

**Implementation and three dimensional  
example applications of a bounding  
surface hypo-plasticity model for sand  
as a C++ UDM for *FLAC*<sup>3D</sup>**

by Fenggang Ma  
Zhi-Liang Wang

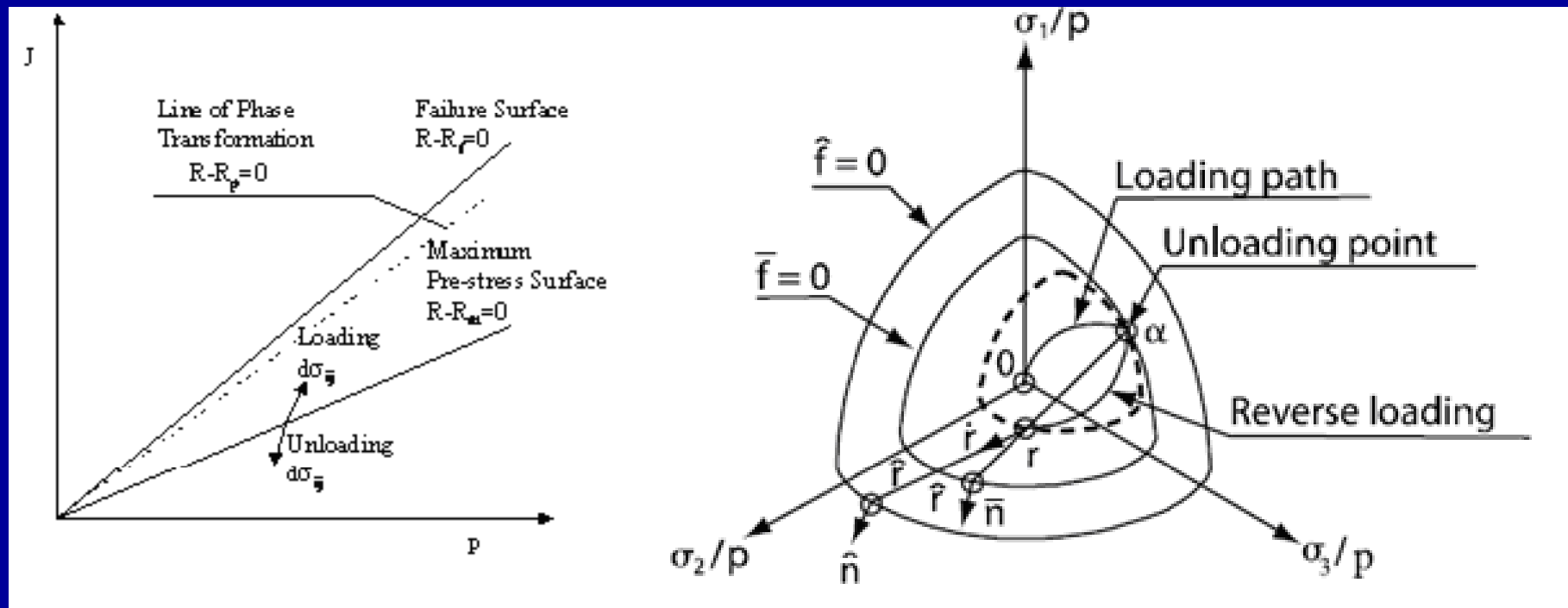
Minneapolis, Aug. 25 – 27, 2008

# Introduction

Demonstrating the capability of Wang model as a C++ UDM with FLAC<sup>3D</sup> in different applications:

1. 3D deformation of a zone using both stress and strain controlled loading conditions;
2. Liquefaction analysis of a Simplified 3D earth dam under cyclic loading; and
3. Liquefaction analysis of a real earth dam (not included in this paper)

# Wang Model



Major advantages:

- Captures the fundamental behaviors of sandy soil under monotonic and cyclic loadings
- Of the 15 model parameters, only 8 are needed for engineering applications.
- All 8 parameters can be calibrated from lab or in-situ tests, such as the N value

# A Single Zone Under Strain Controlled Monotonic Loading

$\varphi$	$c=Mc$ $/Me$	$R_p/$ $R_f$	$G_0$	$\lambda$	$\nu$	$h_p$	$k_{rc},$ $k_{re}$	$h_{rc},$ $h_{re}$	$a$	$b_c,$ $b_e$	$d$	$\alpha$	$z_n$	$z_d$
36.5	0.8	0.68	70	(0.02)	0.3	(35.0)	0.272, 0.0945	0.28, 0.14	1	1	1.2	0	0.5	0.85

Wang, Z.L. 1990. Bounding Surface Hypo-plasticity Model for Granular Soils and Its Application. Ph.D. Dissertation for the University of California at Davis, U.M.I. Dissertation Information Service, Order No. 9110679, 1990.

Yamada, Y. & Ishihara, K. 1979. Anisotropic Deformation Characteristics of sand under three dimensional stress conditions. *Soil and Foundations*. 19(2): 79-93.

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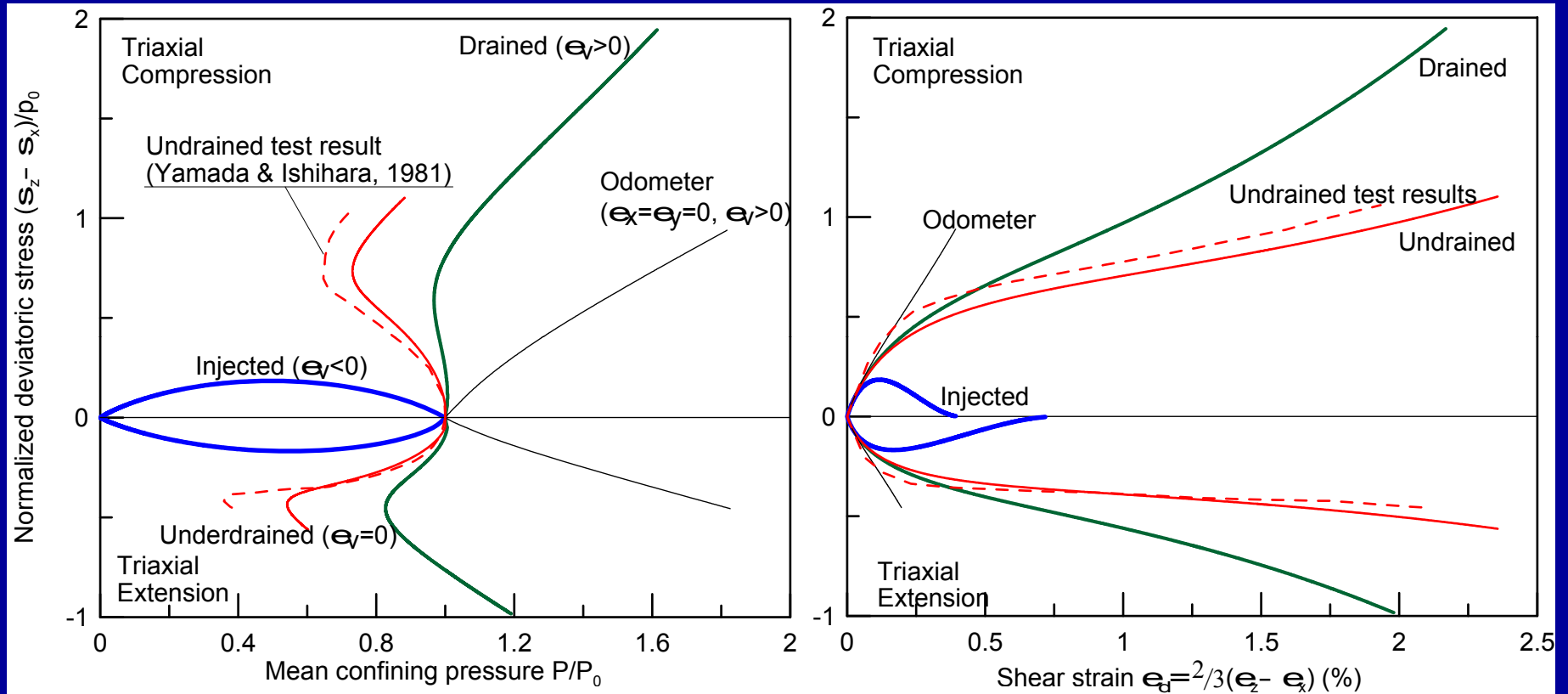
Strain controlled monotonic loading conditions in a cubic zone.

Condition	Undrained ( $\epsilon_v=0$ )	Drained ( $\epsilon_v>0$ )	Injected ( $\epsilon_v<0$ )
Compression ( $\sigma_z-\sigma_x) > 0$	$\epsilon_z > 0$ $\epsilon_x=\epsilon_y = -\epsilon_z / 2$	$\epsilon_z > 0$ $\epsilon_x=\epsilon_y > -\epsilon_z / 2$	$\epsilon_z > 0$ $\epsilon_x=\epsilon_y < -\epsilon_z / 2$
Extension ( $\sigma_z-\sigma_x) < 0$	$\epsilon_z < 0$ $\epsilon_x=\epsilon_y = -\epsilon_z / 2$	$\epsilon_z < 0$ $\epsilon_x=\epsilon_y > -\epsilon_z / 2$	$\epsilon_z < 0$ $\epsilon_x=\epsilon_y < -\epsilon_z / 2$

Note: Volumetric strain  $\epsilon_v > 0$  means contraction.

- The numerical model tests do not explicitly include water material, but the predicted stresses are effective stresses.
- Physically, injected condition represents soil sample expansion due to water injecting into it.
- The computed effective stress paths for the undrained condition (represented by  $\epsilon_v = 0$ ) are compared with test results (Yamada & Ishihara 1981)

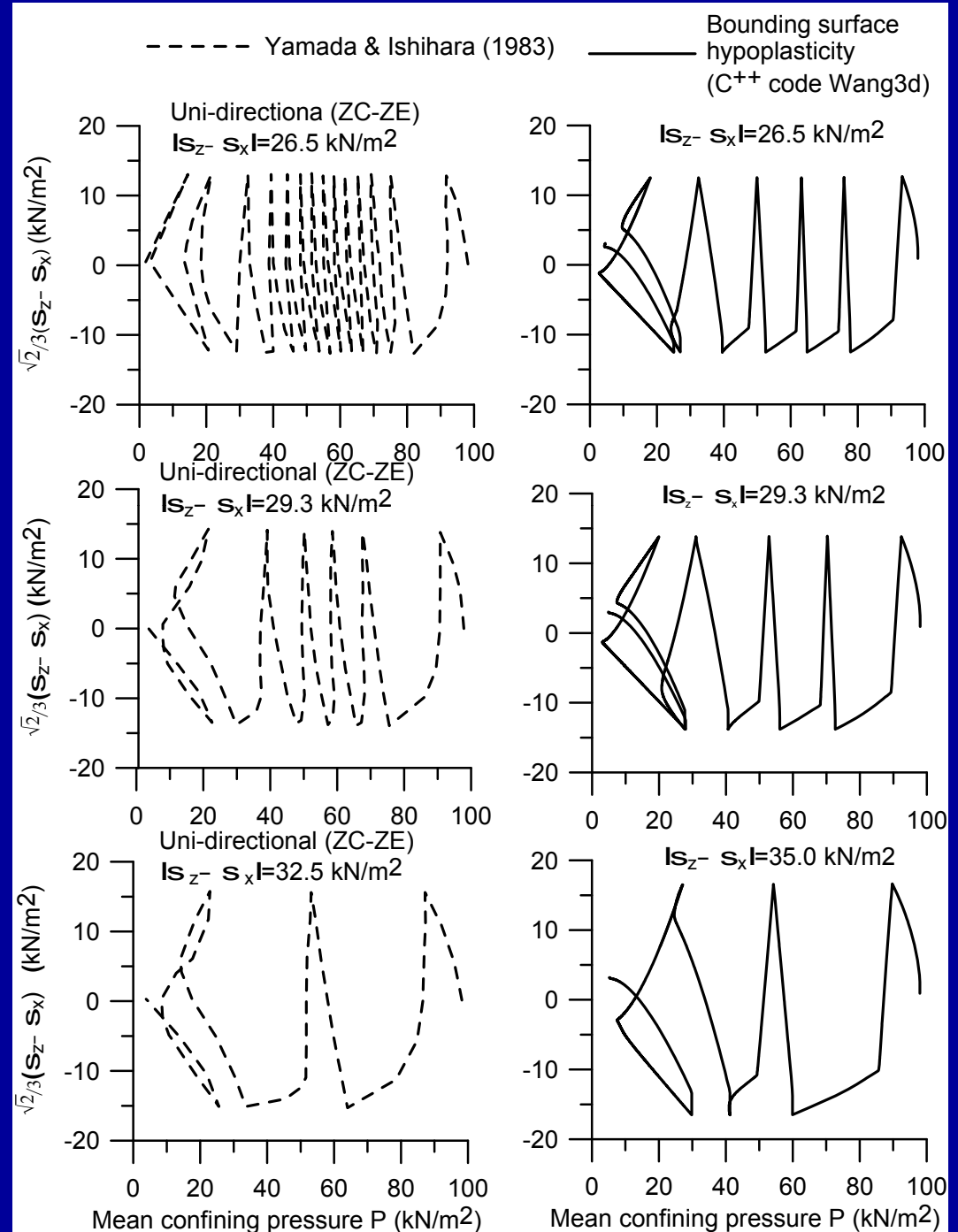
# Cont.



- Injected condition: water accumulates under a low permeability layer Impeding dissipation of excess pore water pressure;
- Different soil behaviors under triaxial compression and extension;
- In undrained condition sand experiencing contraction-dilation, then approaching failure.

# Stress controlled cyclic loading response

- Predictions on the left obtained from a single set of parameters – table on slide 4
- Mean stress reduction higher in the half cycle under triaxial extension than that in the half cycle under triaxial compression
- Shear induced plastic deformation both in loading and unloading phases
- Captured the loading-dilation and unloading-contraction behaviors when crossing the phase transformation line
- Yamada, Y. & Ishihara, K. 1983. Undrained Deformation Characteristics of sand in multi-dimensional shear. *Soil and Foundations*. 23(1): 61-79.



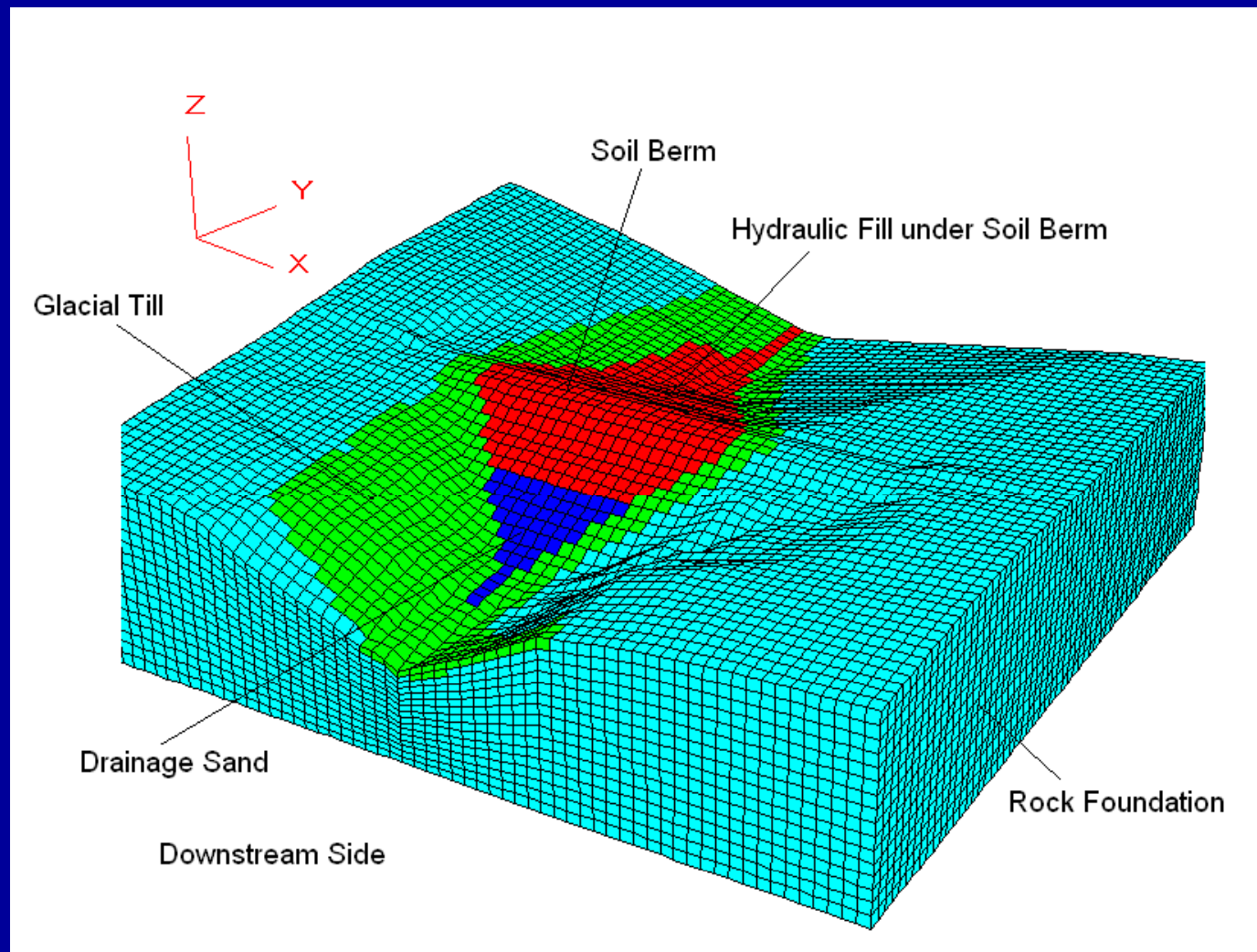
# Liquefaction Analysis of a Hydraulic Fill Earth Dam—not part of the paper

Dam: 200 ft long and 63 ft high

Created using Topo.fis from Itasca Fish lab, draw back is layer within dam can only be modeled approximately.

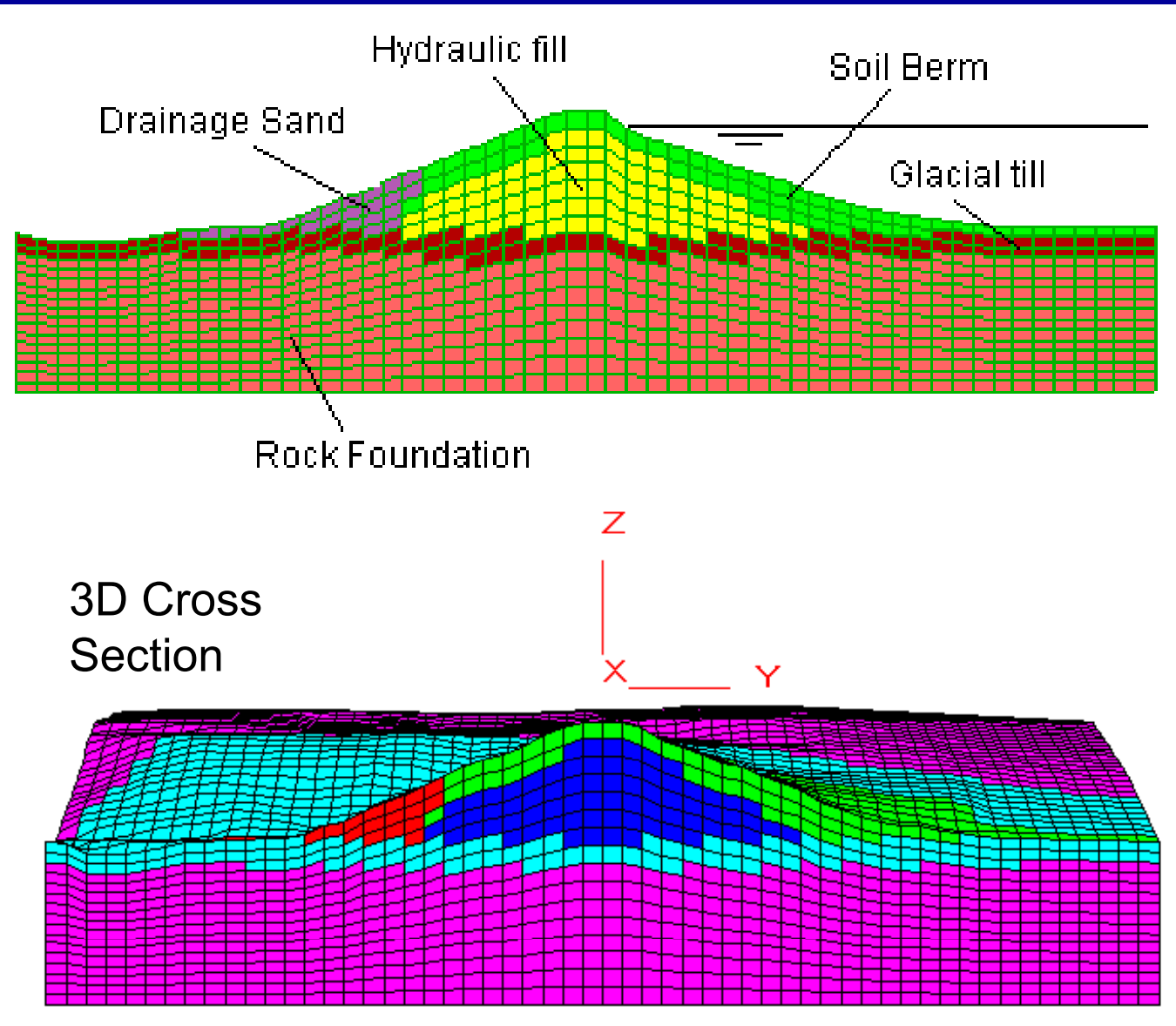
Dimensions: x=620 ft, y=560 ft, z elevations from 2140'-2306'

Tried first using 3DShop 30 day trial, mesh generated had not ideal geometry as result not fine enough zone in the dam core and dynamic time step in the 1e-6 range.



# 2D Model

Physical dimension very close and number zones the same 2D mesh and 3D cross section.



# Static Stress State before Seismic Analysis

- First, the FLAC dam model was set up with static balance being achieved
- Then, a seepage analysis was performed to develop the phreatic surface within the embankment
- This was followed by “turning on” the mechanical effect of seepage to account for the associated effective stress changes within the embankment
- With these steps the FLAC numerical model was judged to reasonably approximate the stress state before the earthquake was applied

# Material Properties and Model Parameters

## Material Properties

Properties	Rock	Glacial till	Hydraulic fill	Drainage sand	Soil berms
Unit Weight (pcf)	150	145	115	120	125
Cohesion (psf)	500	100	0.0	0.0	500
Friction angle (°)	45	40	37	40	45
Shear Modulus (ksf)	6600	6000	800	4900	4900
Bulk Modulus (ksf)	8800	8000	2000	7000	7000
Porosity	0.10	0.14	0.45	0.40	0.10

## Wang Model Parameters

Soil	$G_0$	$h_{rc} = h_{re}$	$\phi$	$k_{rc} = k_{re}$	$d$	$R_p/R_f$	$\nu$	$\lambda$
Hydraulic fill	171	0.09	37	0.5	1.5 and 2.0	0.75	0.32	0.012
Drain Sand	324	0.284	40	100	100	0.75	0.30	0.012
Soil Berm	306	0.388	40	100	100	0.75	0.30	0.012

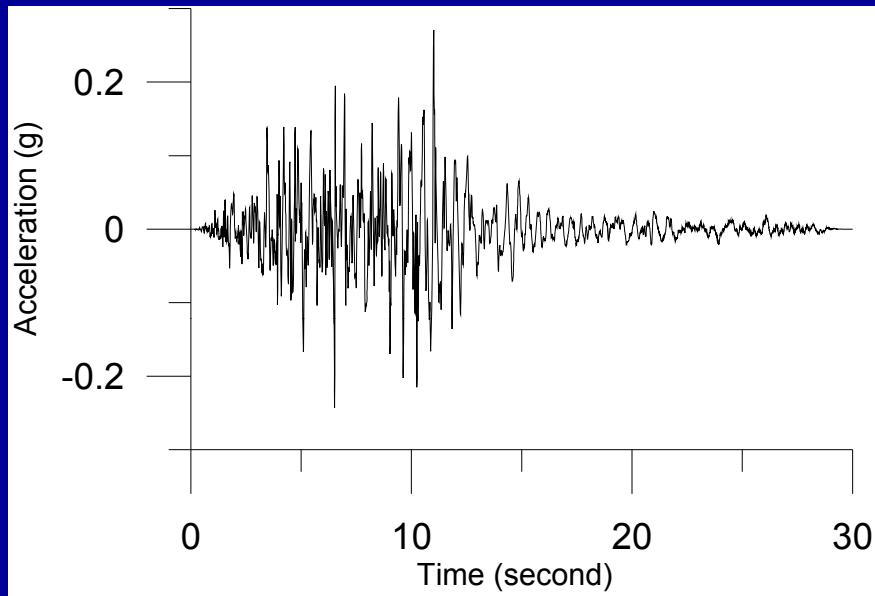
Wang model parameters are dimensionless

# Earthquake Records

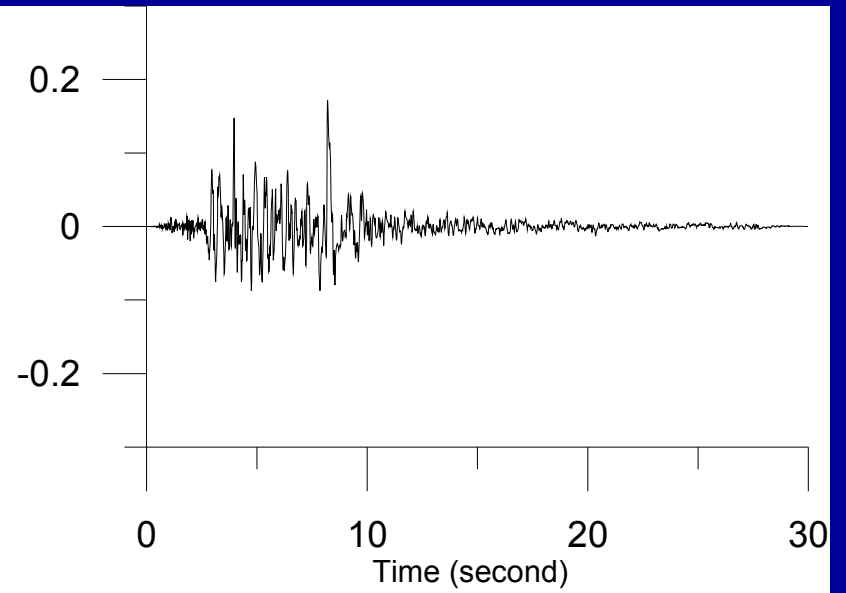
The USGS Seismic Hazard web site (<http://earthquake.usgs.gov/hazmaps/>) was used to determine the scenario earthquakes that contribute to the seismic risk at the site

For 0.5-second period spectral accelerations (approximate fundamental period of the dam-foundation system) at a return period of 2475 years, the primary contributors to the seismic risk are near-field earthquakes of moment magnitudes ( $M_w$ ) 6.4 to 6.6.

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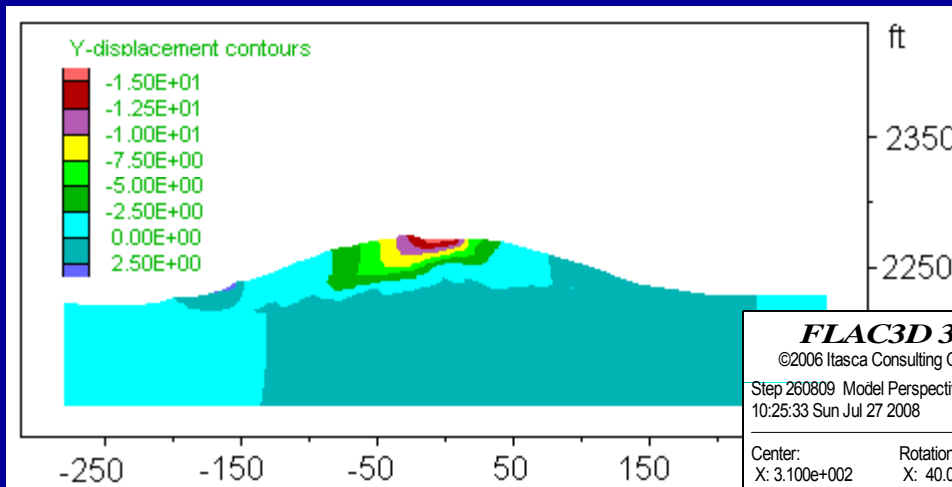


(a) 1980 Ca Mammoth Earthquake



(b) 1994 Ca Northridge Earthquake

# Predictions Results



Vertical y-displacement contour of FLAC at time = 30 se

## FLAC3D 3.10

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Step 260809 Model Perspective  
10:25:33 Sun Jul 27 2008

Center:	Rotation:
X: 3.100e+002	X: 40.000
Y: 0.000e+000	Y: 0.000
Z: 2.223e+003	Z: 330.000
Dist: 1.994e+003	Mag.: 0.8
	Ang.: 22.500

### Contour of Z-Displacement

Magfac = 1.000e+000  
Live mech zones shown

Dark Blue	-2.8216e+000 to -2.5000e+000
Blue	-2.5000e+000 to -2.0000e+000
Light Blue	-2.0000e+000 to -1.5000e+000
Green	-1.5000e+000 to -1.0000e+000
Yellow-Green	-1.0000e+000 to -5.0000e-001
Yellow	-5.0000e-001 to 0.0000e+000
Orange	0.0000e+000 to 5.0000e-001
Red	5.0000e-001 to 5.7771e-001

Interval = 5.0e-001

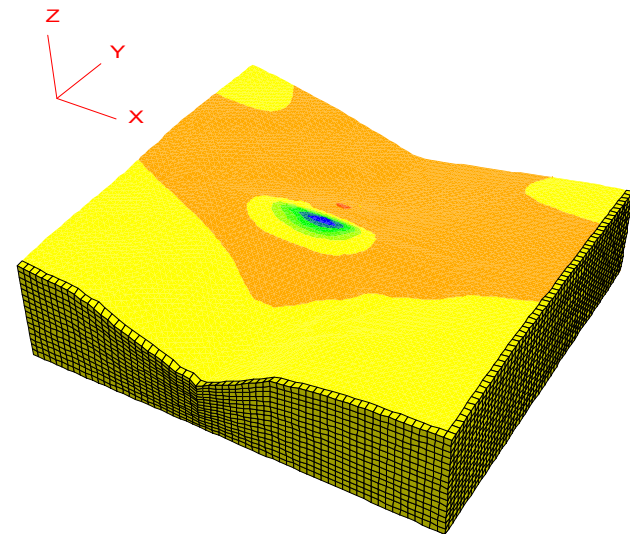
### Surface

Magfac = 1.000e+000  
Live mech zones shown

### Surface

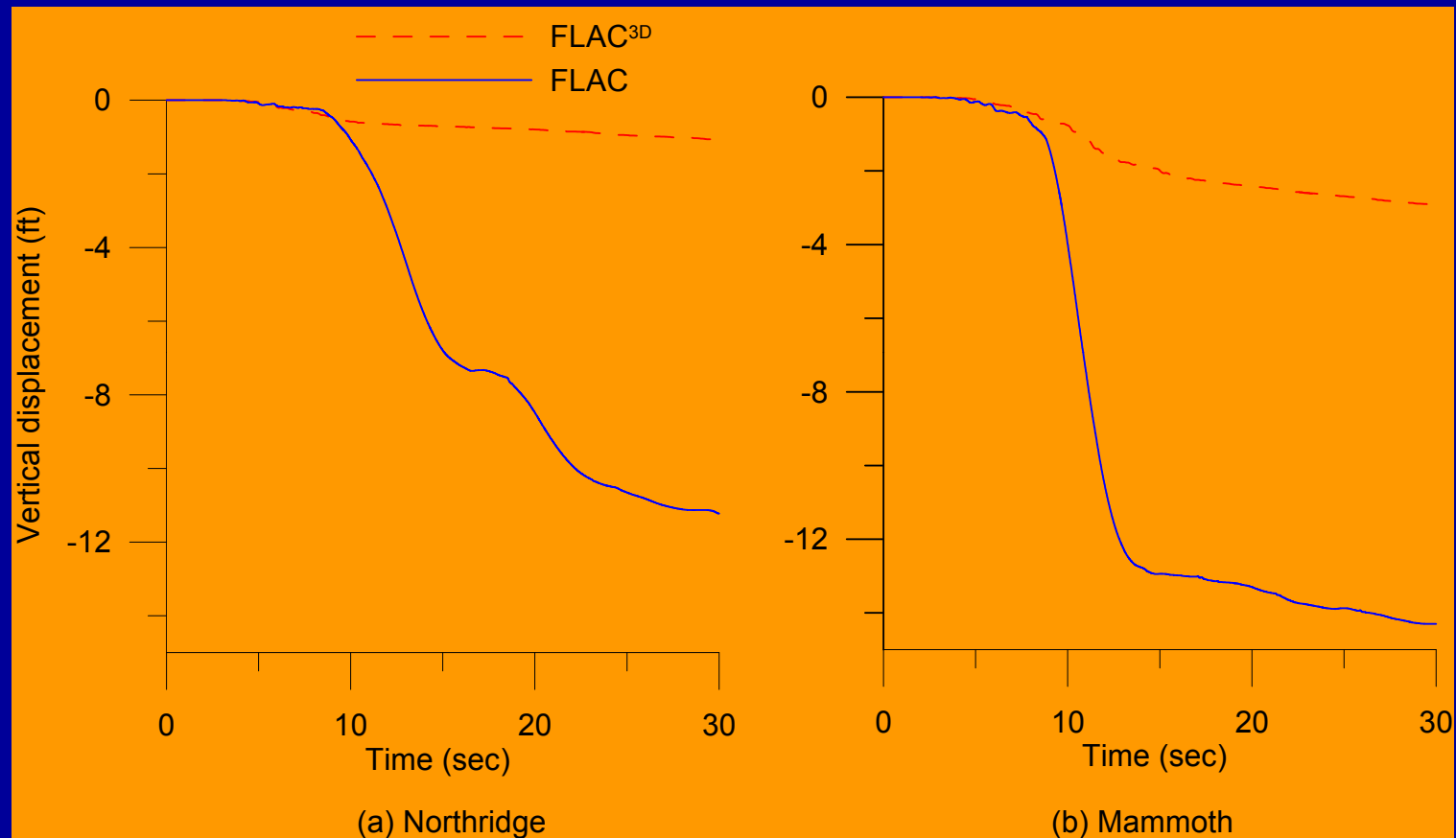
Magfac = 1.000e+000  
Live mech zones shown

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Minneapolis, MN USA



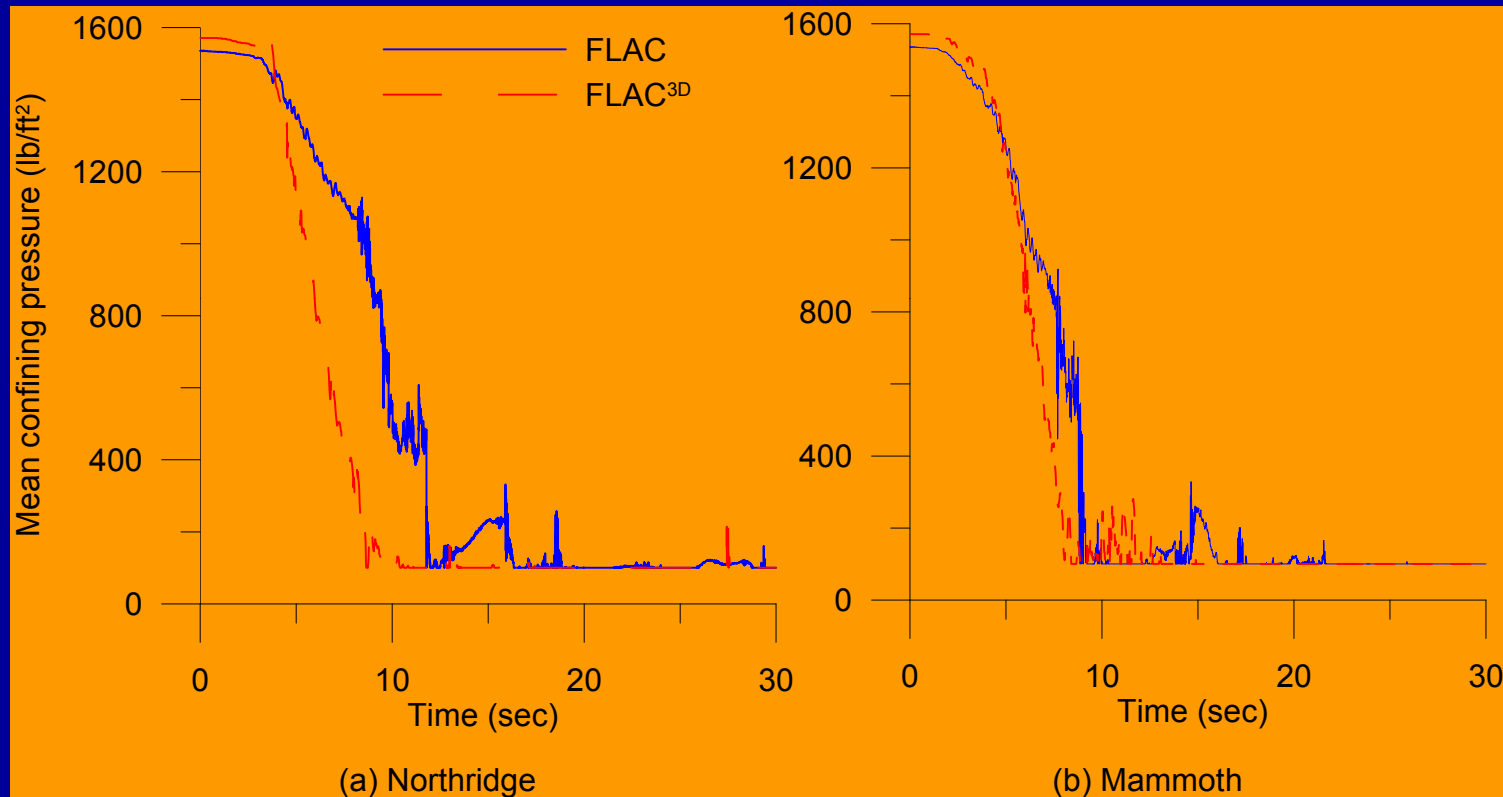
Vertical z-displacement contour of FLAC at time = 30 second

# Dam crest vertical displacement histories



The vertical displacement at the dam crest was almost 3 time larger (2.2 vs. 0.8 ft) using Mammoth quake than using Northridge quake predicted by FLAC<sup>3D</sup>. However, the vertical displacement are almost the same predicted by FLAC at the end of both earthquakes, although the PGA of Mammoth is about 1.6 times larger than Northridge and both earthquakes have approximate 8-second strong motion.

# Liquefaction zones



Although the mean confining pressure reduced faster in the 3D than the 2D model, the vertical displacement at the dam crest predicted by FLAC3D did not show sudden increase due to the liquefaction.

# Potential Sliding Surface

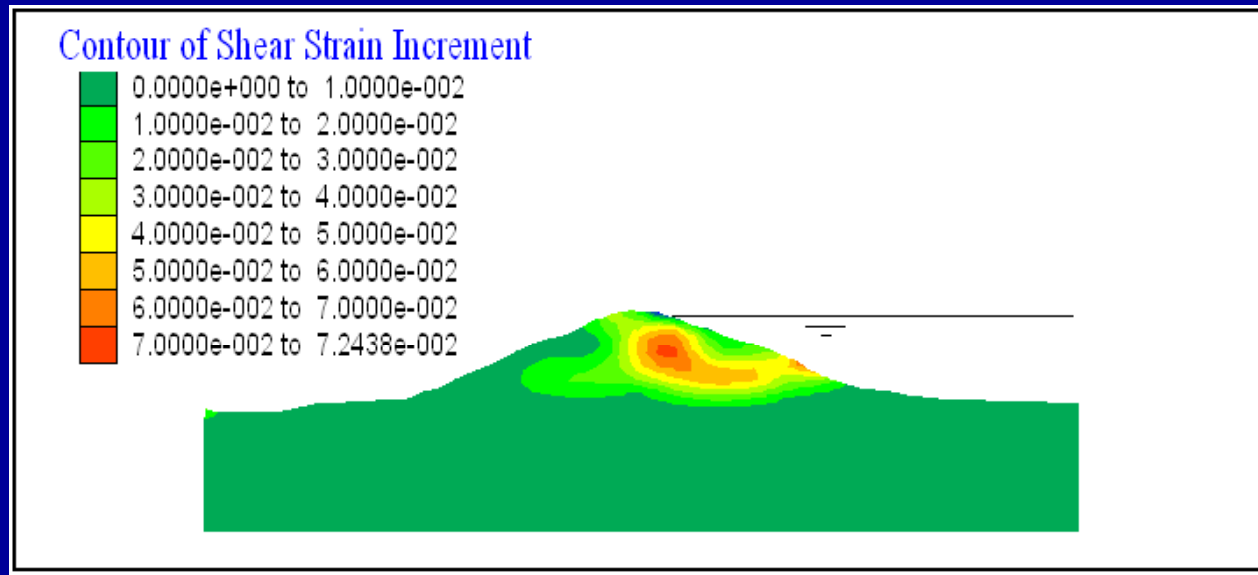
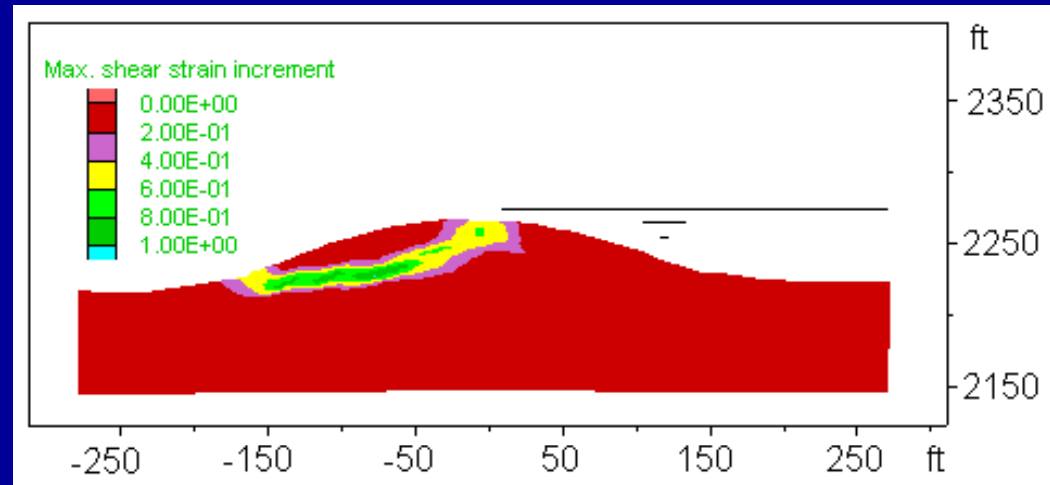
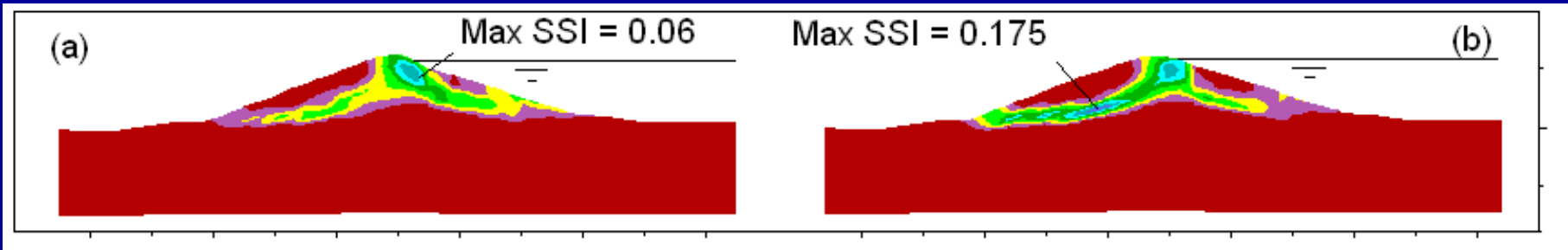


Figure 12 SSI contour at the end of the Mammoth seismic loading by FLAC<sup>3D</sup> at x=

# Cont.



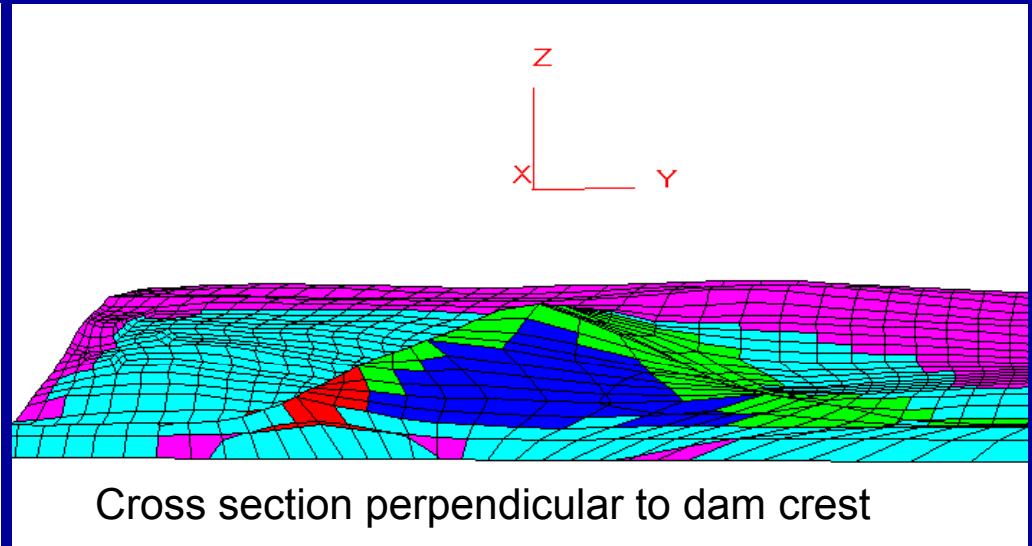
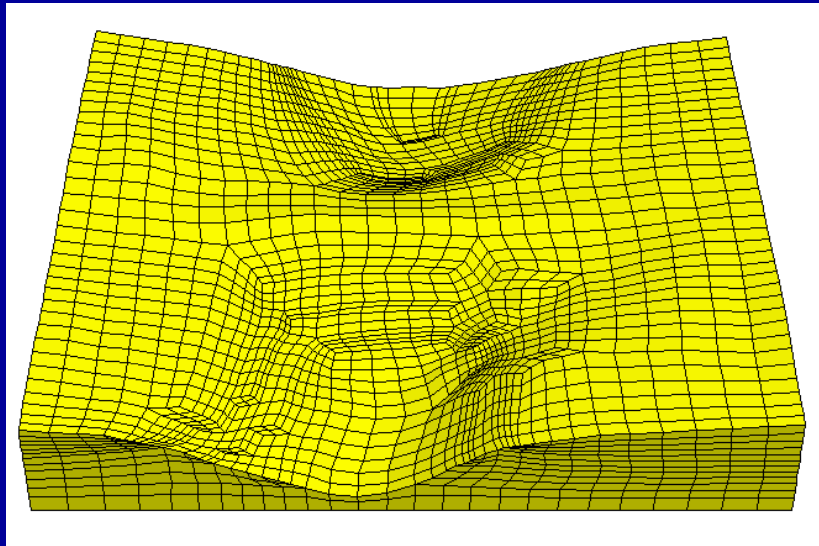
SSI contour at (a) 9 second with corresponding dam crest  $y_{dis}=2$  ft; (b) 10 second with corresponding dam crest  $y_{dis}=5$  ft of Mammoth earthquake by FLAC.

- FLAC2D, the potential sliding surfaces evolved from potential sliding surfaces towards both the up and downstream directions when the embankment experienced relatively smaller deformation, to the final dominating one towards the downstream direction when the embankment experienced major deformation.

# Grid Generations and problems related:

1. Automatic mesh generation programs, such as 3DShop.
2. Drawbacks discovered: no easy way to control zone density at the locations important to the problems, such as liquefiable zones of an earth dam.
3. No practicable way to control the shape of individual zone. Some odd zone shape makes time step very small. Thus dynamic analysis becomes impractical to run

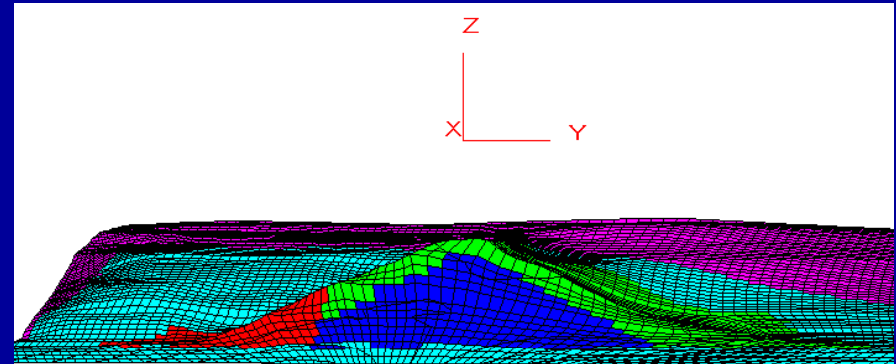
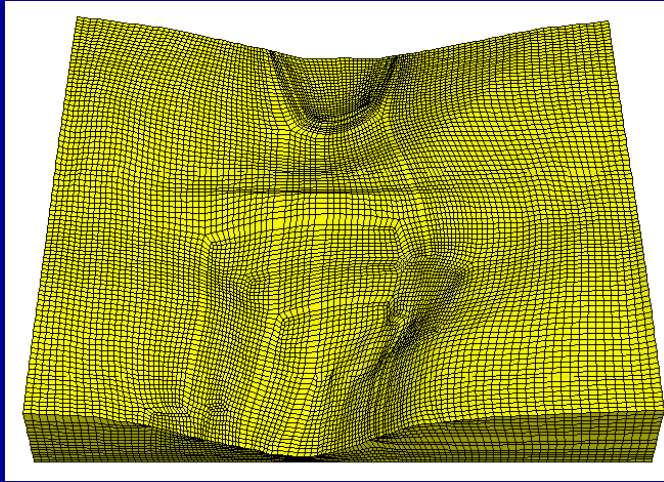
# *Example one of 3DShop: 8032 zones and 9958 grid-points*



Cross section perpendicular to dam crest

With too few zones in the center of the dam where liquefaction is supposed to happen. Still the dynamic time step= $1.125 \times 10^{-5}$ . with damping set at 1% Rayleigh mass only.

## Example two of 3DShop: 117483 zones and 130081 grid-points



Cross section perpendicular to dam crest

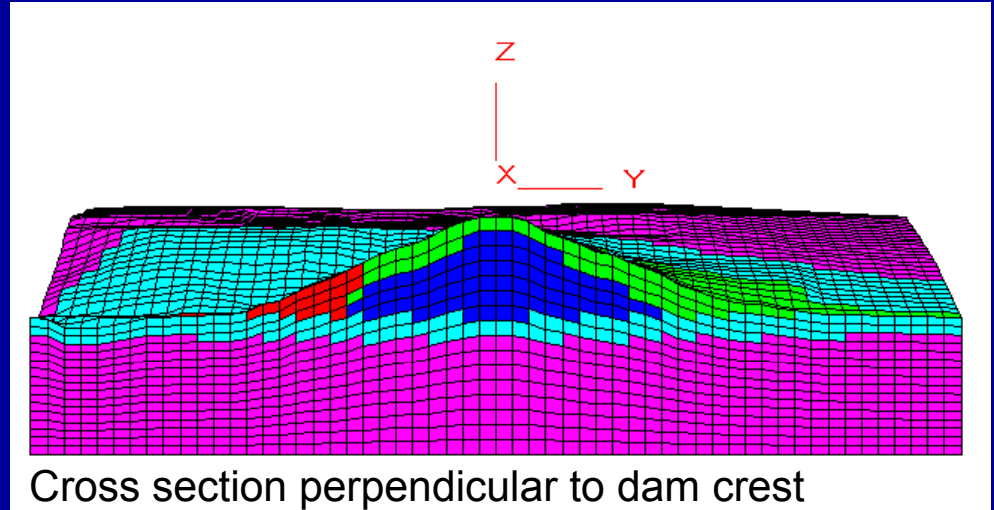
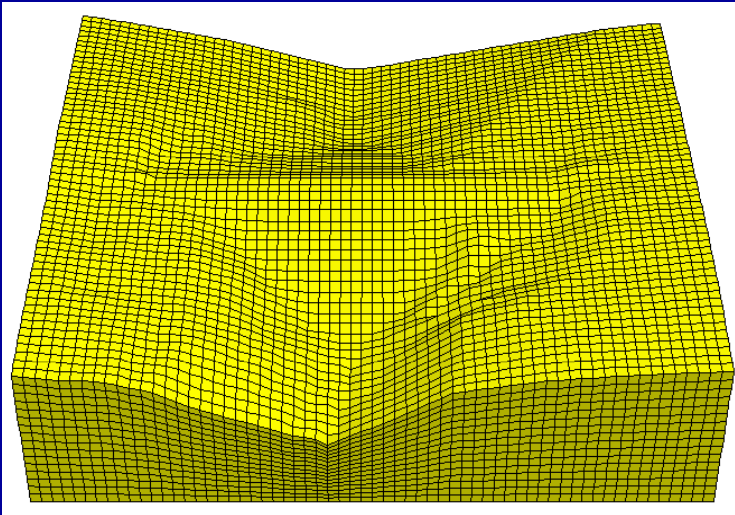
With more zones at the dam center. However, zone shape varies too much with some very odd shaped zones, which made the dynamic time step =  $3.191 \times 10^{-6}$  with damping set at Rayleigh=1% mass only. It would have taken 2.5 month to finish one run on a Dell Duo Quad core PC – almost impossible.

# Changing Course to 3D mesh generation

Switched to topographic based method: input the topographic grid covering the dam site. Generate the 3D mesh under the topo.

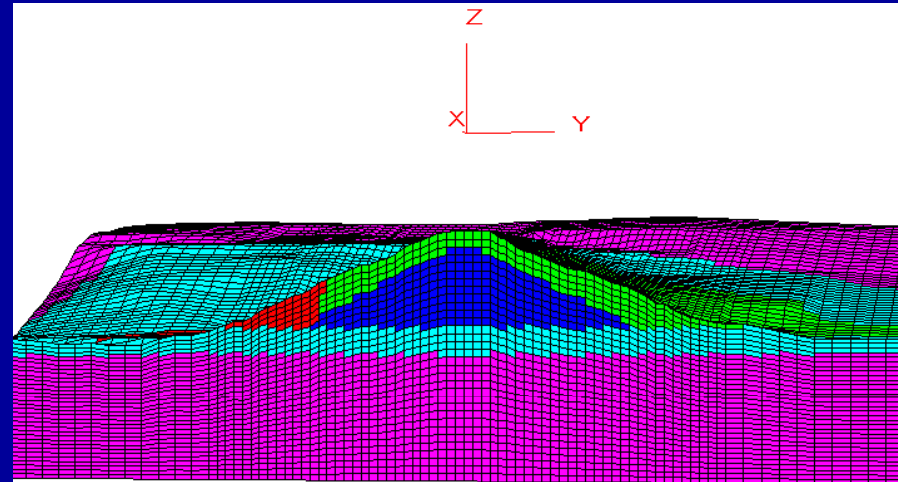
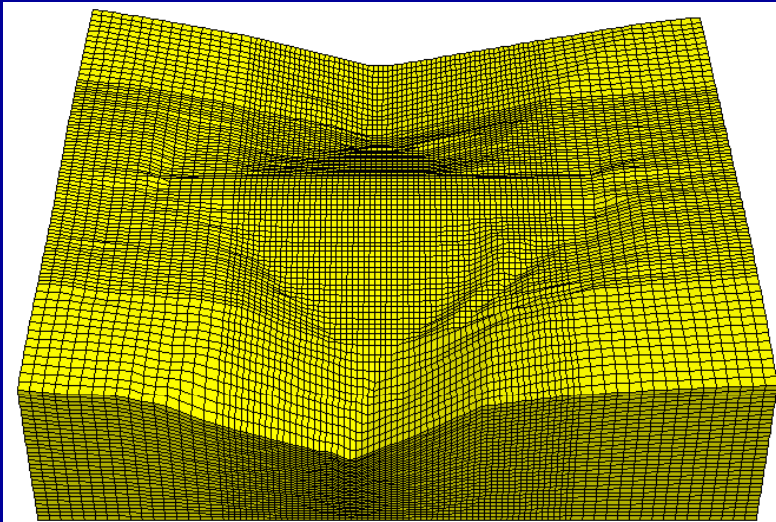
- Benefits: able to control the zone density and shape at the location important, such as the dam. Thus can control the dynamic time step
- Limitations: zones at z direction do not change, so a relatively thick foundation layer must be included

# Example 1 of topo method: 59392 zones and 69479 grid-points



Uniformly density of zones and standard shape with dynamic time step =  $1.801 \times 10^{-4}$  and damping at 1% Rayleigh to both mass and stiffness matrixes

## Example 2 of topo method: 253184 zones and 267003 grid-points



Cross section perpendicular to dam crest

Denser zones at the dam and less zones rest of the model and standard shape with dynamic time step =  $5.401 \times 10^{-5}$  and damping at 1% Rayleigh to both mass and stiffness matrixes

# Summary of Grid Generation

Mesh	Zones	Grid-points	1% Rayleigh Damping		Dynamic time step
			Mass	Stiffness	
3DShop 1	8032	9958	Yes	No	$1.125 \times 10^{-5}$
3DShop 2	117483	130481	Yes	No	$3.191 \times 10^{-6}$
Topo 1	59392	69497	Yes	Yes	$1.801 \times 10^{-4}$
Topo 2	253184	267003	Yes	Yes	$5.401 \times 10^{-5}$

The extreme shape of zones from 3DShop causes very small dynamic time step with few zones overall, especially at locations needed attention.

# Conclusions

1. Using the 2D FLAC and FLAC3D , incorporated with a bounding surface plasticity model, the dynamic analyses predicted liquefaction for an earthfill dam built across a narrow valley.
2. FLAC predicted up-to 12 feet displacement at the dam crest. Because there are only 10 ft freeboard at normal pool of this reservoir, major retrofit would be warranted for the dam to improve the dam performance under seismic loading. However, since
3. FLAC3D only predicted slightly more than 2-ft displacement, no retrofit effort seems necessary.
4. Due to the drastic difference obtained from the 2D and 3D analyses, more analyses should be done to investigate effect of more earthquake records and a finer mesh before a confident conclusion can be made.

# Questions:

- Call Fenggang Ma at (509) 329-3540 or email at [fema461@ecy.wa.gov](mailto:fema461@ecy.wa.gov) or
- Email Zhi-Liang Wang at [ZLWang@geomatrix.com](mailto:ZLWang@geomatrix.com)
- New Reference: F.G. Ma, J. LaVassar and Z.-L. Wang. 2008. THREE DIMENSIONAL VERSUS TWO DIMENSIONAL LIQUEFACTION ANALYSES OF A HYDRAULIC FILL EARTH DAM. Paper to be included in the CD of The 14<sup>th</sup> World Conference on Earthquake Engineering, October 12-17, Beijing, China.