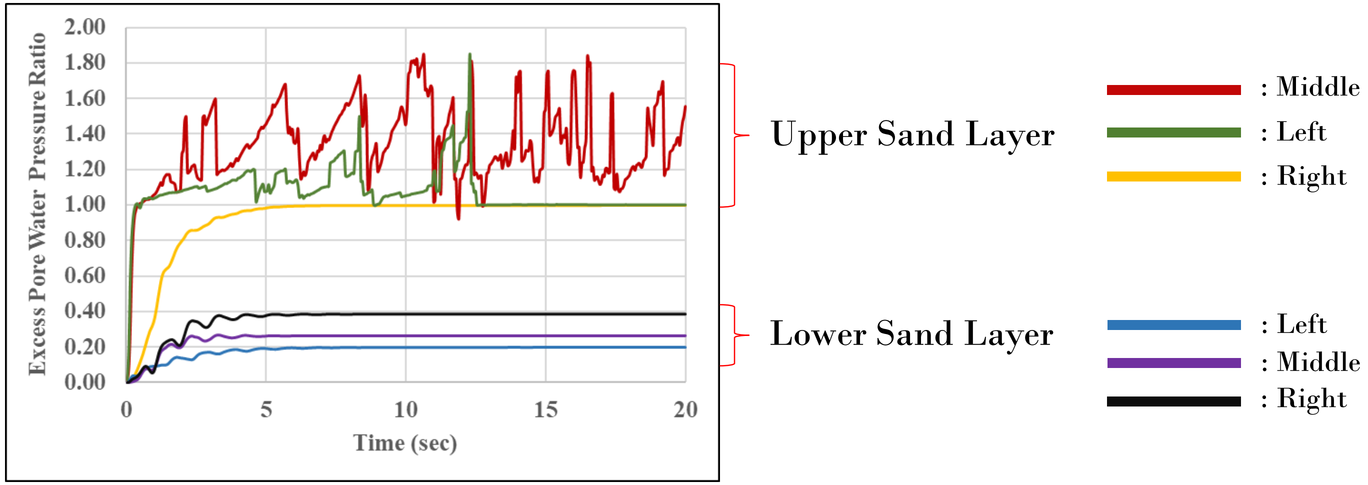


t=0.3 s



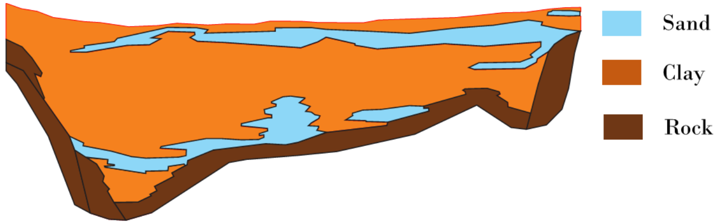
t=20 s



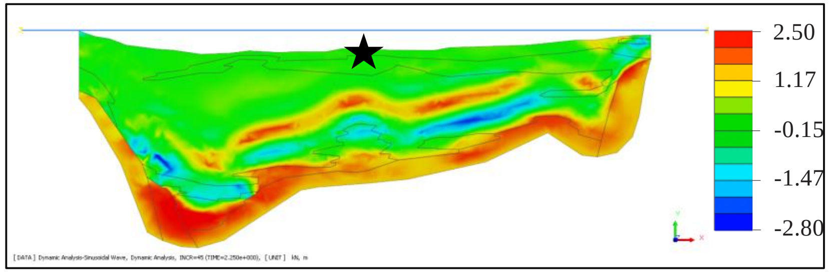


★ =Analysis Point

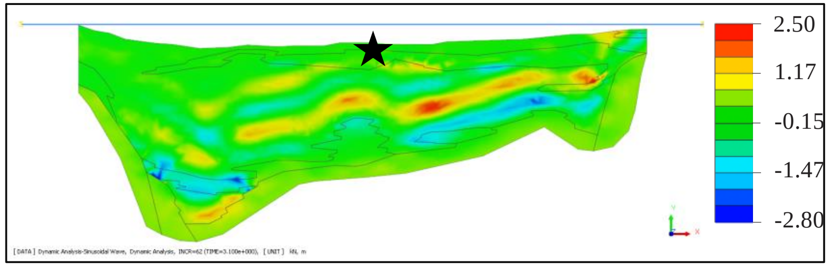
Horizontal Acceleration

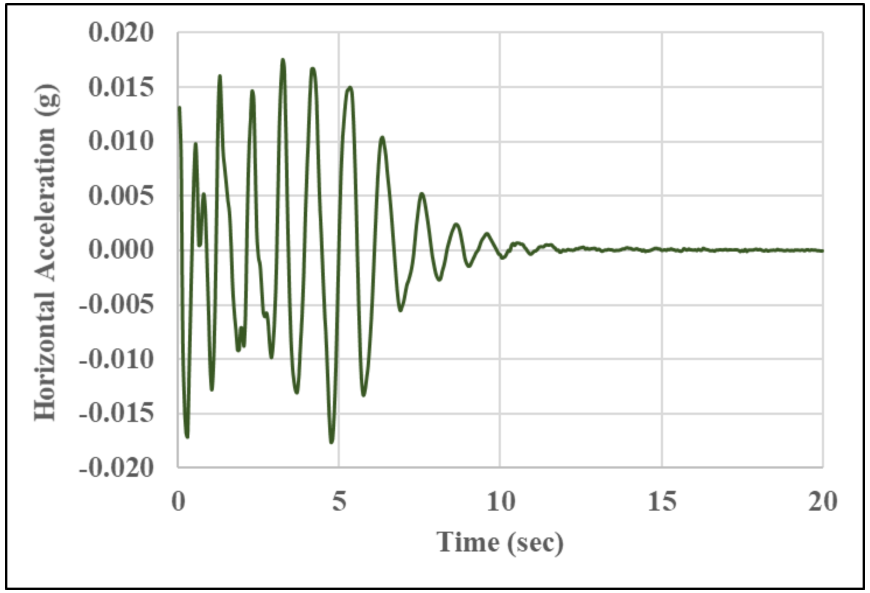


t=2.25 s



t=3.1 s

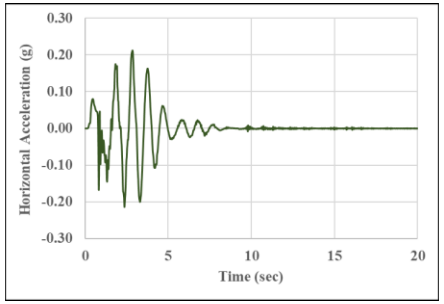




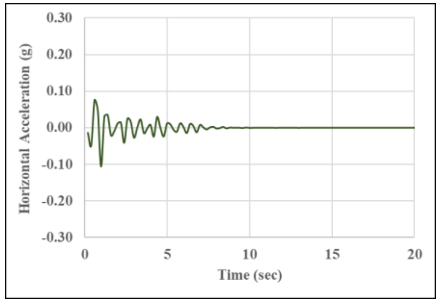
★ =Analysis Point

Acceleration and Hydrogeological Model Complexity

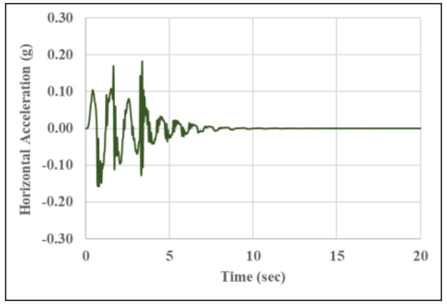
Result comparison (Undrained Condition)



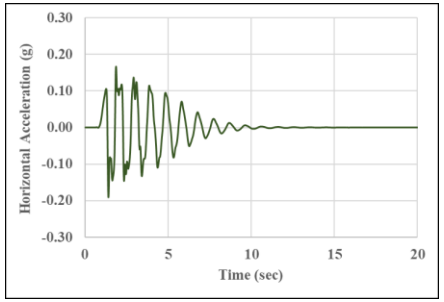
Perfect Layer System



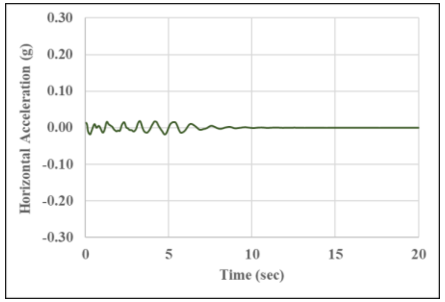
Pinch-out (Fault Dislocation) System



Lens (Riverbed Deposit) System

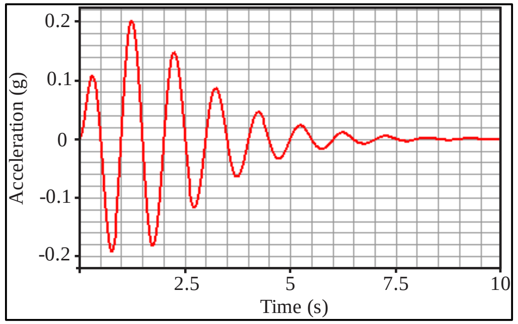


Shallow Hydrogeological Soil Profile

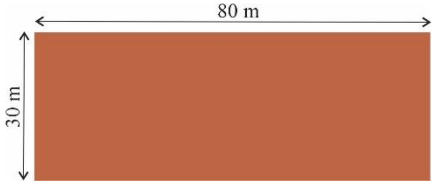


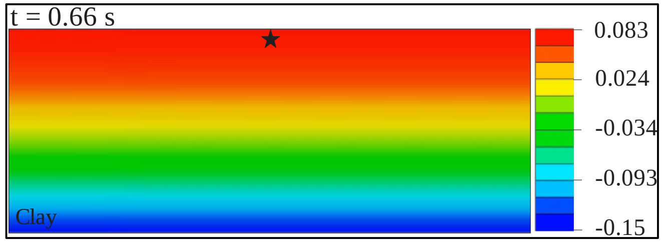
Deep Hydrogeological Soil Profile

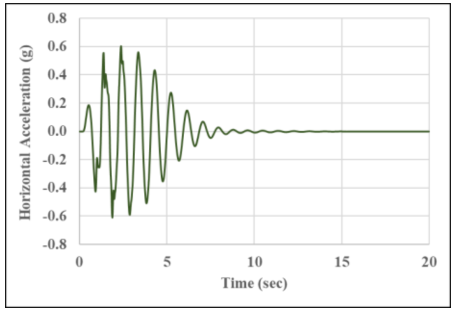
Input Acceleration



Homogeneous Clay Layer







The acceleration decreases due to soil liquefaction and the frequency increase due to the complexity of the hydrogeological model (reflection of the wave propagation).

Conclusions

- Pore water pressure generation:

The presence of the angle in the pinch-out, lens, and real case system led to an accumulation of pore water pressure in the corner area, which has a high potential to reach the liquefaction limit.

- Horizontal acceleration:

Results prove the presence of sand layer altered (decrease) the wave propagation. The complexity of the hydrogeological model affects the frequency of the acceleration.

- Vertical displacement:

The pinch-out system has non-uniform ground settlement as well as the lens system which lead the higher risk for the building to collapse due to soil liquefaction.

So, the difference in the geological model significantly affected the transient behavior of acceleration, pore water pressure, and vertical displacement.

Thank You

Model Set up

Simplified Synthetic Hydrogeological Model

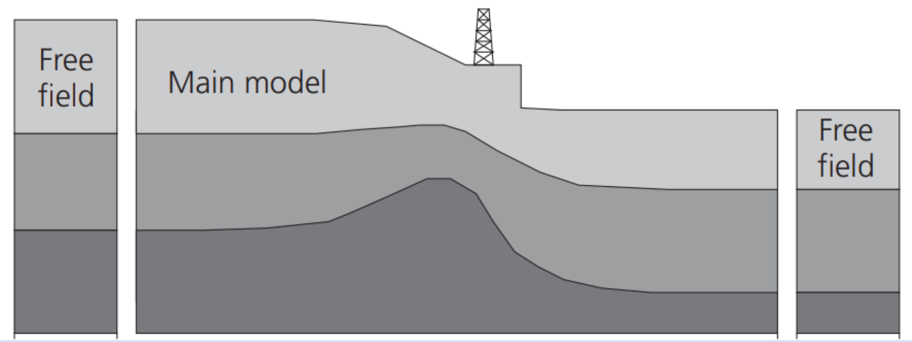
Soil Parameter

Input and Boundary Condition

Absorbent boundary equation:

$$f_x = -\rho\, c_p (v_x^m - v_x^{ff})$$

$$f_y = -\rho\, c_s (v_y^m - v_y^{ff})$$

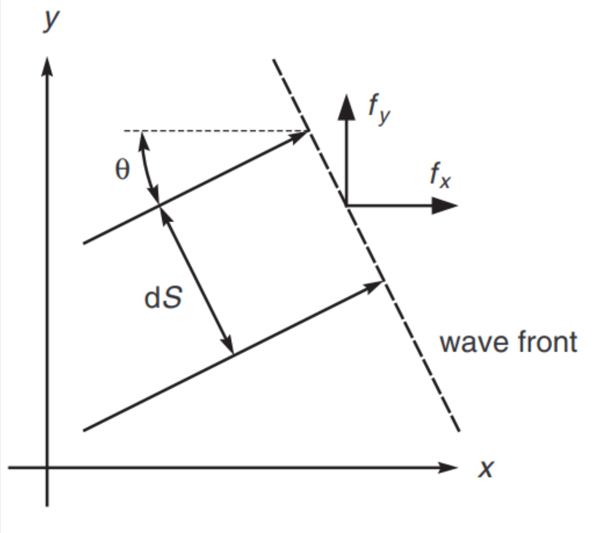


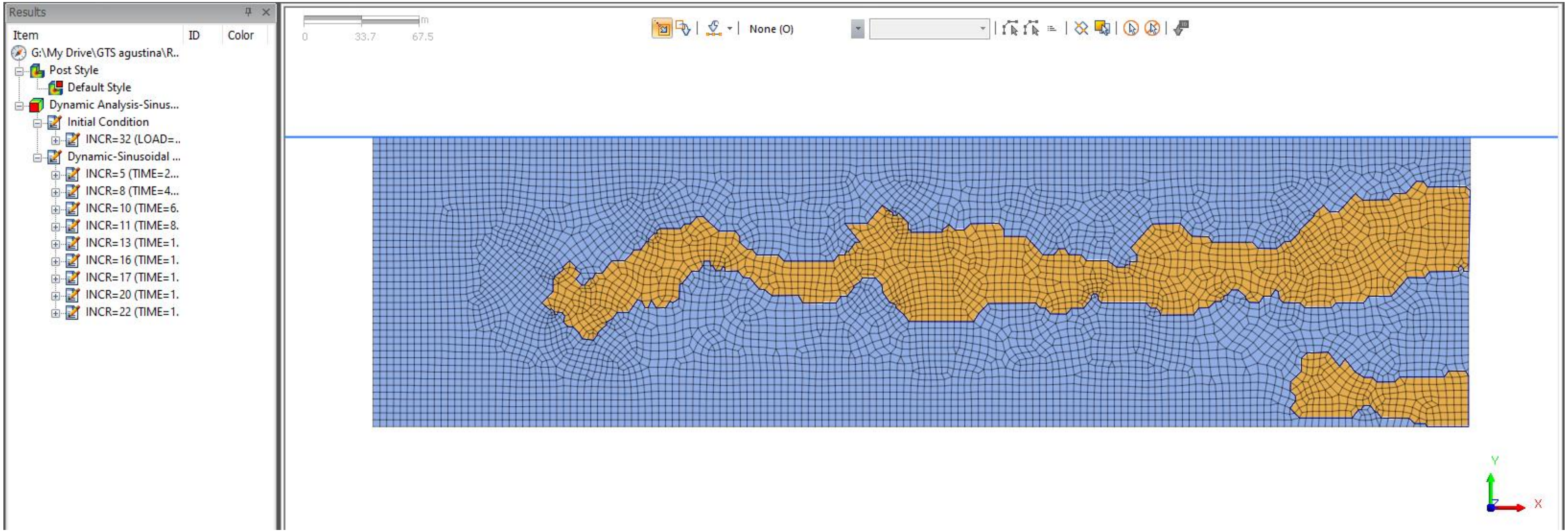
Where:

f_x, f_y = Tractions added
ρ = Density
c_p, c_s = P-wave and S-wave velocity
v^m = Velocity of model boundary
v^{ff} = Velocity of free field domain
A = Domain Area
λ = Volume modulus
G = Shear modulus ($G = E/2(1+\nu)$)

$$c_p = \rho A \sqrt{\frac{\lambda + 2G}{\rho}}$$

$$c_s = \rho A \sqrt{\frac{G}{\rho}}$$




Results
Item
ID
Color
G:\My Drive\GTS agustina\R...
Post Style
Default Style
Dynamic Analysis-Sinus...
Initial Condition
INCR=32 (LOAD=...
Dynamic-Sinusoidal ...
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INCR=11 (TIME=8.
INCR=13 (TIME=1.
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INCR=20 (TIME=1.
INCR=22 (TIME=1.
m
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33.7
67.5
None (O)
Y
X

Problem 2

Sand Layer:

Modulus of elasticity (E)	877 kN/m^2
Elastic shear modulus number (K_G^e)	1,100
Elastic shear modulus index (ne)	0.5
Plastic shear modulus number (K_G^p)	310
Plastic shear modulus index (np)	0.4
Poisson's ratio	0.1
Undrained Poisson's ratio	0.495
Unit weight (γ_{unsat})	18 kN/m^3
Unit weight (γ_{sat})	20 kN/m^3
Cohesion (c)	0 kPa
Peak friction angle ($\emptyset_p$)	33.8
Constant volume friction angle ($\emptyset_{cv}$)	33
Earth pressure coefficient (K_0)	1
Post liquefaction calibration	0.6
Reference pressure (P_{ref})	100 kN/m^2
Failure ratio (R_f)	0.9

Clay Layer:

Modulus of elasticity (E)	8500 kN/m^2
Poisson's ratio	0.3
Undrained Poisson's ratio	0.495
Unit weight (γ_{unsat})	16 kN/m^3
Unit weight (γ_{sat})	20 kN/m^3
Cohesion (c)	10 kN/m^2
Frictional angle ($\emptyset$)	20
Dilatancy angle (ψ)	0
Earth pressure coefficient (K_0)	1

Stiffness drastically decreases

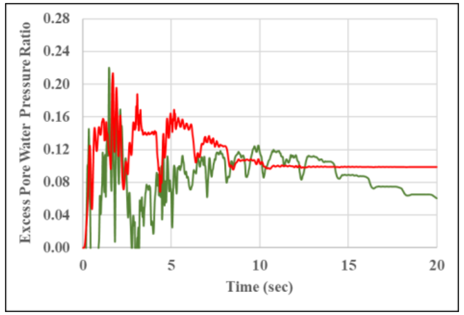
```
Output
> TIME=8.6000e-01, INCREMENT=231 ( 4.30%), ITERATION= 7, ERROR NORMS: P( 3.29E-02/ 1.0E-03) W( 8.25E-07/ 1.0E-06)
> NUMERICAL INSTABILITY DETECTED DURING ELEMENT COMPUTATIONS. BISECTING LOAD INCREMENT (BISECT LEVEL=3)
> TIME=8.5750e-01, INCREMENT=231 ( 4.29%), ITERATION= 33, ERROR NORMS: P( 2.79E-03/ 1.0E-03) W( 5.05E-09/ 1.0E-06)
> CONVERGENCE NOT LIKELY. BISECTING LOAD INCREMENT (BISECT LEVEL=4)
> TIME=8.5625e-01, INCREMENT=231 ( 4.28%), ITERATION= 16, ERROR NORMS: P( 1.10E-02/ 1.0E-03) W( 3.97E-08/ 1.0E-06)
> CONVERGENCE NOT LIKELY. BISECTING LOAD INCREMENT (BISECT LEVEL=5)
> TIME=8.5562e-01, INCREMENT=231 ( 4.28%), ITERATION= 49, ERROR NORMS: P( 6.00E-03/ 1.0E-03) W( 7.84E-08/ 1.0E-06)
> WARNING [4024] : FAILED TO CONVERGE IN NONLINEAR ANALYSIS. LOAD INCREMENT=231.
> TIME=8.5625e-01, INCREMENT=232 ( 4.28%), ITERATION= 47, ERROR NORMS: P( 1.60E-03/ 1.0E-03) W( 4.17E-10/ 1.0E-06)
```

Parameter type	Material	Sand fill of breakwater	Gravel cushion	Sandy silt/clay	Sand (1)		Sand (2)		Break-water
	Color in the cross-sections in Fig. 1								
	Model / Parameter	UBC MC	UBC MC	UBC MC	UBC	MC	UBC	MC	UBC MC
Basic	γ_{unsat} [kN/m^3]	18.0	19.0	18.0	19.7		19.7		n/a
	γ_{sat} [kN/m^3]	21.0	22.0	21.0	21.8		21.8		
	e_{init}	0.5	0.5	0.5	0.74		0.74		
	E [kPa]	83 330	225 000	11 140	98 000		98 000		
	ν	0.25	0.2	0.3	n/a	0.3	n/a	0,3	
	G [kPa]	33 330	93 750	4 286		28 000		28 000	
	c_{ref} [kPa]	5.0	5.0	60.0	0.0		0.0		
	φ [°]	35.0	40.0	33.0	22.0		22.0		
	ψ [°]	0.0	0.0	0.0	19.0		18.0		
	k_x, k_y [m/s]	2.2e-3	5.0e-3	0.5e-7	0.5e-6		2.0e-6		
Constitutive model	φ_{cv} [°]	n/a	n/a	n/a	20.0	n/a	20.0	n/a	n/a
	φ_p [°]				22.0		23.0		
	K_G^e				854.6		954.1		
	K_G^p				250.0		424.7		
	K_B^e				598.2		667.9		
	me				0.5		0.5		
	ne				0.5		0.5		
	np				0.5		0.5		
	R_f				0.811		0.771		
	P_A [kPa]				100.0		100.0		
	σ_t [kPa]				0.0		0.0		
	fac_{hard}				0.2		0.2		
	$(N1)_{60}$				7.65		10.65		
	fac_{post}				0.02		0.02		
Rigid body	EA_1 [kN/m]	n/a	n/a	n/a	n/a		n/a		12.0e6
	EA_2 [kN/m]								12.0e6
	EI [kPa/m]								160.0e3
	d [m]								0.4
	w [kN/m/m]								20.0

(Borowiec, 2016)

Comparison

Excess Pore Water Pressure Ratio



Perfect Layer System

: Top Sand Layer

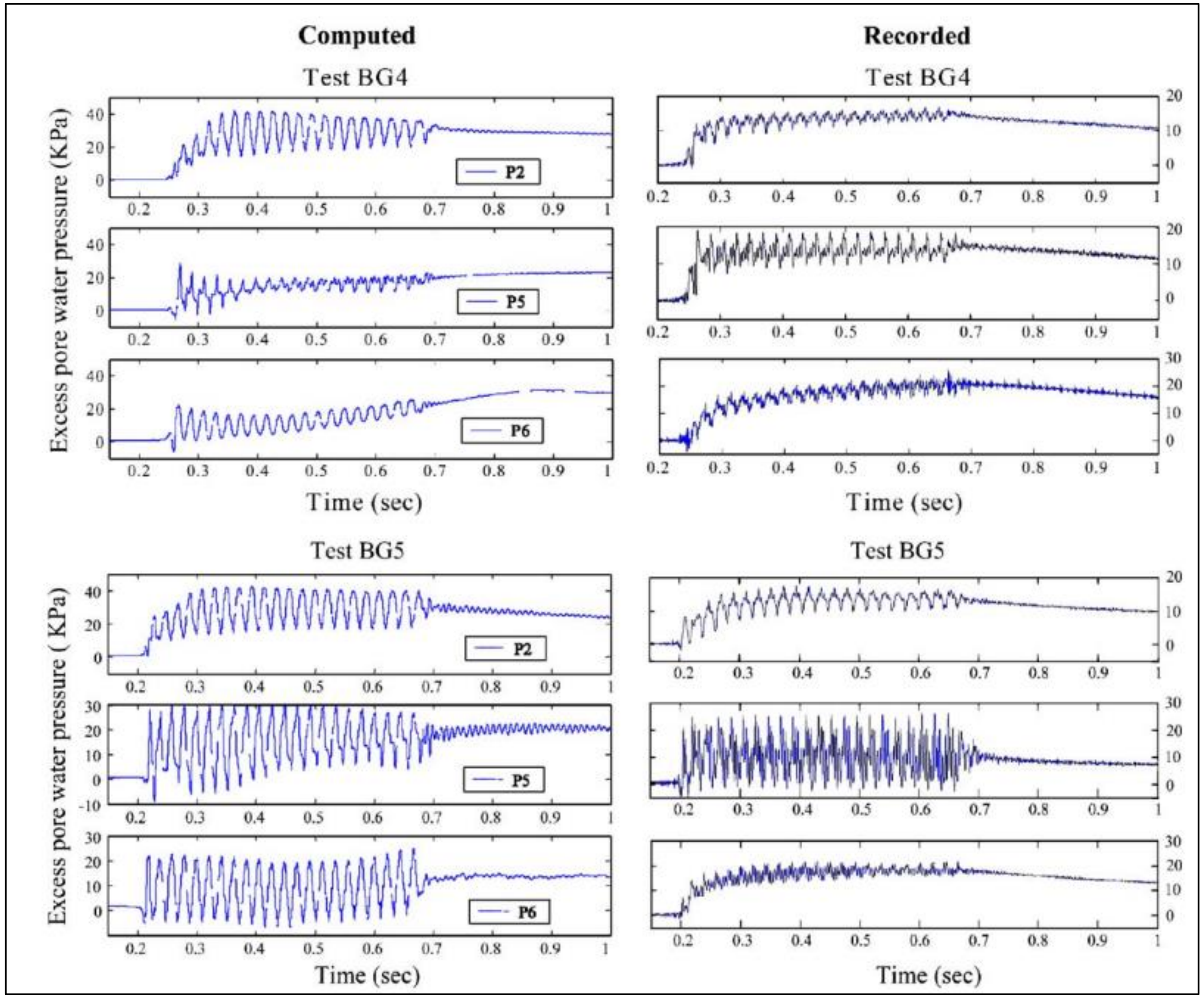
: Bottom Sand Layer

: Top Left

: Top Right

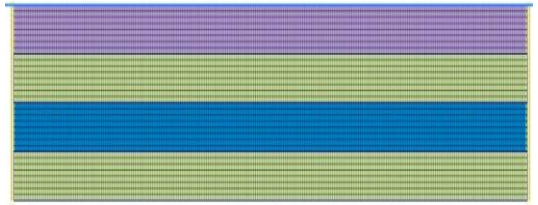
: Bottom Left

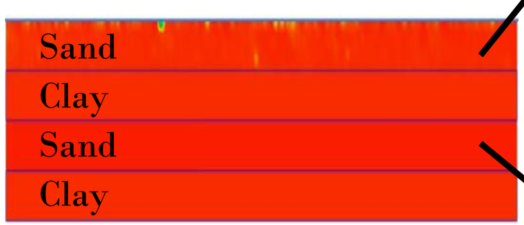
: Bottom Right



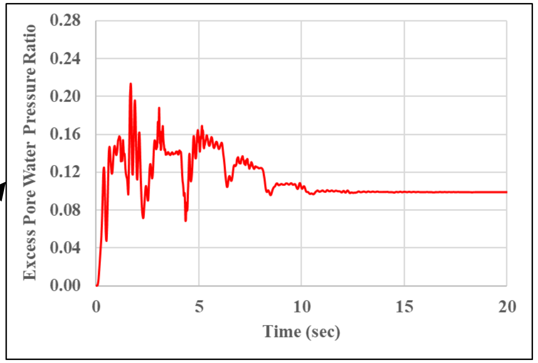
Popescu, 2006

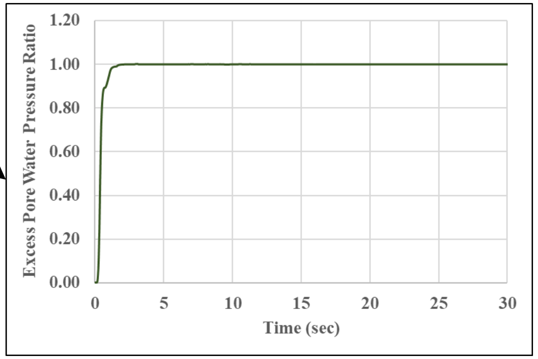
Problem 1





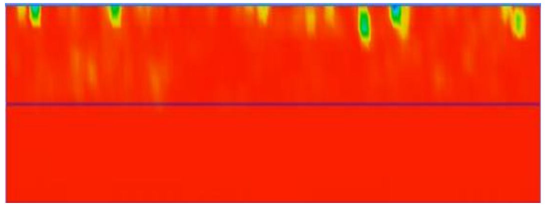
Expectation:





Undrained:

Drained:



Problem: this only occurs when the upper layer is the drained sand layer.

Luque, R., & Bray, J. D. (2017). Dynamic analyses of two buildings founded on liquefiable soils during the Canterbury earthquake sequence. *Journal of Geotechnical and Geoenvironmental Engineering*, *143*(9), 04017067.