2-D Liquefaction Evaluation with *Q4Mesh*

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Presentation Outline

- Liquefaction Evaluation Overview
- Overview of Quad4m
- Overview of Q4Mesh
- Liquefaction Evaluation with Q4Mesh
- Example Q4Mesh Liquefaction Model

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Liquefaction Evaluation Overview

- Two-dimensional seismic response and liquefaction evaluations of earth structures and soil deposits can be complex and time intensive

- Techniques available for their evaluation range from simplified models to advanced constitutive and non-linear models

Liquefaction Evaluation Overview

- Simplified Models
  - Simplified Seed and Idriss procedures
  - 1-D equivalent linear SHAKE type analysis at multiple locations
  - Evaluations can be made quickly
- Advanced Models
  - Most accommodate the non-linear behavior of soils
  - Evaluations are more complex and time intensive
- Equivalent Linear Models
  - Can be used to approximate the actual nonlinear behavior of the soil
  - Quad4m (two-dimensional seismic response)

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Overview of Quad4m

- Quad4m (A Computer Program For Evaluating The Seismic Response Of Soil Structures)
  - U.C.Davis, 1993
  - by Martin Byrd Hudson, I.M.Idriss, and Mohsen Beikae
- MODIFIED FROM QUAD4, 1973
  - by I.M. Idriss, J. Lysmer, R. Hwang and H. Bolton Seed

Overview of Quad4m

- The Quad4m analysis numerically models a continuum with a finite number of elements interconnected at their common nodes

- The analysis is done exclusively in the time domain, and the response of the soil deposit follows the same approximation of nonlinear hysteretic manner that is conventional SHAKE (1-D) analysis when subject to loading

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Overview of Quad4m

- Direct numerical integration by the software is used to solve an equation of motion for the finite element mesh to determine the developed:

  - Peak Element Shear Stresses (sig-xy, τ_{max})
  - Peak Element Shearing Strains (eps, γ_{max})
  - Peak Element Principle Stresses (sig-x, sig-y)
  - Peak Nodal Accelerations (a_{max})

Overview of Q4Mesh

- The Q4Mesh program is a modification of the WinMesh program to create and analyze Quad4m data

- Q4mesh was developed by ERDC (Engineering Research and Development Center) at WES (Waterways Experimental Station) with some assistance provided from the USACE Sacramento District

Overview of Q4Mesh

- Q4Mesh can be used to:
  - Create the Quad4m finite element mesh
  - Interpret the output files from Quad4m and two additional user files to conduct a liquefaction evaluation

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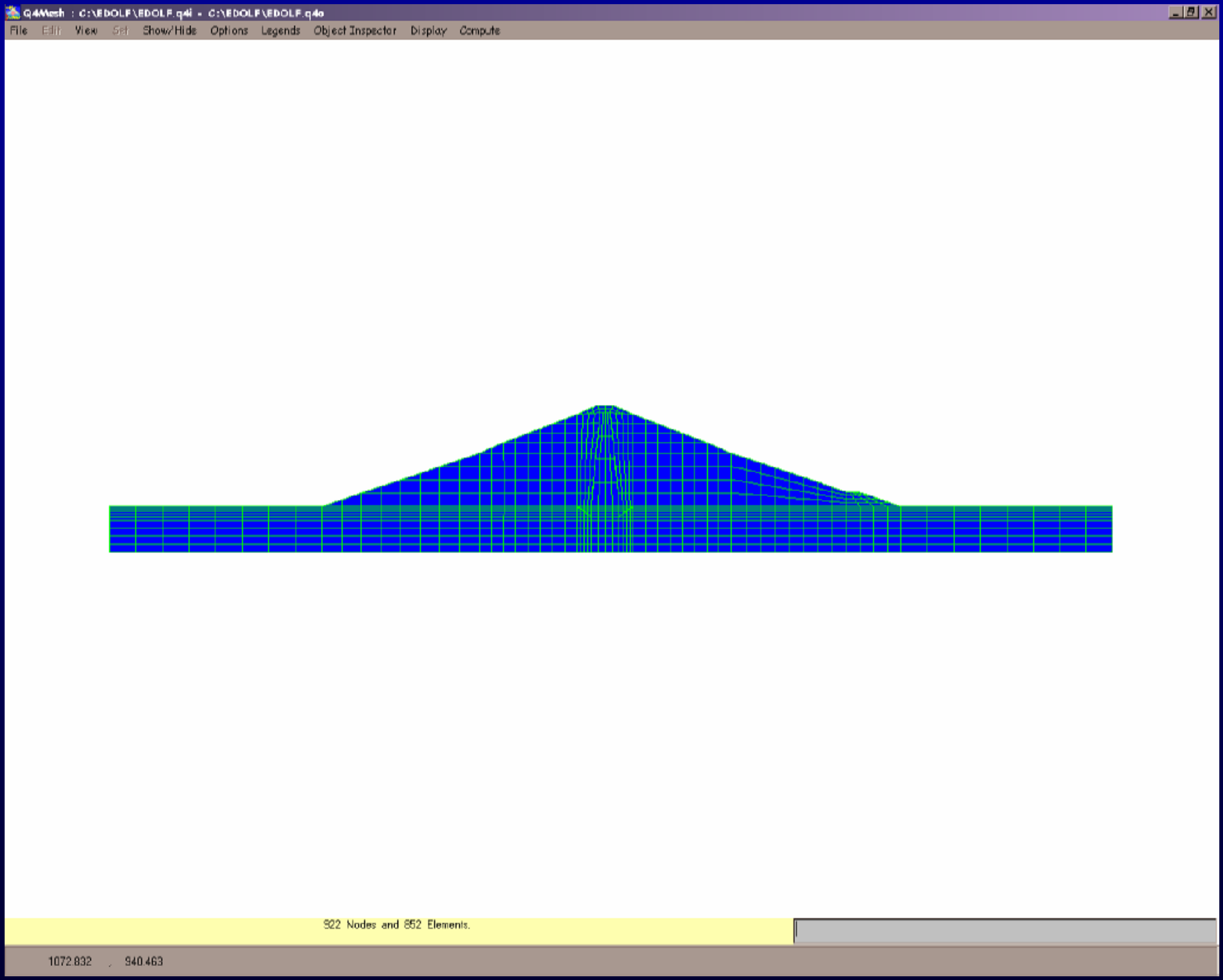
Overview of Q4Mesh

- Q4Mesh
  - (Main Screen)



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Overview of Q4Mesh

Additional Input Files for Q4Mesh

EDOLF_PHREATIC.dat - Notepad

File Edit Format Help

```
1) 6.75   0.28   0.0   1.0   135   130
2) 12
3) 700       550
1000      550
1131.3    590
1221.6    625.0
1316.9    662.5
1387.8    691.5
1410.3    691.5
1576.5    625
1739      570
1754      570
1815      550
2114      550
4) 6
5) 700     662.5
1316.9    662.5
1389.2    653.25
1415.75    582.875
1439     550
2114     550

1) magnitude, pga, fines (not used), factor of safety, sat_unit_weight, moist_unit_weight
2) Number of Ground Surface Points
3) Ground Surface X, Y Values
4) Number of Phreatic Surface Points
5) Phreatic Surface X, Y Values
```

Surface, Phreatic, and Earthquake File

EDOLF_N160_DATA.dat - Notepad

File Edit Format Help

```
1     50
2     50
3     50
4     45
5     50
6     50
7     50
8     10
9     15
10     20
11     10
12     15
13     20
14     60
Layer     Blowcount
```

Blowcount File

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Overview of Q4Mesh

- Basic Liquefaction Procedure Equation

$$F.S._{LIQ} = \left(\frac{CRR_{()}}{CSR_{()}}\right)[MSF][k_\sigma][K_\alpha]$$

CSR	(Cyclic Stress Ratio)
CRR	(Cyclic Resistance Ratio)
$K\sigma$	(Stress Correction
$K\alpha$	(Sloping Ground Correction)
MSF	(Magnitude Scaling Factor)

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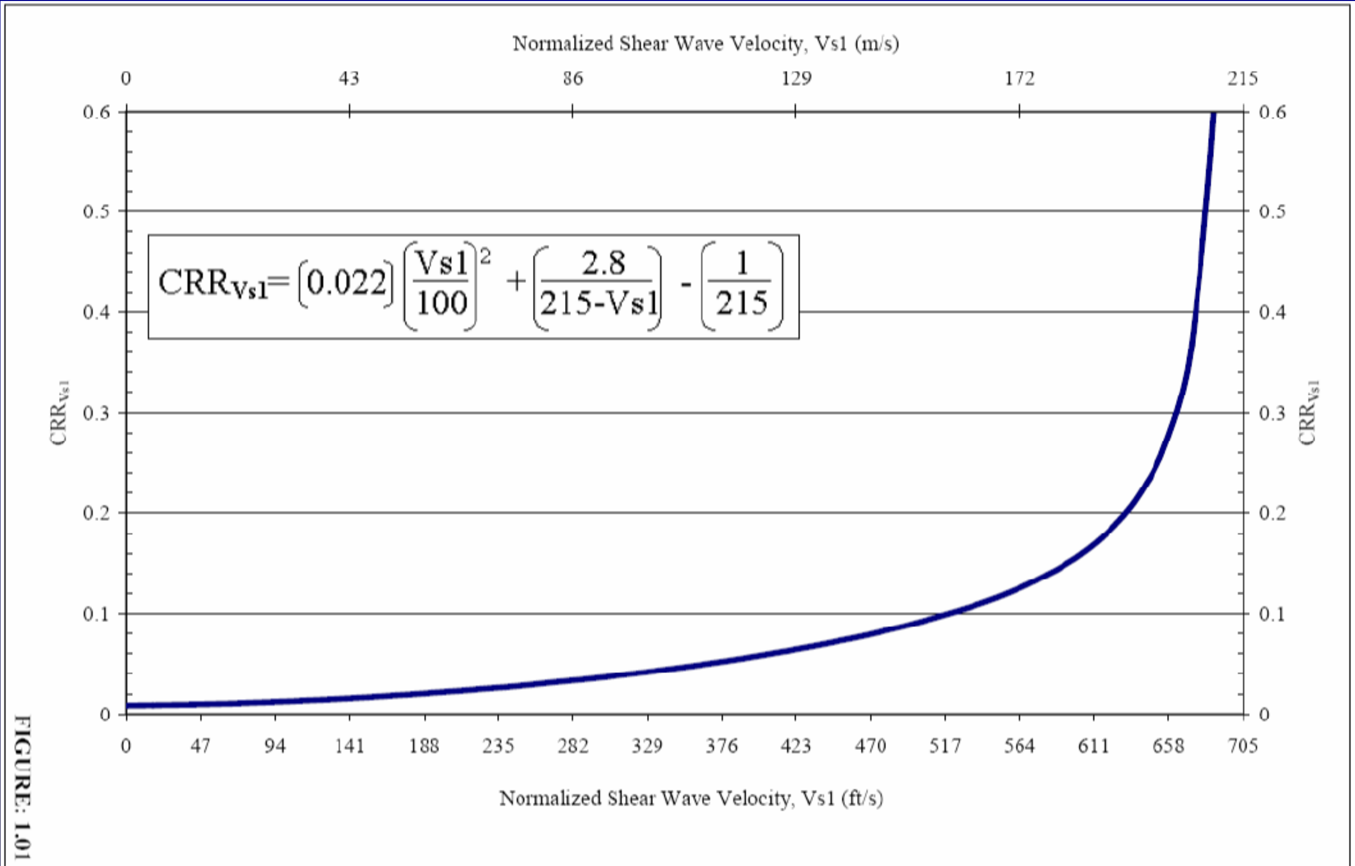
Example Q4Mesh Liquefaction Model

- Cyclic Resistance Ratio, CRR (Vs1 Data)



Cyclic Resistance Ratio, CRR, from Vs1

(Youd and Idriss, 2001)

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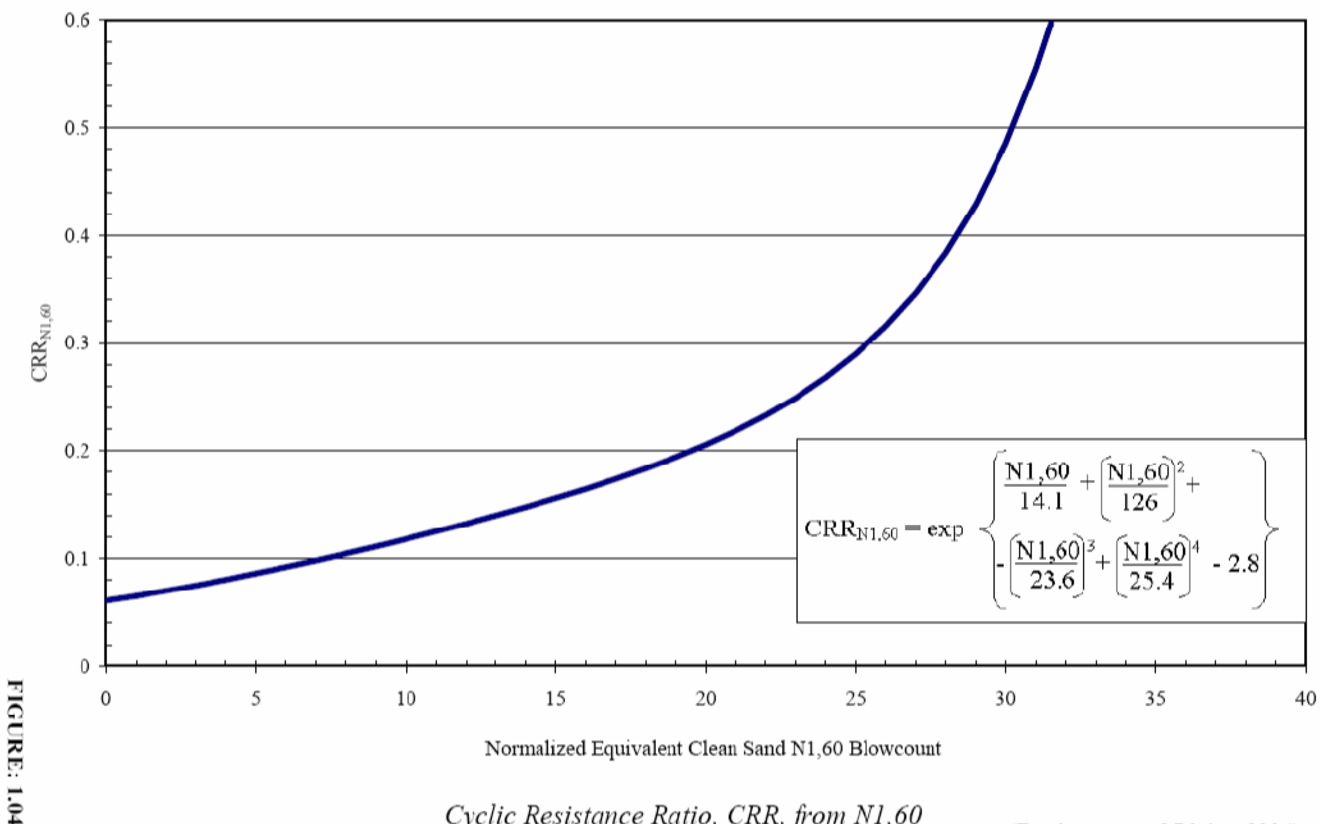
Example Q4Mesh Liquefaction Model

- Cyclic Resistance Ratio, CRR (N1,60 Data)



Cyclic Resistance Ratio, CRR, from N1,60

(Boulanger and Idriss, 2004)

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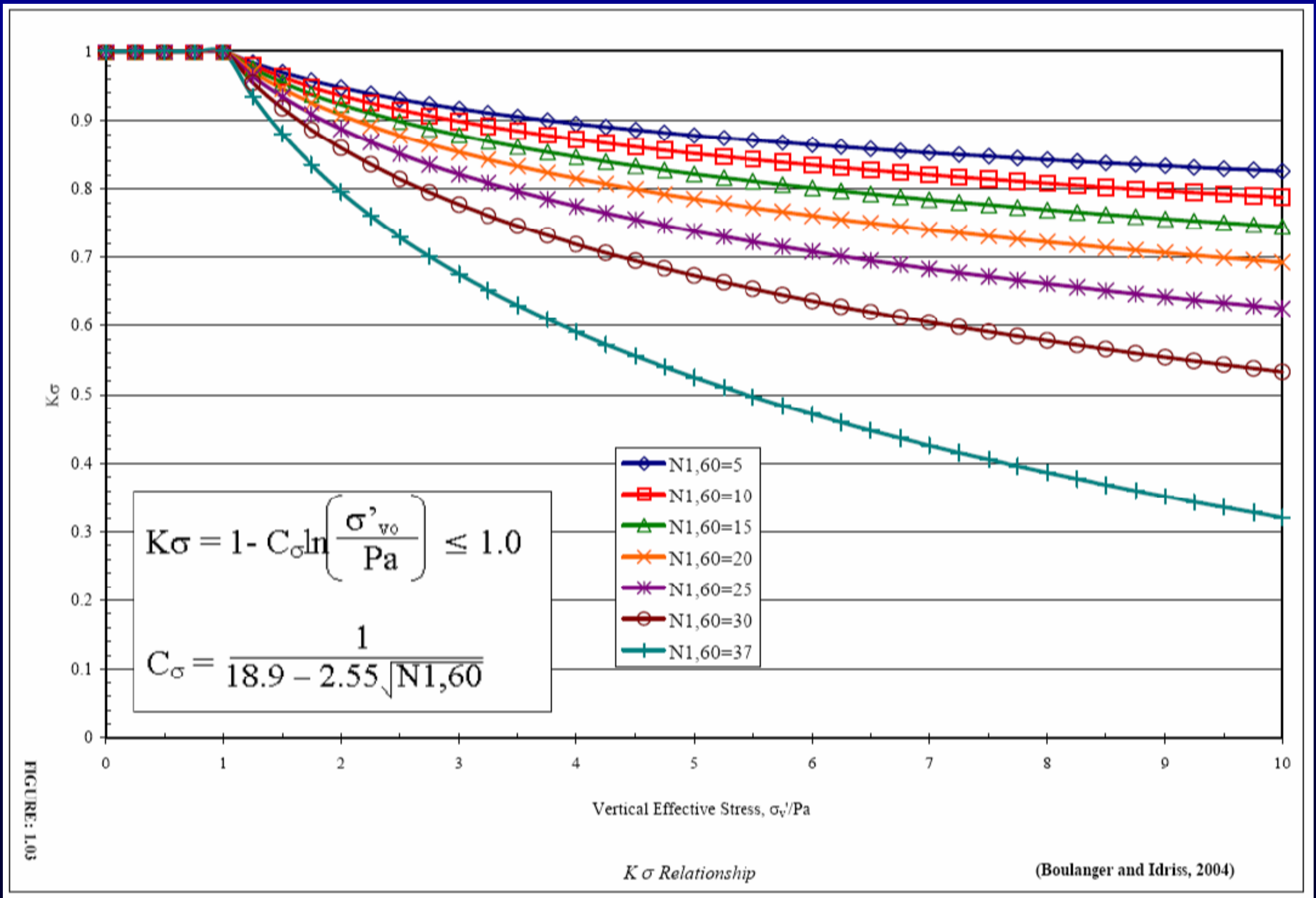
Example Q4Mesh Liquefaction Model

- Stress Correction Factor, Kσ



Default
Kα=1.0

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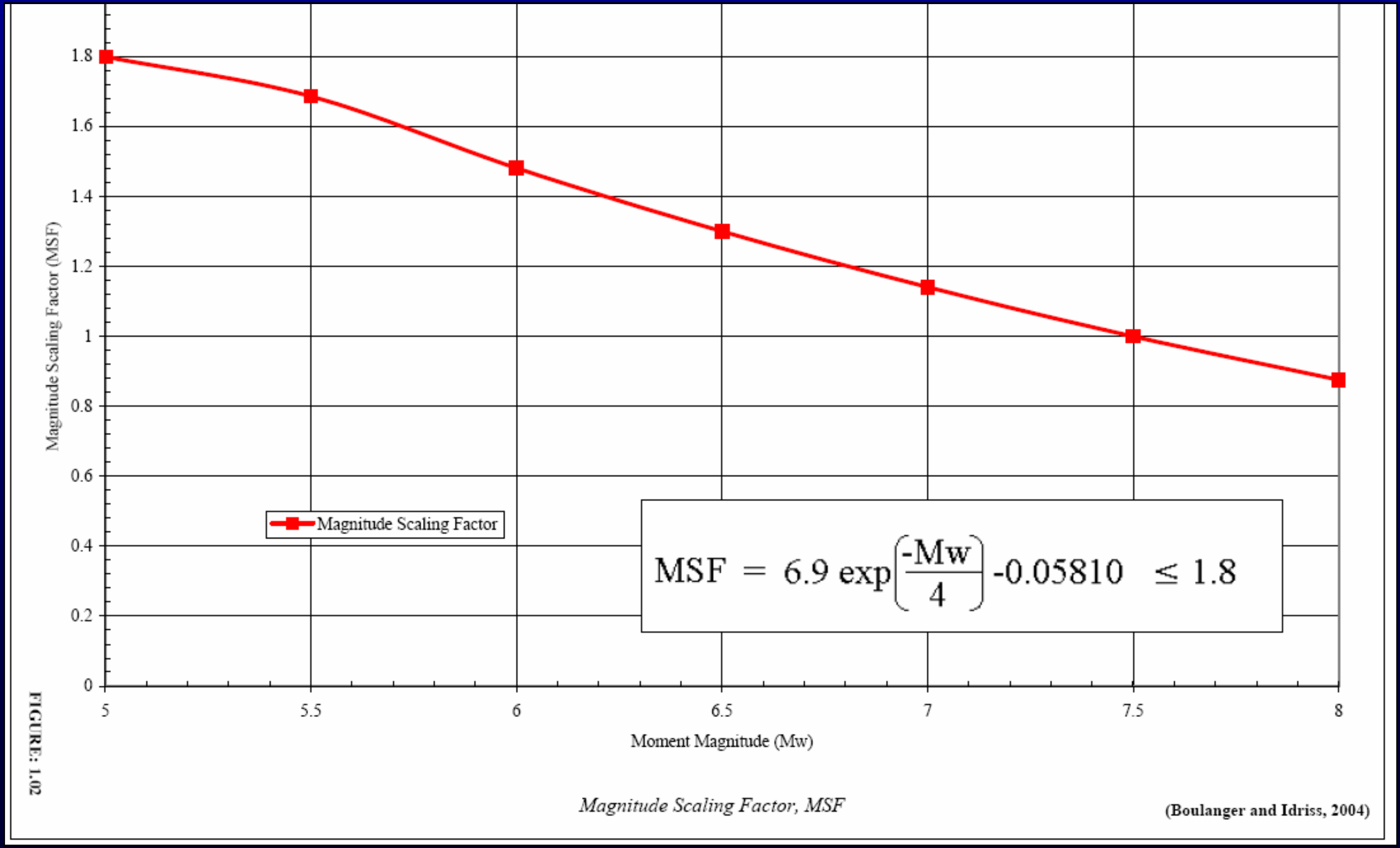
Example Q4Mesh Liquefaction Model

- Magnitude Scaling Factor (MSF)



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Example Q4Mesh Liquefaction Model

Embankment Dam on a Liquefiable Foundation (EDOLF)

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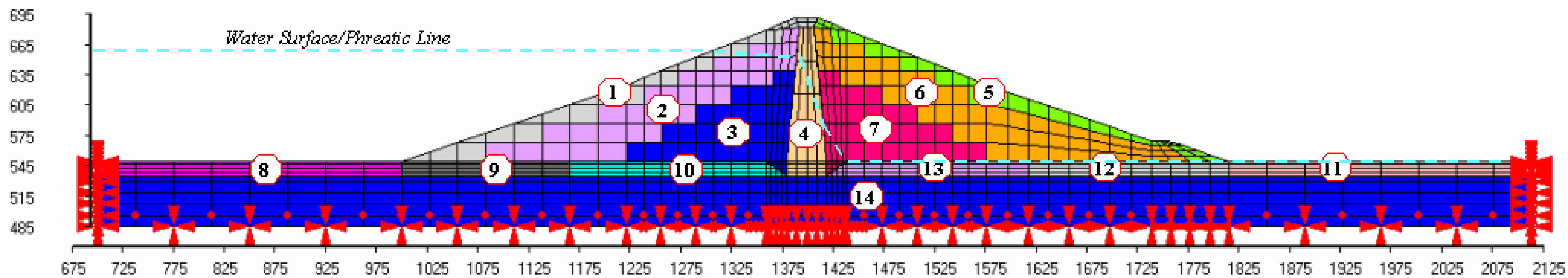
Example Q4Mesh Liquefaction Model

■ Finite Element Mesh



Embankment Dam on Liquefiable Foundation (EDOLF)

- Finite Element Mesh with Zones
- Location of Water Surface/Phreatic Surface
- Boundary Conditions

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Example Q4Mesh Liquefaction Model

- Material Properties

Material Properties:

Zone	Material	Vs (ft/s)	$(N_1)_{60}$	Shear Modulus Degradation Curve	Material Damping Curve
1	Embankment Shell	800	50	Sand Upper Bound (Seed & Idriss 1970)	Sand Upper Bound (Seed & Idriss 1970)
2	Embankment Shell	1000	50	Sand Upper Bound (Seed & Idriss 1970)	Sand Upper Bound (Seed & Idriss 1970)
3	Embankment Shell	1200	50	Sand Upper Bound (Seed & Idriss 1970)	Sand Upper Bound (Seed & Idriss 1970)
4	Core	1200	45	Clay (PI=10-20 Sun et al. 1988)	Clay Average (Seed & Idriss 1970)
5	Embankment Shell	800	50	Sand Upper Bound (Seed & Idriss 1970)	Sand Upper Bound (Seed & Idriss 1970)
6	Embankment Shell	1000	50	Sand Upper Bound (Seed & Idriss 1970)	Sand Upper Bound (Seed & Idriss 1970)
7	Embankment Shell	1200	50	Sand Upper Bound (Seed & Idriss 1970)	Sand Upper Bound (Seed & Idriss 1970)
8	Recent Alluvium	450	10	Sand Average (Seed & Idriss 1970)	Sand Average (Seed & Idriss 1970)
9	Recent Alluvium	550	15	Sand Average (Seed & Idriss 1970)	Sand Average (Seed & Idriss 1970)
10	Recent Alluvium	650	20	Sand Average (Seed & Idriss 1970)	Sand Average (Seed & Idriss 1970)
11	Recent Alluvium	450	10	Sand Average (Seed & Idriss 1970)	Sand Average (Seed & Idriss 1970)
12	Recent Alluvium	550	15	Sand Average (Seed & Idriss 1970)	Sand Average (Seed & Idriss 1970)
13	Recent Alluvium	650	20	Sand Average (Seed & Idriss 1970)	Sand Average (Seed & Idriss 1970)
14	Older Alluvium	2000	60	Clay Upper Range (Idriss, 1990)	Clay (Idriss, 1990)

Example Q4Mesh Liquefaction Model

- Input Earthquake Record
  - IMPERIAL VALLEY EARTHQUAKE, CA; OCT 15, 1979
  - Mw=6.75 at 22km
  - Amax=0.28g
  - Filtered Record Low-Pass=20hz
  - Bracketed Duration ~22 seconds
  - "ROCK OUTCROP MOTION"

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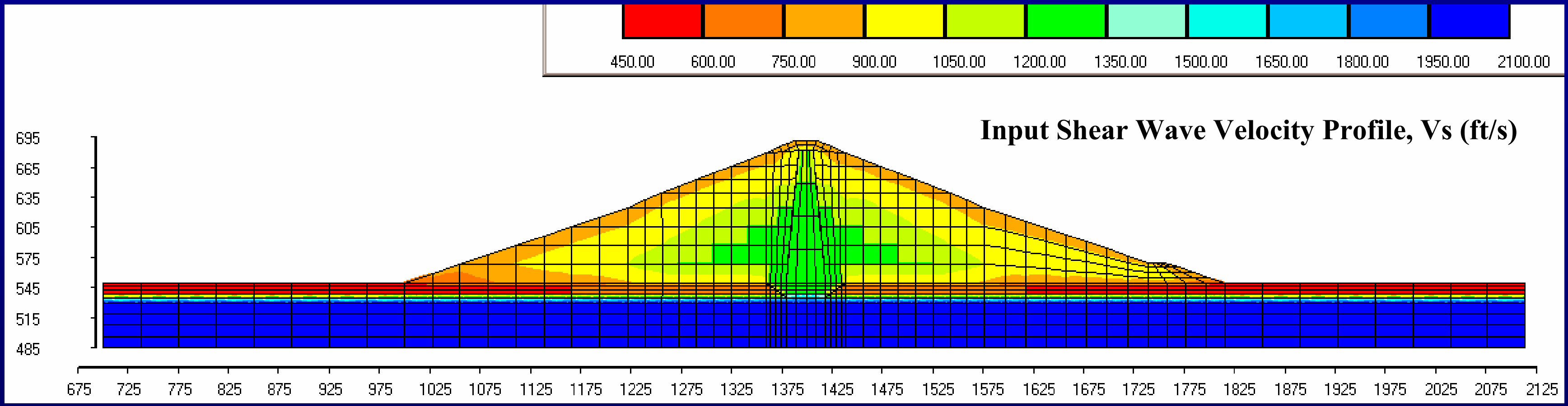
Example Q4Mesh Liquefaction Model

- Input Shear Wave Velocities



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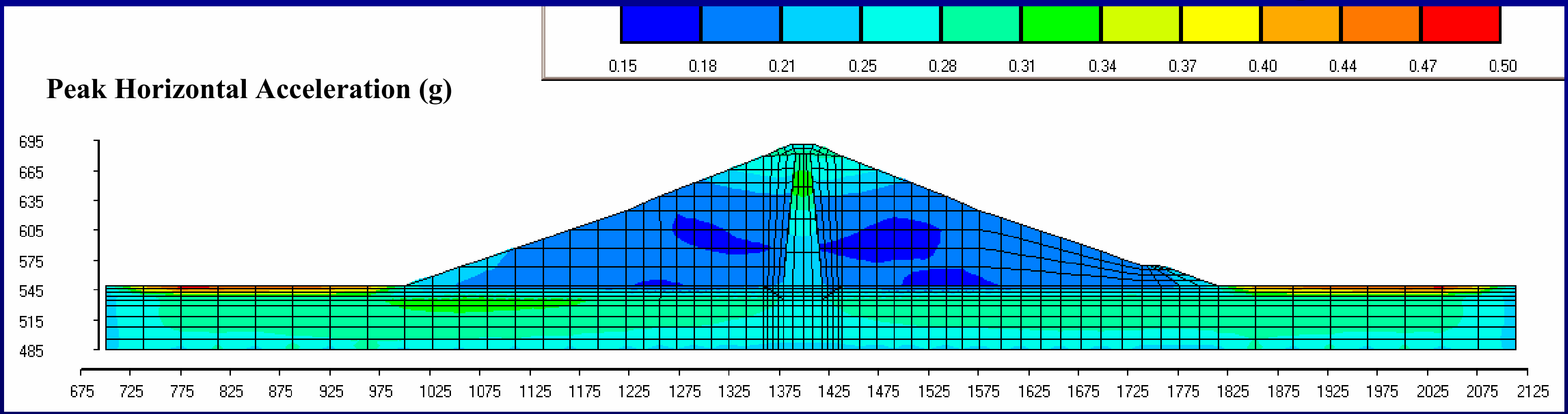
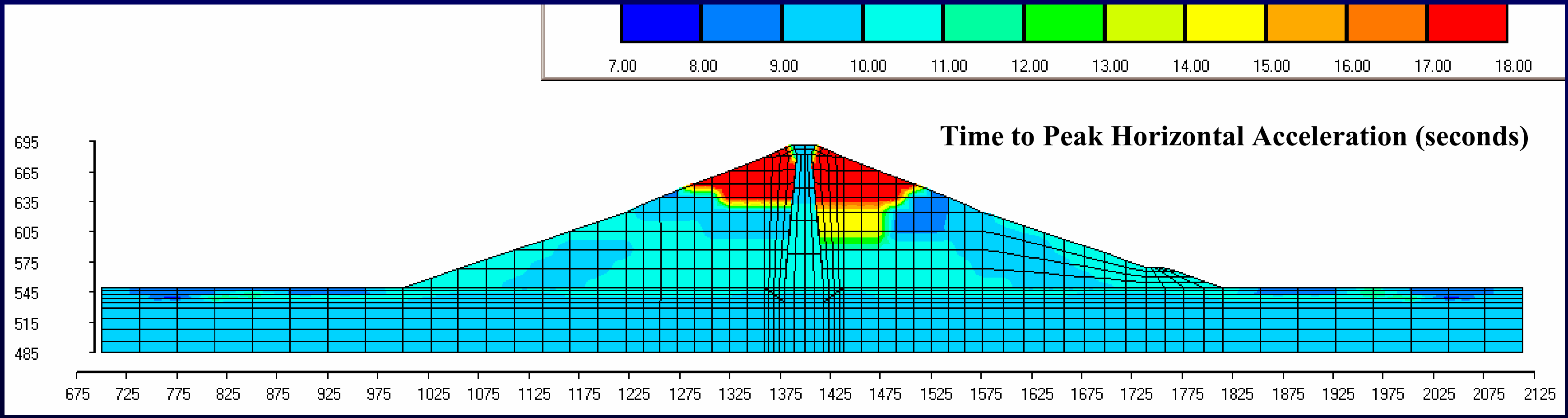
Example Q4Mesh Liquefaction Model

Quad4m Analysis Results

Example Q4Mesh Liquefaction Model

- Peak Nodal Horizontal Acceleration (g)





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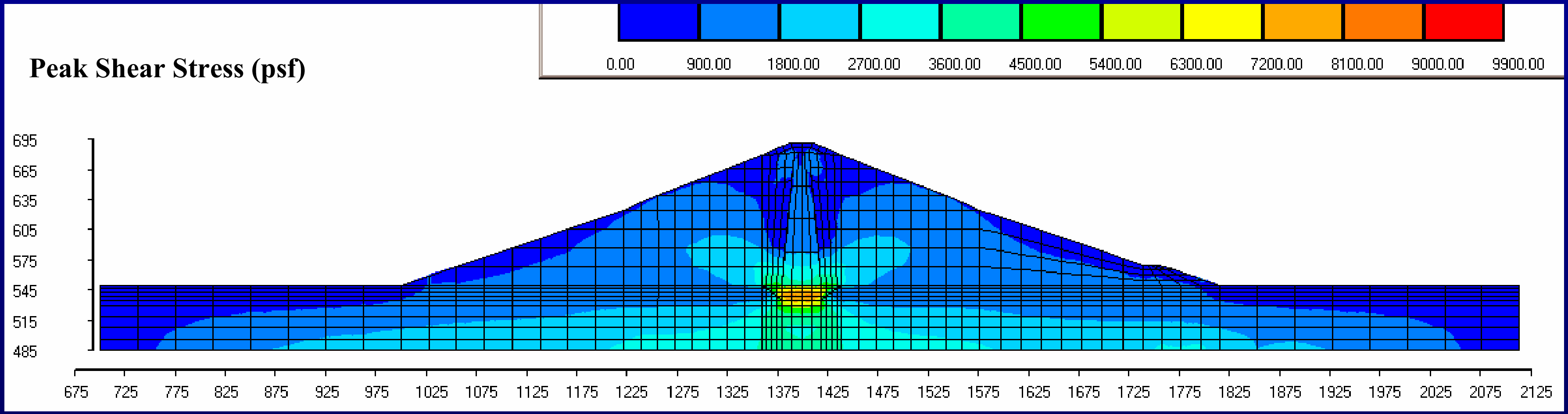
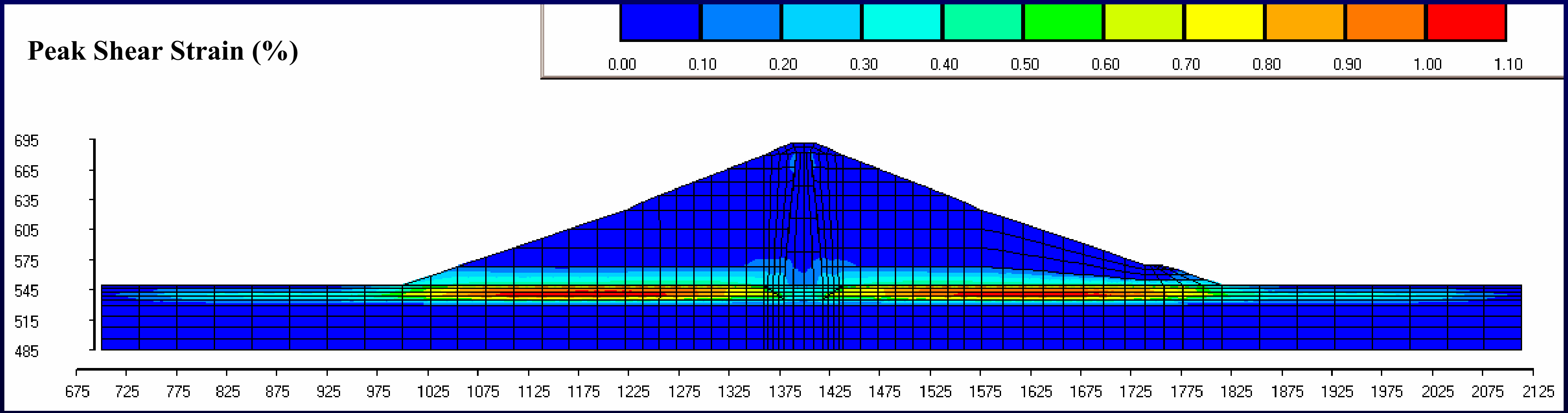
Example Q4Mesh Liquefaction Model

- Peak Element Induced Shear Stress and Strain



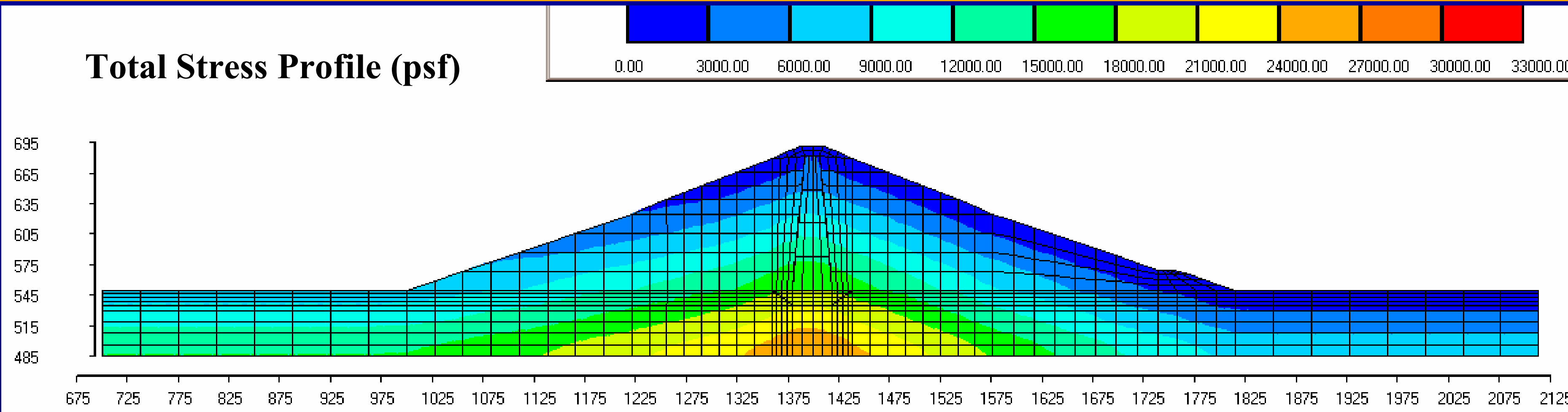


Example Q4Mesh Liquefaction Model

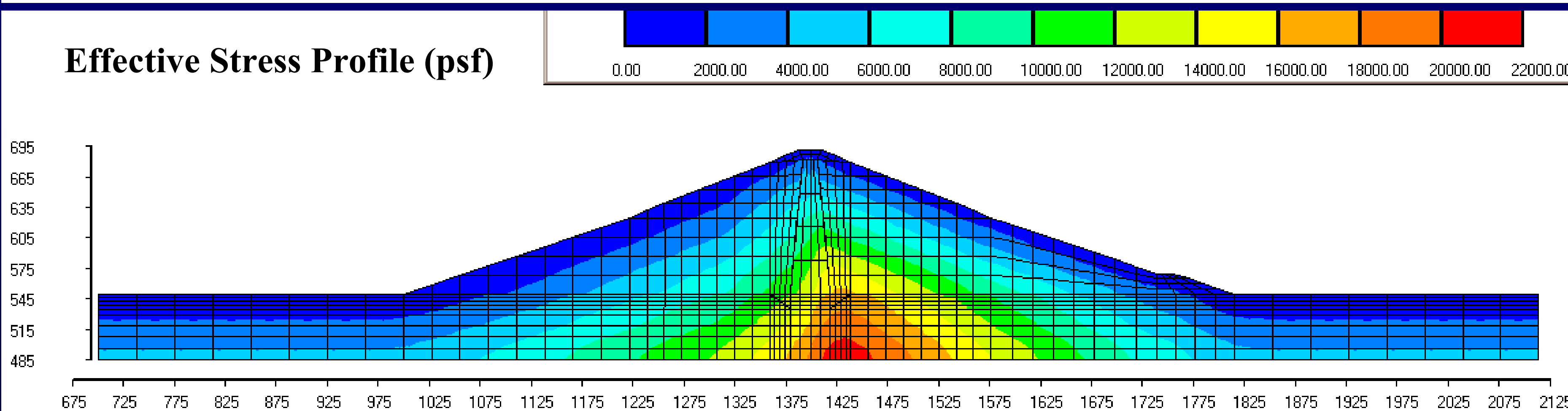
Q4Mesh Analysis and Results

Example Model

Total Stress Profile (psf)



Effective Stress Profile (psf)



Given: γ_{sat} =135pcf, γ_{moist} =130pcf for all elements

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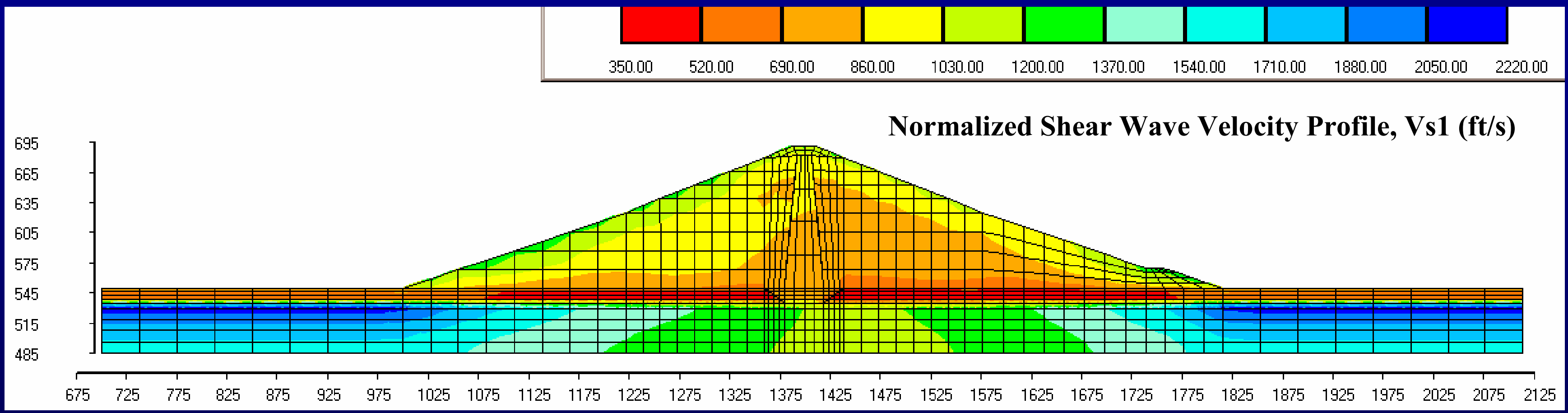
Example Q4Mesh Liquefaction Model

- Normalized Shear Wave Velocities



$$Vs1 = \left[Vs\right]\left(\frac{Pa}{\sigma_{vo}'}\right)^{0.25}$$

Pa = Reference Stress of 2000 psf

σ_{vo}' = Vertical Effective stress, Calculated using Q4MESH

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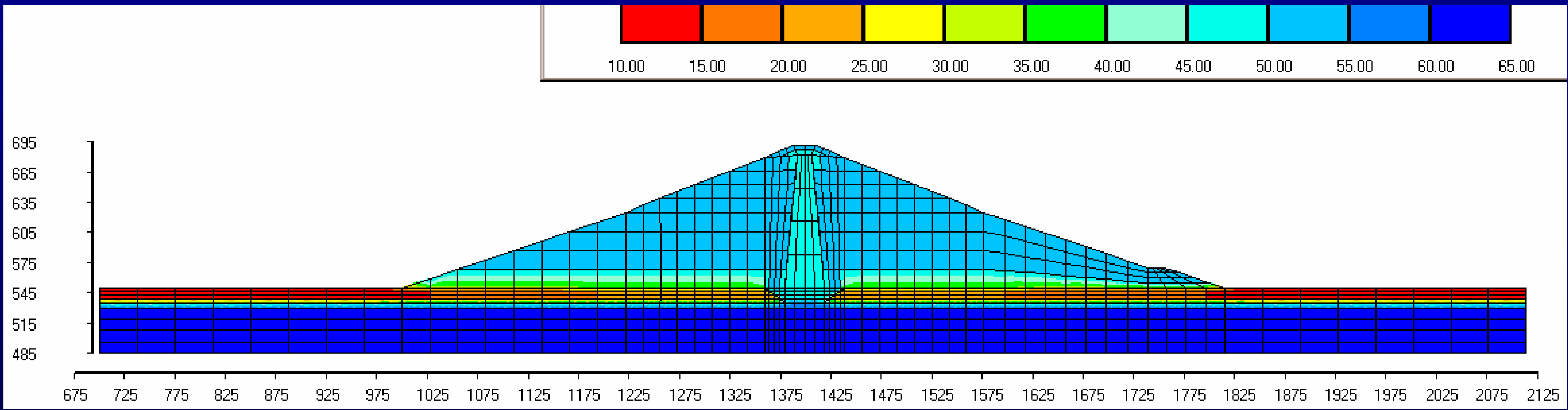
Example Q4Mesh Liquefaction Model

- Input Blowcount Data, $(N_1)_{60}$ (blows/ft)



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Example Q4Mesh Liquefaction Model

Cyclic Resistance Ratio CRR

- Vs1 Values
- $(N_1)_{60}$ Blowcount Values

Example Q4Mesh Liquefaction Model

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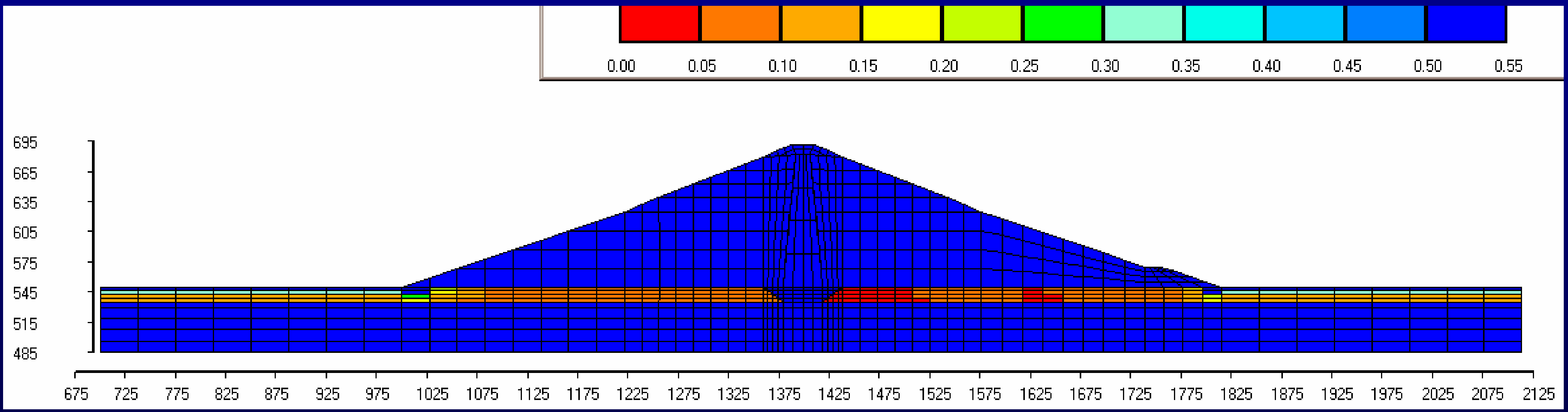
- Cyclic Resistance Ratio, CRR
  - (Calculated from the Vs1 Values)

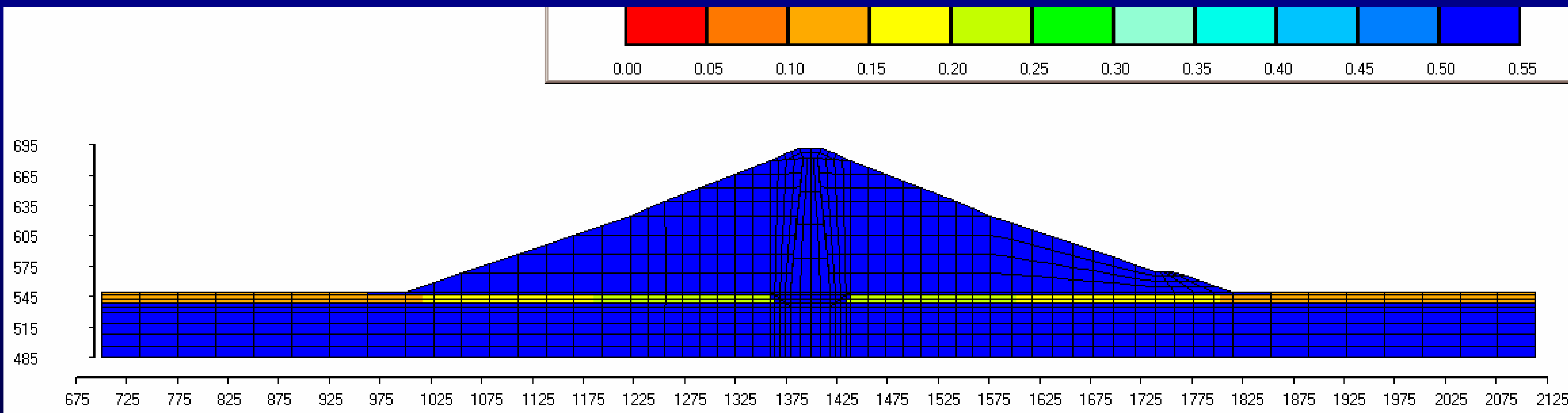


$$CRR_{Vs1} = (0.022)\left(\frac{Vs1}{100}\right)^2 + \left(\frac{2.8}{215 - Vs1}\right) - \left(\frac{2.8}{215}\right)$$

NCEER Workshop
Andrus and Stokoe (1997)

Example Q4Mesh Liquefaction Model

- Cyclic Resistance Ratio, CRR
  - (Calculated from the $(N_1)_{60}$ Values)



$$CRR_{N1,60} = \exp\left\{ \frac{N1,60}{14.1} + \left(\frac{N1,60}{126}\right)^2 + -\left(\frac{N1,60}{23.6}\right)^3 + \left(\frac{N1,60}{25.4}\right)^4 - 2.8 \right\}$$

ICSDEE and ICEGE Conference
Idriss and Boulanger (2004)

Example Q4Mesh Liquefaction Model

Cyclic Stress Ratio CSR

- Peak Element Stresses
- Seed and Idriss Simplified Procedure

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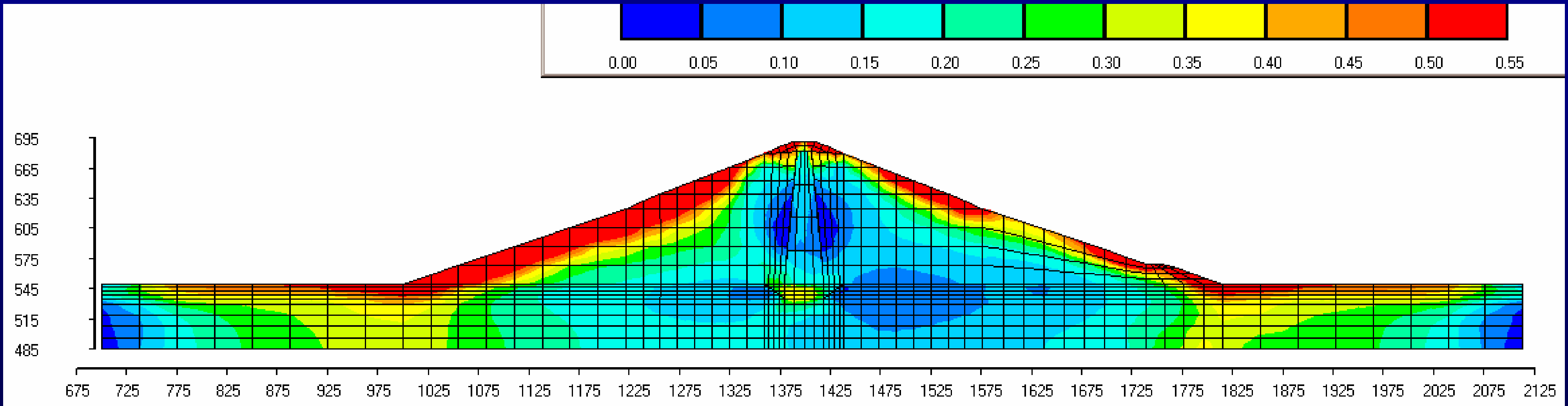
Example Q4Mesh Liquefaction Model

- Cyclic Stress Ratio, CSR
  - (Calculated from Quad4m Peak Induced Shear Stresses)



$$CSR = \frac{(0.65)(\tau_{max})}{(\sigma_{vo}')}$$

τ_{max} = Peak Element Shear Stress from Quad4m

σ_{vo}' = Vertical Effective stress, Calculated using Q4MESH

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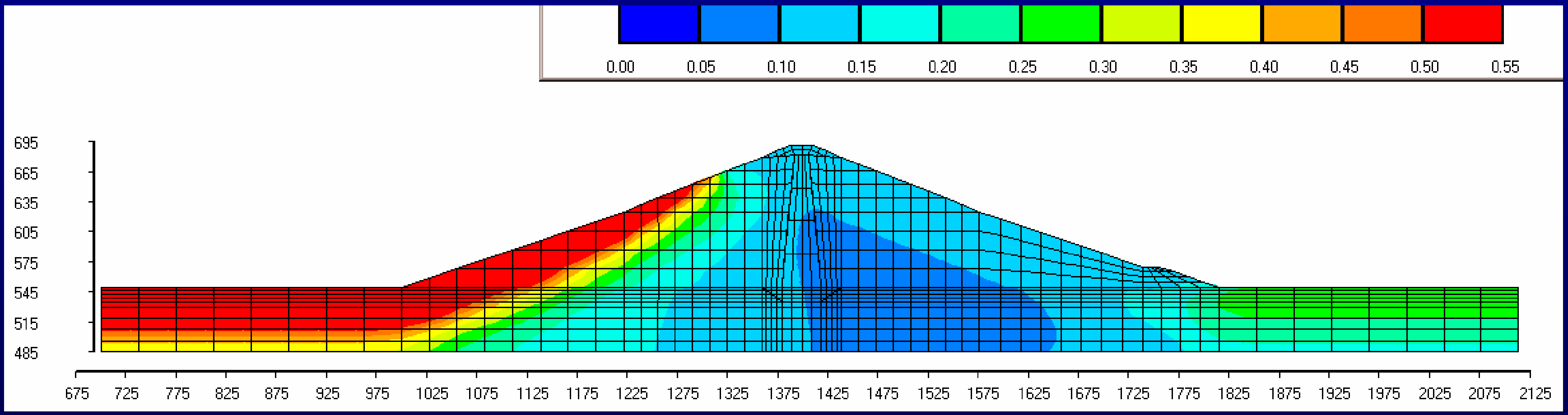
Example Q4Mesh Liquefaction Model

- Cyclic Stress Ratio, CSR
  - (Calculated from Simplified Procedure)



$$CSR = (\tau_{av}/\sigma'_{vo}) = 0.65(a_{max}/g)(\sigma_{vo}/\sigma'_{vo})rd$$

Parameters as Defined by Youd and Idriss 2001

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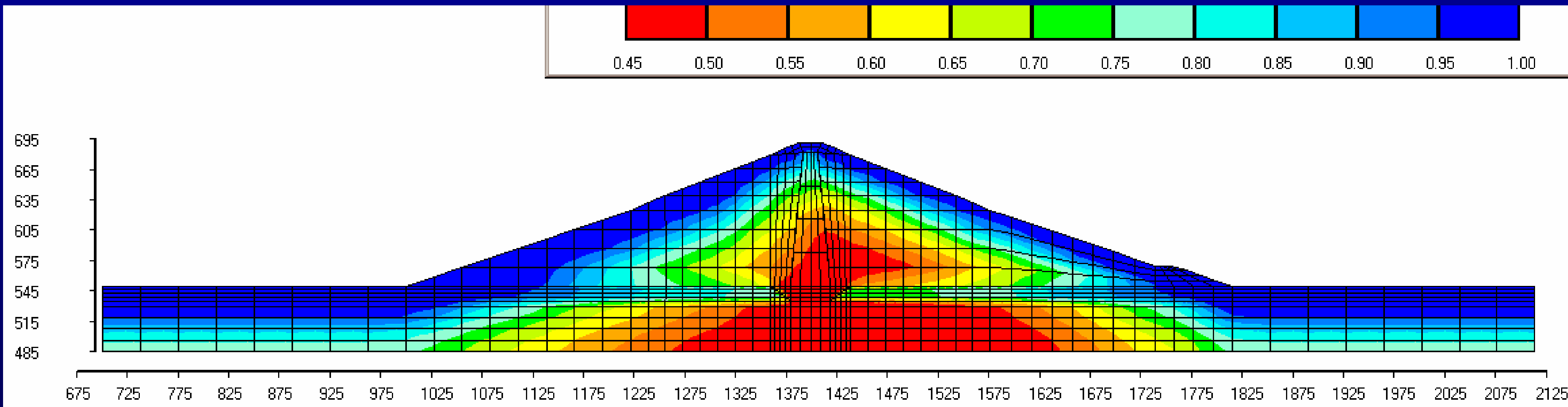
Example Q4Mesh Liquefaction Model

- Stress Correction Factor, Kσ



$$K\sigma = 1 - C_{\sigma} \ln\left(\frac{\sigma'_{vo}}{Pa}\right) \leq 1.0$$

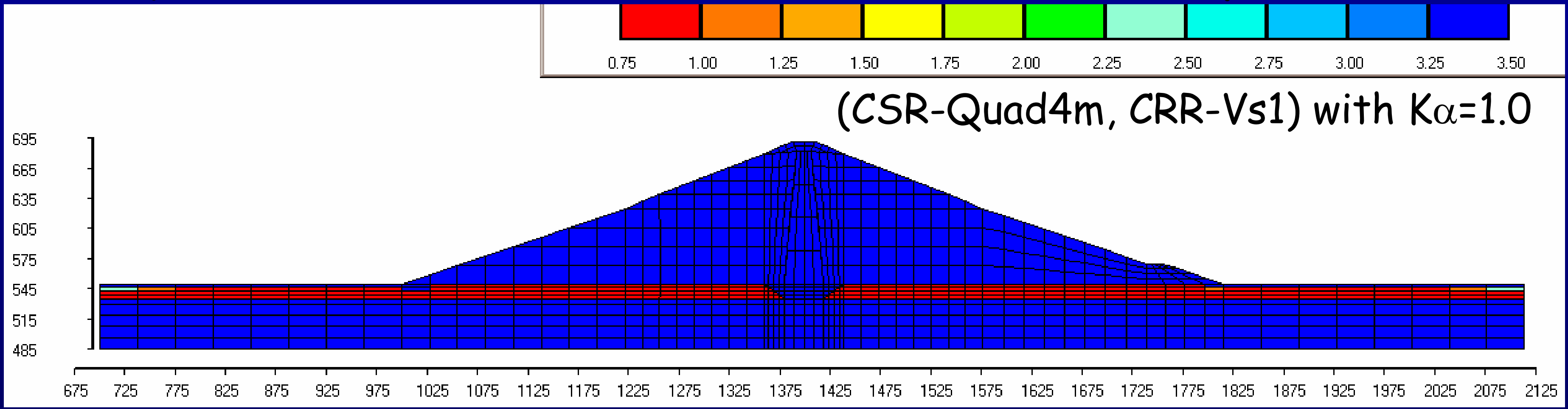
$$C_{\sigma} = \frac{1}{18.9 - 2.55\sqrt{N1,60}}$$

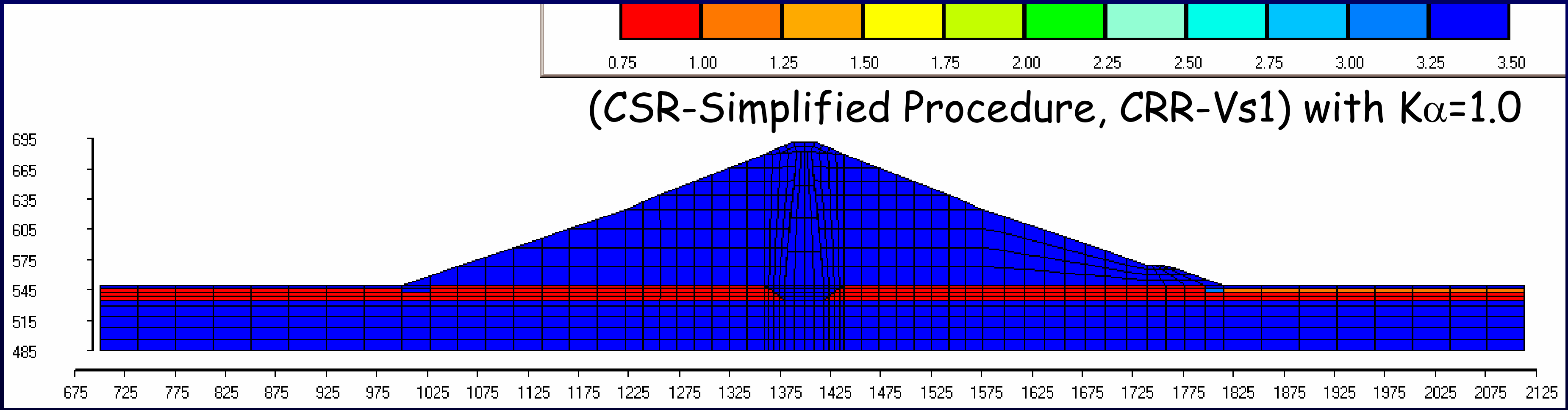
ICSDEE and ICEGE Conference

Idriss and Boulanger (2004)

Example Q4Mesh Liquefaction Model

- Liquefaction Potential Factor of Safety, Vs_1 Data





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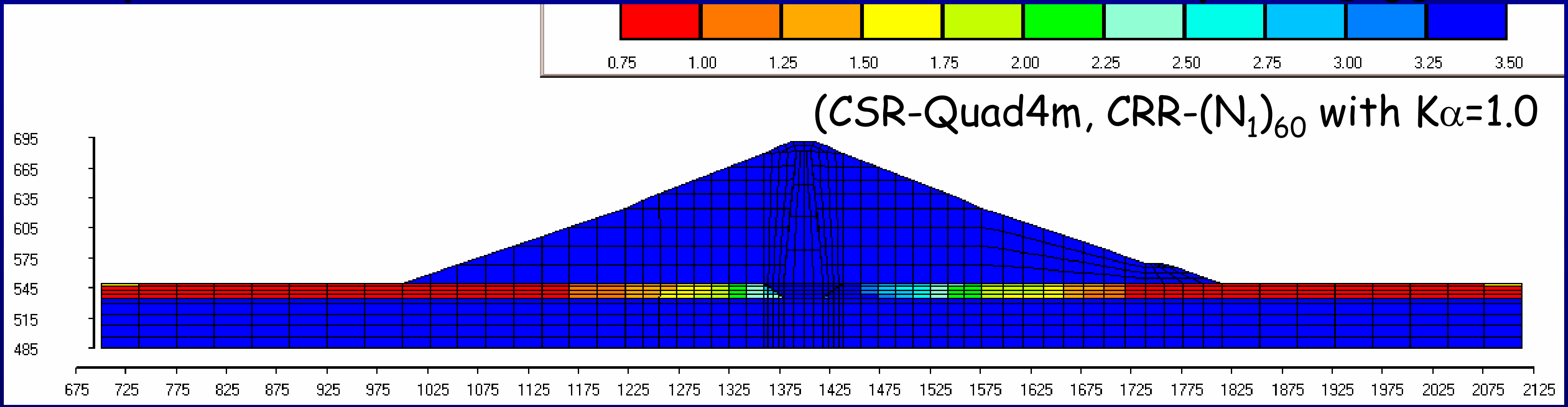
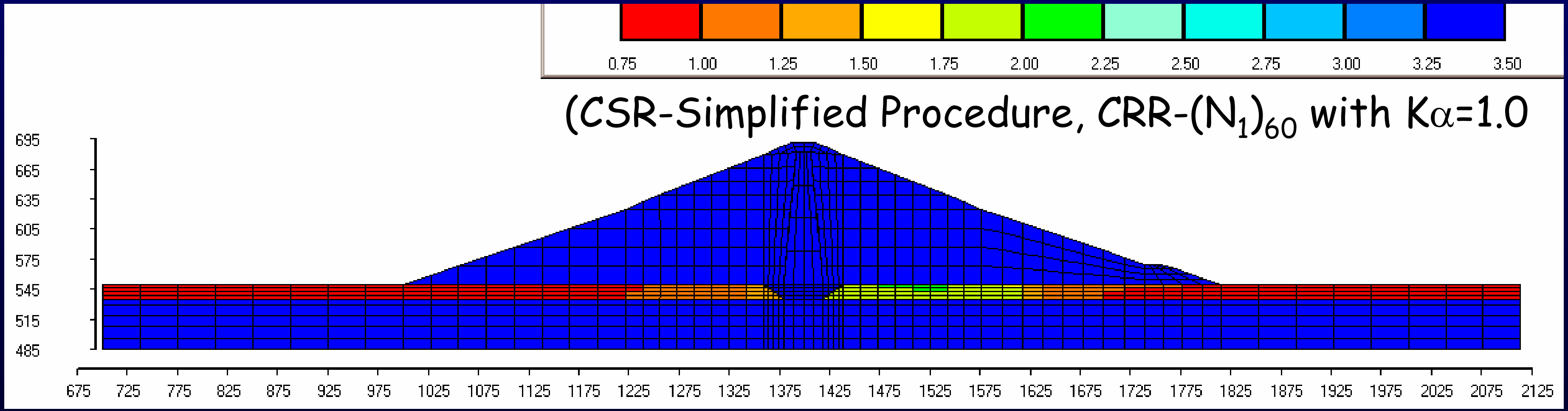
Example Q4Mesh Liquefaction Model

- Liquefaction Potential Factor of Safety, $(N_1)_{60}$ Data





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Concluding Remarks

- Q4Mesh enables the ability to conduct 2-D liquefaction potential evaluations from Quad4m output data
- Quad4m and Q4Mesh can be used as a first step evaluation before more advanced models are implemented
- User experience and correct model generation is important when evaluating the Quad4m output files

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References

- Idriss, I. M., and Boulanger, R. W. (2004). "Semi-empirical procedures for evaluating liquefaction potential during earthquakes." Proc., 11th International Conference on Soil Dynamics and Earthquake Engineering, and 3rd International Conference on Earthquake Geotechnical Engineering, D. Doolin et al., eds., Stallion Press, Vol. 1, 32-56.

- Boulanger, R. W. and Idriss, I. M. (2004). "State normalization of penetration resistances and the effect of overburden stress on liquefaction resistance." Proc., 11th International Conference on Soil Dynamics and Earthquake Engineering, and 3rd International Conference on Earthquake Geotechnical Engineering, D. Doolin et al., eds., Stallion Press, Vol. 2, 484-491.

- Youd, T. L. and Idriss, I. M. (2001). "Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils," Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 127, No. 4, pp. 297-313.

Thank you!

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