

DYNAMIC RESPONSE APPROACH AND METHODOLOGY

Traditional seismic stability procedures

VS

coupled effective-stress approach.





Traditional seismic stability procedures:

- Empirical and laboratory corrections and simplified procedure to evaluate the potential for liquefactions of embankment and foundation soils-SPT, CPT or Vs based methods.
- Limit equilibrium stability analyses to evaluate postearthquake stability.
- Newmark-type estimates of permanent deformation.





What Traditional Seismic Stability Assessment Give you and Can't Give you

• DO:

- State-of-practice estimates of the potential for occurrence or nonoccurrence of liquefaction during and at the end of strong earthquake shaking.
- DON'T:
 - model the progressive changes in the soil's state during earthquake shaking,
 - the potential for buildup of pore water pressure,
 - The occurrence of liquefaction,
 - The resulting permanent deformations during and after the earthquake





Coupled Effective-Stress Analysis of this Webinar

- To estimate the performance of the embankment during and after earthquakes
 - model the progressive changes in the soil's state during earthquake shaking,
 - the pore water pressure build up,
 - If liquefaction occurs or not,
 - The resulting permanent deformations during and after the earthquake



Problem Descriptions



- The pond is located along a river. Liquefaction screening results indicate that zones within the pond embankment are potentially susceptible to liquefaction based on the estimated seismicity for the design seismic event with a 2,475 year return period. The susceptible zones are composed of embankment fill at depths ranging from 15 to 30 feet below the ground surface.
- Preliminary post-earthquake limit equilibrium slope stability analyses based on the results of the screening level liquefaction analysis suggest that the part of the pond Dam do not meet the required slope stability factors of safety. To bring more insight into the liquefaction potential of the site materials and seismic stability of the embankment, more sophisticated nonlinear dynamic analyses are performed herein under the design level earthquake shaking.





Representative Section From Slop Stability Analysis with Liquefiable Embankment Layer.







Relevant Soil Exploration Data



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Potentially Liquefiable Soil Layers based on (N1)60:

 a liquefiable layer in the weathered rock was added and the slope of the weathered rock was revised





Vertical Distance (x100 feet)



Steps of Coupled Effective-Stress Analysis

- Evaluation of initial static stresses
- Establishing phreatic surface using water table or through seepage analysis
- Switching nonlinear soil constitutive model to the liquefiable layers
- Obtaining earthquake input motion through site specific hazard analysis or building code
- Seismic runs and result processing





This Webinar Does not cover details of following

- Static initial stress state was established from a construction stage and phreatic surface was input as a water table based prior anlysis.
- Three Earthquake records was obtained through a site specific hazard analysis but only one is used in this demonstration





Focus on Liquefaction

- Liquefaction: Liquefaction occurs when effective stresses become or close to zero due to generation of excess pore water pressure.
- For civil or geotechnical engineers, when we talk liquefaction, we mainly are talking about saturated cohesionless soil under short term loading such as earthquake when there is no time for the excess pore pressure to dissipate.





Consequences of liquefaction

- liquefied soil softens and loss its shear strength so potential large deformation could occur.
- For embankment of impoundment, when large deformation occurs due to liquefaction, dam could fail or lose its functionality.
- For structures, the foundation bearing capacity could be reduced to an extent to cause detrimental effects to the structure such as differential/large settlements, cracking, etc.





Key for Modeling Liquefaction

- The single most important task in liquefaction modeling is to capture the excess pore pressure reasonably accurate by the chosen soil constitutive model.
- Great effort has been spent in this area for many years by academia and engineers. The available models are UBCSand, URS Model, PM4Sand (UC Davis), WangCS (Amec Foster Wheeler) among others.
- The first two are models modified from the Mohr-Coulomb model and the last two are models developed using bounding surface plasticity theory. UBCSand is the first and only one available for Midas users at this time.



1. UBC Sand Model

- An effective stress model for predicting liquefaction behavior of sand under seismic loading.
- GTSNX Liquefaction Model is extended to a full 3D implementation of the modified UBCSAND model using implicit method.



- Exponential function per effective pressure

 $G^{e} = K_{G}^{e} p_{ref} \left(\frac{p' + p_{t}}{p_{ref}} \right)^{ne}$

- Plasticity / Shear
- Yield function : Mohr Coulomb
- Flow rule : Menetrey-Willam (non-associated)
- Hardening behavior : Hyperbolic hardening

$$\Delta \sin \phi_m = \frac{G^p}{p'} \Delta \kappa_s = K_G^p \left(\frac{p'}{p_{ref}}\right)^{np-1} \left\{ 1 - \left(\frac{\sin \phi_m}{\sin \phi_p}\right) R_f \right\}^2 \Delta \kappa_s$$
$$\Delta \kappa_s = \left| \Delta \varepsilon_1^p - \Delta \varepsilon_3^p \right|$$

- Plasticity / Compression (cap)
- Yield function : Modified Mohr-Coulomb Cap

$$f_2 = \left(p + \Delta p\right)^2 + \alpha \left(\frac{q}{R_2(\theta)}\right)^2 - p_c^2 = 0$$

- Flow rule : Same with yield function (Associated flow)
- Hardening behavior : Hardening of allowable compression per volumetric strain

$$\Delta p_{c} = K_{B}^{p} p_{ref} \left(\frac{p'}{p_{ref}} \right)^{mp} \Delta \varepsilon_{ref}$$

- Plasticity / Pressure cut-off
- Yield function & Flow rule

$$f_{pr} = p_{cut} - p$$

- No Hardening behavior

Cyclic loading behavior

- Consider Shear, Plasticity function for primary and secondary yield surface respectively → Check difference of hardening behavior
- Primary yield surface: In case that the current stress ratio (or mobilized friction angle) reach to the critical (MAX) state of the material
- Secondary yield surface: In case that the current stress ratio is smaller than the critical (MAX) state of the material according to the unloading/reloading conditions
- Secondary hardening (Soil Densification)

$$\Delta \sin \phi_m = K_{G,2}^p \left(\frac{p}{p_{ref}}\right)^{np-1} \left\{ 1 - \left(\frac{\sin \phi_m}{\sin \phi_p}\right) R_f \right\}^2 \Delta \kappa_s, \quad K_{G,2}^p = K_G^p \left(4 + \frac{n-1}{2}\right) F_{dens}$$

$$q \bigoplus_{\substack{p \in S^2 \\ p \in S^2}} p \bigoplus_{\substack{p \in S^2 \\$$



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UBC Sand Model Parameters

Additional parameters to simulate liquefaction

Estimation of each parameter using Standard Penetration Test (SPT) - ((N₁)₆₀ : Equivalent SPT blow count for clean sand.

Parameter	Description	Reference]
Pref	Reference Pressure	In-situ horizontal stress at mid- level of soil layer	0 223
	Elastic (Power Law)	·	$K_G^e = 21.7 \times 20.0 \times (N_1)_{60}^{0.000}$
K_G^e	Elastic shear modulus number	Dimensionless	$\frac{1}{20^{0}} < \phi < 24^{0}$
ne	Elastic shear modulus exponent	Dimensionless	$50 < \varphi_{cv} < 54$
	Plastic / Shear	·	v = 0.0163
$\phi_{_{p}}$	Peak Friction Angle	Failure parameter as in MC model	$V^{p} = V^{e}(N)^{-2} \times 0.002 \pm 100.0$
ϕ_{cv}	Constant Volume Friction Angle	-	$\mathbf{K}_{G} = \mathbf{K}_{G} (N_{1})_{60} \times 0.003 + 100.0$
С	Cohesion	Failure parameter as in MC model	ne = 0.5
K_G^p	Plastic shear modulus number	Dimensionless	np = 0.4
np	Plastic shear modulus exponent	Dimensionless	
R_{f}	Failure ratio (qf / qa)	0.7~0.98 (< 1), decreases with increasing relative density	$\phi_{p} = \begin{pmatrix} \phi_{cv} + (N_{1})_{60} / 10.0 & ((N_{1})_{60} - 15) \\ \phi_{cv} + (N_{2}) / 10.0 + \max\left(0.0 (N_{1})_{60} - 15\right) & ((N_{2})_{60} - 15) \\ ((N_{2})_{60} - 15) & ((N_{2})_{60} - 15) \\ ((N_{2})_{60$
$F_{\it post}$	Post Liquefaction Calibration Factor	Residual shear modulus	$\left(\psi_{cv} + (N_1)_{60} + 10.0 + 10000 + 10000 + 10000 + 10000 + 1000 + 1000 + 1000 + 1000 + 1000 +$
F_{dens}	Soil Densification Calibration Factor	Cyclic Behavior	
	Advanced parameters	•	$R_f = 1.1 \times (N_1)_{60}^{-0.15}$
Pcut	Plastic/Pressure Cutoff (Tensile Strength)	-	
$K_{\scriptscriptstyle B}^{p}$	Cap Bulk Modulus Number	-	[Parameters and Equations for Calibration]
тр	Plastic Cap Modulus Exponent	-]
OCR	Over Consolidation Ratio	Normal stress / Pre-overburden pressure	





Input Parameter

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$p_{\rm ref}$	Reference pressure
K_{G}^{e}	Elastic shear modulus number
ne	Elastic shear modulus exponent
ϕ_p	Peak friction angle
ϕ_{cv}	Constant volume friction angle
С	Cohesion
K_G^p	Plastic shear modulus number
np	Plastic shear modulus exponent
R_f	Failure ratio
F _{post}	Post liquefaction calibration factor
F_{dens}	Soil densification calibration factor
p_{cut}	Pressure cut-off
K^p_B	Plastic bulk modulus number
mp	Plastic bulk modulus exponent
OCR	Over consolidation ratio



Modified UBCSAND _ GTSNX



- Nonlinear Elastic
 - Exponential function per effective pressure

$$G^{e} = K_{G}^{e} p_{ref} \left(\frac{p' + p_{t}}{p_{ref}}\right)^{ne}$$

- Plasticity/Shear
 - Yield Function: Mohr-Coulomb
 - Flow Rule: Menetrey-Willam (non-associated)
 - Hardening behavior : Hyperbolic Hardening

$$\Delta \sin \phi_m = \frac{G^p}{p'} \Delta \kappa_s = K_G^p \left(\frac{p'}{p_{ref}}\right)^{np-1} \left\{ 1 - \left(\frac{\sin \phi_m}{\sin \phi_p}\right) R_f \right\}^2 \Delta \kappa_s$$
$$\Delta \kappa_s = \left| \Delta \varepsilon_1^p - \Delta \varepsilon_3^p \right|$$







- Plasticity/Compression (cap)
 - Yield Function: Modified Mohr-Coulomb Cap

$$f_2 = \left(p + \Delta p\right)^2 + \alpha \left(\frac{q}{R_2(\theta)}\right)^2 - p_c^2 = 0$$

- Flow Rule: Same with Yield Function (Associated flow)
- Hardening Behavior: Hardening of allowable compression per volumetric strain

$$\Delta p_{c} = K_{B}^{p} p_{ref} \left(\frac{p'}{p_{ref}} \right)^{mp} \Delta \mathcal{E}_{v}^{p}$$

- Plasticity/Pressure cut-off
 - Yield Function & Flow Rule:

$$f_{pr} = p_{cut} - p$$

- No Hardening Behavior



- Cyclic loading behavior
 - Consider Shear, Plasticity function for primary and secondary yield surface respectively → Check difference of hardening behavior
 - Primary yield surface: In case that the current stress ratio (or mobilized friction angle) reach to the critical (MAX) state of the material
 - Secondary yield surface: In case that the current stress ratio is smaller than the critical (MAX) state of the material according to the unloading/reloading conditions



<Secondary hardening (Soil densification)>

$$\Delta \sin \phi_m = K_{G,2}^p \left(\frac{p'}{p_{ref}}\right)^{np-1} \left\{ 1 - \left(\frac{\sin \phi_m}{\sin \phi_p}\right) R_f \right\}^2 \Delta \kappa_s, \quad K_{G,2}^p = K_G^p \left(4 + \frac{n-1}{2}\right) F_{dens}$$



Model Calibration



• Lab test

- Monotonic and cyclic drained Direct Simple Shear (DSS) test (skeleton response)
- Constant volume DSS test (undrained test)
- Single element test (3D or 2D), calibration





Model Calibration – initial estimates



- Standard Penetration Test (SPT), Calibration (Beaty, Byrne)
 - Clean sand equivalent SPT blow count measurement: $(N_1)_{60}$

 $K_{G}^{e} = 21.7 \times 20.0 \times (N_{1})_{60}^{0.333} \qquad 30^{0} < \phi_{cv} < 34^{0}$ $v = 0.0163 \qquad ne = 0.5$ $K_{G}^{p} = K_{G}^{e} (N_{1})_{60}^{2} \times 0.003 + 100.0 \qquad np = 0.4$ $\phi_{p} = \begin{pmatrix} \phi_{cv} + (N_{1})_{60} / 10.0 & ((N_{1})_{60} - 15) \\ \phi_{cv} + (N_{1})_{60} / 10.0 + \max\left(0.0, \frac{(N_{1})_{60} - 15}{5}\right) & ((N_{1})_{60} \ge 15.0) \end{pmatrix}$

 $R_f = 1.1 \times (N_1)_{60}^{-0.15}$





Undrained DSS (Monotonic)





Undrained DSS (Cyclic)





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UBC SAND _ Model Calibration_Summary

- Monotonic and cyclic drained Direct Simple Shear (DSS) test (skeleton response).
- Constant volume DSS test (undrained test)



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Bounding Surface Plasticity Wang Model



(b) Surfaces and stress variables in p = constant plane



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Wang Critical State Model

Wang captures most of cohesionless soil behaviors under complex loading such as cyclic. Two simple observations (the UBCSand-Slide 14 can't capture): pore pressure build-up during unloading phase; and dilation when loading beyond the phase transformation line.



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More Model comparisons with Dynamic Simple Shear (J. Wu and R. Seed, 2003)



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Wang Model Parameters

Table 1 Model Parameters of Sand (Dr=45% or 60%)

Туре	Dr (%)	ф' degree	Go	hr	kr	d	Poisson ratio	gamma	ita	Rp/Rf	Void ratio e ¹
1	45	28	181	0.15	0.2	4	0.33	15	7	0.50	0.69
2	60	28	242	0.15	0.2	6	0.33	15	20	0.50	0.73

Notes:

(1) Void ratio e=0.541 + Dr*0.314 where assuming emax=0.855 and emin=0.541



Continue – Wang model parameters





Fig. A2.4 Influences of d, k_r, b, and R_p



Continue - Model Parameters hr calibrated from G/Gmax and damping curves



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Continue – Model Parameter Go that defined the Initialmer (maximum) Elastic Modulus





Cyclic Stress Ratio CSR Normalized with initial vertical effective stress

-0.2

-0.3

amec Continue – last 2 Model Parameters gamma and ita, which control the post-liquefaction strain accumulations, i.e. stress path stabilized (left figure) but strain continue accumulating (right figure) volter

Wet-Pluviated Fully Saturated Test MS79J 0.3 Cyclic Stress Ratio CSR Normalized with initial vertical effective stress 5 0.251 i٩ 0.1 1.0 08 10 -15 5 -0.3

Normalized vertical effective stress ratio





Shear strain, %





Pre-Existing Shear Stress, k_α effect

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Figure 6.1. Undrained cyclic DSS loading response for d=4 (loose sand) with vertical effective consolidation stress of 1 atm and with initial static shear stress ratios of 0.0, 0.1, and 0.2.



Figure 6.2. Undrained cyclic DSS loading response for d=6 (median dense sand) with vertical effective consolidation stress of 1 atm and with initial static shear stress ratios of 0.0, 0.1, and 0.2.



UBC Sand Post Processing – Liquefiable Area or Pore Pressure Ratio or Ruc

- Specific results which can check the liquefiable area directly
- Two types of results are available to measure the possibility of liquefaction.

Pore Pressure Ratio (PPR)

- The ratio of excessive pore pressure change and the initial effective pressure

$$PPR = -\frac{\Delta p_{w}}{p_{init}} = \frac{p_{init} - p_{current}}{p_{init}}$$

Δp_w	Excessive Pore Pressure Change
p_{init}	Initial Effective Pressure
<i>p</i> _{current}	Current Effective Pressure

Normalized Max Stress Ratio

- The ratio of mobilized friction angle and the peak friction angle
- When the Max stress ratio is reached, the mobilized friction angle is close to the peak friction angle, liquefaction is triggered (1 = Liquefaction)







UBC Sand Normalized Max Stress Ratio





[Nonlinear Time History Analysis under the cyclic loading]





Analysis options (Large deformation, Excessive Pore Water Pressure, Post-Processing)



GTS NX 2017 1. Boundary Conditions for the damping effect

Damper Free Field (Infinite boundary, Absorbent boundary)



1) Damper (Mesh > Element > Create > Other > Ground Surface Spring)

Element	Create/	Delete			×
1D	2D	3D	Other	Delete	
Grour	nd Surfa	ce Spring			\sim
		Select	Mesh Se	t(s)	
Grou	und Surf	ace Spring	,		
	1odulus (of Subgra	de Reacti	ion	
м	odulus o	felasticity	/ coeff. a	1	1
	amping)	Constant	/Area		
Bour	ndary Se	t			
Fix	ed Botto	om Conditi	on		
Bot	tom			\sim	\$
Deserve					
343	1 343.	Surface	Poring No	de ID 03 s	
010	545.	Surface a	phing_rea	JUE ID 32	
Mesh Se	t [Ground S	urface Sp	ring	\sim
👳 🥒			ОК	Cancel	Apply

- The viscous boundary element required as a model boundary condition for time history analysis.
- The viscous boundary element can be created from the following steps.

1. Compute Cp, Cs : Cp, Cs can be calculated using the equation below.

$$C_{p} = \rho \cdot A \cdot \sqrt{\frac{\lambda + 2G}{\rho}} = W \cdot A \cdot \sqrt{\frac{\lambda + 2G}{W \cdot 9.81}} = c_{p} \cdot A$$

$$C_{s} = \rho \cdot A \cdot \sqrt{\frac{G}{\rho}} = W \cdot A \cdot \sqrt{\frac{G}{W \cdot 9.81}} = c_{s} \cdot A$$

$$A = \frac{v \cdot E}{(1 + v)(1 - 2v)} \qquad G = \frac{E}{2(1 + v)}$$

 λ : Bulk modulus, G : Shear modulus, E : Elastic modulus, v : Poisson's ratio, A : Cross-section area

2. The cross-section area is automatically considered until the surface spring is created, so only the Cp, Cs needs to be computed. When creating the viscous boundary element automatically, the spring is automatically created by considering the element area (effective length*unit width) as shown below. Input the Cp value for the normal direction coefficient at the point of spring creation and input the Cs value for the parallel direction.



1. Boundary Conditions for the damping effect

Damper Free Field (Infinite boundary, Absorbent boundary)



2) Free Field (Mesh > Element > Free Field)

RZ

Create Free Field	×		
Line Plane			
Element ID Target Object Type From Free-Edge	14291		
Select Elemen	nt(s)		
Property 8 8: Other Property Mesh Set			
Create/Modify Other Property			
ID 8 Name Ot	her Property	Color	~
Free Field Type Type	Line Absorbent Boundary	~	
	Eroo Hold		

sorbent Bound/

RX

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Cancel

For the seismic analysis, users need to model infinite ground to eliminate the boundary effect caused by reflection wave. Since it is not possible to model infinite ground, users can apply Free Field Element at the boundary.

Absorbent Boundary : Enable to eliminate reflection wave at the ground boundary Width Factor (Penalty Parameter) : In order to minimize the size effect of the model, users have to input more than 10⁴, This value will be multiplied by model width (In case of 2D, this is plain strain thickness (unit width).





Width Factor

DOF

⊡ DX

DY

⊡ DZ

OK

×

Name

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Original

Description

O Consider

1) Ground Acceleration (Dynamic Analysis > Load > Ground Acceleration) amec foster wheeler **Time History Load Function** Х Time Function Data Type th function Normalized Acceleration \sim Normalized Acceleration lf Weight Graph Option Earthquake Acceleration Import X-axis Log Scale Velocity 81000001 m/sec2 Displacement \mathbf{A} Y-axis Log Scale Time Value Force (sec) (g) Moments Normal -0.0022 0.0000 0.06 0.0050 -0.0022 0.05 -0.0021 0.0100 0.04 0.0150 -0.0021 0.03 0.0200 -0.0021 0.02 0.01 0.0250 -0.0021 Value 0.0300 -0.0021 -0.01 0.0350 -0.0021 -0.02 0.0400 -0.0021 -0.03 0.0450 -0.0021 -0.04 -0.05 0.0500 -0.0021 -0.06 Base Line Correction (Acceleration) -0.07 0 1 2 3 4 5 6 7 8 9 11 13 15 17 19 21 23 Time

25 27 29 31

Apply

Cancel

OK

Ground Acceleration Ground Acceleration-1 Name X Direction ÞÐ th function \sim Function Scale Factor 1 Arrival Time 0 sec Y Direction None (Constant) Function 1 Scale Factor Arrival Time 0 sec Z Direction None (Constant) Function Scale Factor Arrival Time 0 sec Dynamic Load Set-1 Dynamic Load Set 1 \sim 夏 🥒 OK Cancel Apply

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Ground Acceleration

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2) Analysis Time : Define Time Step for the analysis and the output

Construction S	tage Set Name	Free Field		~				
Stage ID	2: Acceleration	~	Move to Previous	Move to Next		New	Insert	Delete
Stage Name	Acceleration					\checkmark	Analysis Cont	rol
Stage Type	Nonlinear Time History	~	Time Step				Output Contr	rol
Set Data	line Free Field	Activated Data	dary Condition	Deactivated Data	ondition	Initial Con	dition e Water Level F D ^m None	or Global
Time Step		South	×	Define Time Step	onakion			× h Set
Time Step	for Analysis and Output Define	Time Step		Name Time Duration	1	30 sec	Add	
Summary Total Time	Duration		30	Time Increment Intermediate Output(Every N Time		0.01 sec 10	Modify	
		ОК	Close	No Name	Time Duration	Time Increment	Inter. Output	
Stati	c Load ree field_force gravity amic Load Dynamic Load Set-1	× Show Data					Close	



GTS NX 2017 3. Analysis Options

1) Undrained Condition : Allow Undrained Material Behavior to check the generated excessive pore water pressure under short term loading like earthquake foster

laterial	×
ID 4 Name emb poten liqu	ue Color 🗸 🗸
Model Type Modified UBCSAND	✓ Structure
General Porous Non-Linear	
Unit Weight(Saturated)	19.6359391 kN/m ³
Initial Void Ratio(eo)	0.65
Unsaturated Property	~
Drainage Parameters	
Undrained (Effective Stiffness/Effective	re Strength) \sim
Undrained Poisson's Ratio	0.495
◯ Skempton`s B Coefficient	0.97826087
Permeability Coefficients kx ky 1e-005 1e-005 Void Ratio Dependency of Permeability Specific Storativity(Ss) 1.28335	kz 1e-005 m/sec ility(ck) 0.5 50 1/m Auto

- Material > Porous > Drainage Parameters

- Analysis Control > Undrained Condition (for each analysis case or for each stage)

alysis Control X
General
Initial Temperature
Initial Temperature By Value 0 [T]
Water Level
🗹 Define Water Level 1 m Water Level(🗸 🍋
Define Water Level for Mesh Set Input Water Level
Eigenvectors
Number of Modes 100
Frequency Range of Interest
Lowest 0 Highest 0
Unit: [Cyde]/ sec
Sturm Sequence Check
Saturation Effects
Consider Partially Saturated Effects for Stress Analysis
Max. Negative Pore Pressure
Max. Negative Pore Pressure Limit 0 kN/m ²
Undrained Condition
Allow Undrained Material Behavior
Mass Parameters
Coupled Mass Calculation
OK Cased

nalysis Co	ontrol					>
General	Dynamic	Nonlinear				
Initia	Stress					
Es	timate Initi	al Stress of	Activated	Elements		
– Undra	ained Cond	ition				
- Undra	ained Condi Iow Undrair	ition ned Materia	l Behavior			
- Undra	ained Condi low Undrair	ition ned Materia	l Behavior			
Undra Al	ained Condi low Undrair	ition ned Materia	l Behavior			
Undra	ained Condi low Undrair	ition ned Materia	l Behavior			

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GTS NX 2017 3. Analysis Options

- 2) Geometry Nonlinearlity
- Consider Geometric Nonlinear Effects to simulate large deformation (Analysis Case > Analysis Control > Nonlinear)
- Analysis can take into account load nonlinearity which is reflecting the effects of follower loads, where the load direction changes with the deformation. Depending on the deformed shape, the pore water pressure can be updated automatically.

Analysis Case Set	ting			Basic Nonlinear
Title	Free Field			Load Steps
Description			Analysis Control	Number o
Solution Type	Construction Stage		Output Cor trol	Inte
Construction Sta	ge Set	Free Field	\checkmark	O Manual w
Analysis Case Mo	del			O Time Steps
	All Sets	<< >>	Active Sets	Time(Dura
				Number of
				Inte
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				Initialized type
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				Convergence C
				Displacemen
				Load(P)
				Work(W)

Geometry Nonlinearlity	
Consider Geometric Nonlinear Effects	
Update Pore Pressure with Deforma	ition
asic Nonlinear Parameters	
Load Steps Number of Increments	
Intermediate Output Request	Last Increment V
O Manual with User-Defined Steps	Load Step
Time Steps	
Time(Duration)	86400 sec
Number of Increments	1
Intermediate Output Request	Last Increment \sim
O Manual with User-Defined Steps	Time Step
itialized type	
General CEnha	nced init stress
Convergence Criteria / Error Tolerance —	
Displacement(U)	0.03
Load(P)	0.001
⊇ Work(W)	1e-006
	etting

7	A A A A A A A A A A A A A A A A A A A	1		\int
	Normal pressure	Pressure	in specified	direction





GTS NX 2017 3. Analysis Options

3) Element Formulation (Analysis > Tools > Options > Analysis/Results > Element Formulation)

- Hybrid (Default setting)
- Standard (for large deformation, geometric nonlinear option)

neral Geometry/Mesh/Connections L	Loads/B.C.	Analysis/Results		
Analysis Analysis Control Results General Contour Vector Deform No Results Diagram Animation Legend	Number of Enable Element f Hybrid Reduct Stand Equation Auto Maximum Converg 2D Eleme Unique Consid	of Processors e GPU Acceleration Formulation d (Accuracy) ced (Efficiency) lard (Stability) a Solver Multifrontal n Iteration yence Tolerance ent Setting e Shell Normal Gener der Drilling DOF	O Dense	4 ਦ () AMG 10 0.01 20 [deg]

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1) History Output Probes

(Analysis > History > History Output Probes & Result > Special Post > History > Graph)



History Output Probes	X				
Probe Type Displ/Vel/Accel	~				
Type of Result		History Probes Graph			×
 Displacement Velocity Acceleration Components Rel.TX Displacement Function Data Name Relative TX Selected 1 Object(s) Reference Node Node [9507] Sele History Step All Output Step Frequency Step Time O Time Component Ist ex Plane Strain Ex. Pore Pressure 	cted sec Add Modify	Analysis Case Free Field Probe Type Displ/Vel/Accel X-Axis Time Y-Axis Define History Result Time Total TX I Node 6377 Node 6377	Define Graph Graph Option Name Graph Name X-Axis Name Y-Axis Name Y-Axis Name 2.3399e-003 2.3399e-003 -2.3399e-003 -2.3399e-003 -4.6799e-003 -4.6799e-003 -4.6799e-003 -4.6799e-003	15 History Probes Graph Time Functions History Probes Graph History Probes Graph Comparison of the second	3
2nd ex Plane Strain Ex. Pore Pressure 1st tot Plane Strain Pore Pressure	Delete	Reset Draw Close		Time Evport Image file Evport Image to Word Evport to Ev	
2nd to Plane Strain Pore Pressure Total TX Displ/Vel/Accel TX Displacement Relativ Displ/Vel/Accel Rel.TX Displacem		react unaw Uose		Export amage me Export amage to word Export to Exce	
	Close				





Case Study

(Tailings Pond Embankment Seismic Stability – Excess Pore Pressure and Permanent Displacement using FLAC and GTSNX)



1. The FLAC Model.

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One of the difficulty of using FLAC is the creating of the most appropriate grid for the problem such as more zone density at the highly deformed location of the liquefiable layer.



Horizontal Distance (x100 feet)





Constitutive Models in FLAC

- FLAC built in Finn model
- User defined dlls: UBCSand, Wang model, PM4Sand among others.
- The one used for this project: Wang bounding surface plasticity model



Wang Model Parameters: Most of them have clear physical meaning and can be calibrated from routine lab and/or field tests

Material Description	Friction Angle φ (deg)	G ₀	h _r	d	kr	fp	bc	ein	Poisson
Potentially Liquefiable (i.e., Saturated) Embankment Fill	31	380	0.25	2.5	0.5	0.75	2	0.65	0.4
Potentially Liquefiable Foundation Soils (Alluvium)	34	150	0.08	1.2	0.5	0.75	2	0.78	0.4



Input Earthquake Record:

PGA=0.055g. Three earthquake records were obtained from a site specific hazard analysis but for this presentation only the short duration record is used.





MIDAS

Dam Crest Displacement Histories

Negative sign for the horizontal direction indicates toward the downstream side; and negative sign for the vertical direction indicates settlement.





Mean Effective Confining Pressure P Histories: P reduced some but not close to liquefaction when P should be close to zero (0).

Left figure is for a zone near the downstream toe in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable foundation layer; and right figure is for a zone in the liquefiable found





Dam Crest Horizontal Acceleration: the input acceleration (slide 32) was amplified more than two times









Result Summary

- Dam embankment experience some shake but with very limit permanent displacements
- Some excess pore pressure generated in the liquefiable foundation and embankment layers but not enough to cause liquefaction
- This result seems reasonable as the input motion has a pga of 0.055g only

