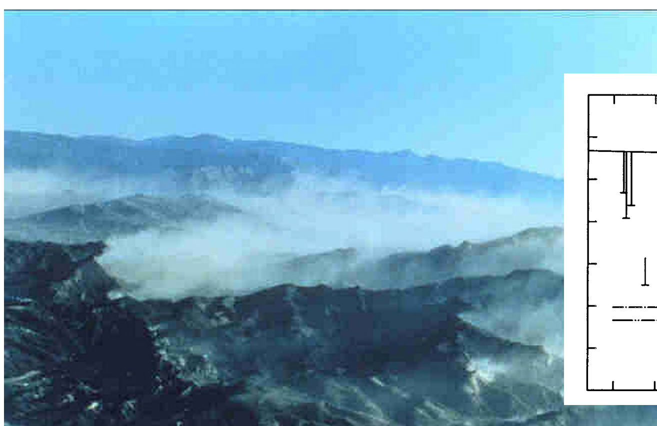
NORTHRIDGE 20
SYMPOSIUM

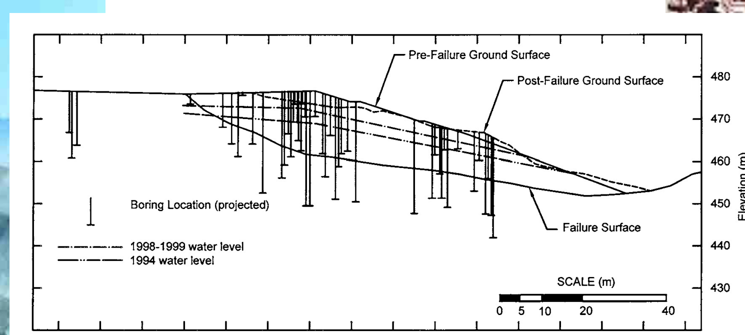
STATIC & SEISMIC SLOPE STABILITY ANALYSES

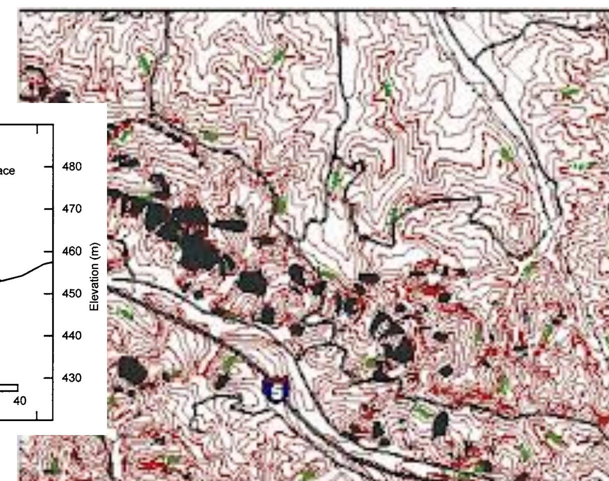
Thomas F. Blake, Fugro Consultants

January 2014 - University of California, Los Angeles

Earthquakes Trigger Landslides, and Northridge was No Exception

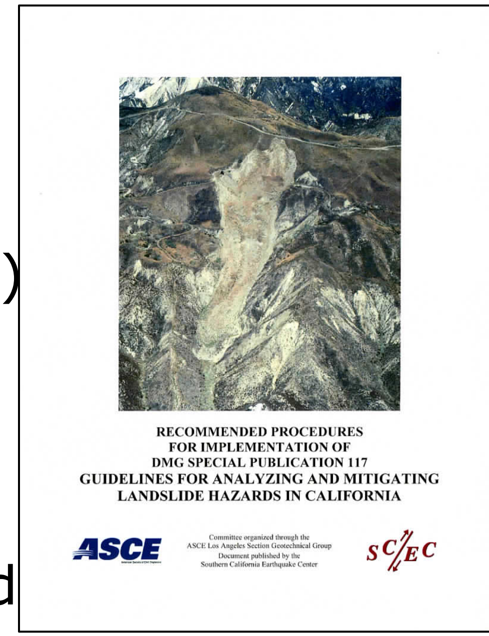






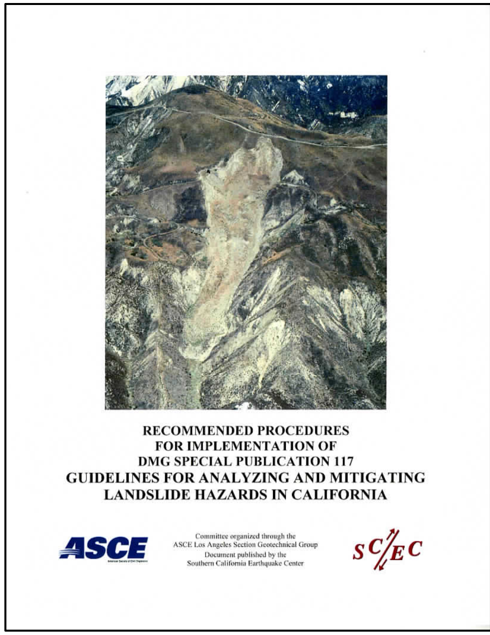
A Few Years After Northridge Regulators Convened a Committee

- Result of Seismic Hazard Mapping Act
  - Needed guidelines to implement CDMG SP-117
- Committee of 15 (I chaired)
  - Represented regulators, academia, and practicing consultants (also peer reviewed)
  - Worked for over 3 ½ years & developed consensus guidelines document
- Document in 2002
  - Covered exploration, testing, analysis, and mitigation procedures
  - Recommended that seismic displacement analyses should replace pseudostatic methods



Only Parts of Document Were Ultimately Adopted in Practice

- In spite of the consensus represented by the Committee, the guidelines document was usually only adopted in part, and typically omitting the recommendation to perform seismic slope displacement analyses
- Often opposed by consultants, with the common reasons given that it would be "too hard to perform," "too expensive," or "too restrictive to future development"
- This is something to think about as we go forward here looking at how we might recommend changing future practices
- Sometimes sound technical recommendations go unadopted for political reasons


RECOMMENDED PROCEDURES
FOR IMPLEMENTATION OF
DMG SPECIAL PUBLICATION 117
GUIDELINES FOR ANALYZING AND MITIGATING
LANDSLIDE HAZARDS IN CALIFORNIA

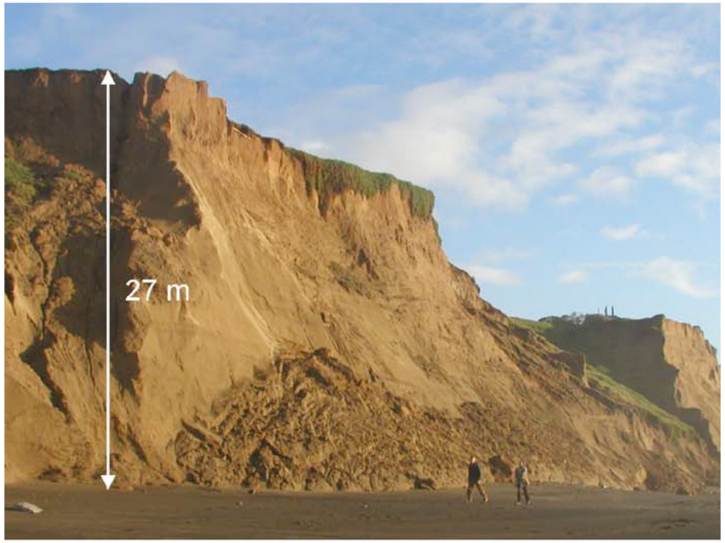
ASCE

Committee organized through the
ASCE Los Angeles Section Geotechnical Group
Document published by the
Southern California Earthquake Center

SCEC

Organization of Presentation

- Static Slope Stability
  - Historical introduction
  - Since Northridge Earthquake
- Seismic Slope Stability
  - Historical introduction
  - Since Northridge Earthquake

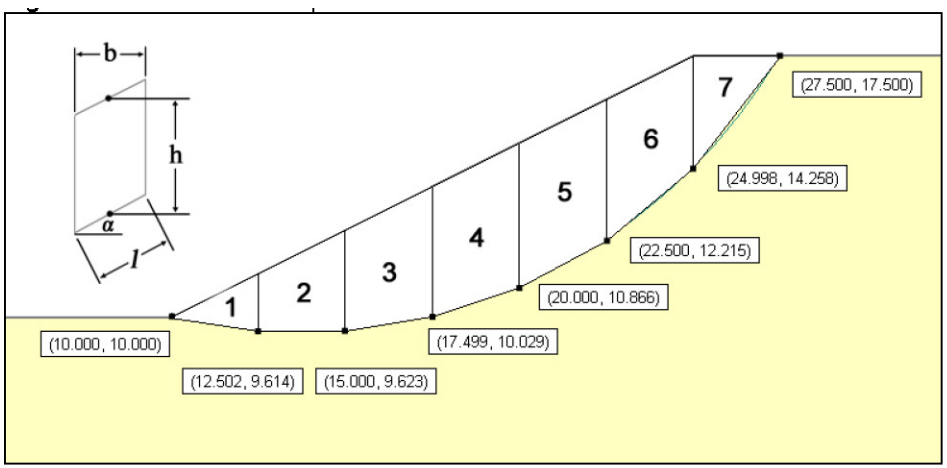


From: Collins & Sitar, 2011

- Special cases of steep slopes, rock wedges, rockfalls, 3-D stability

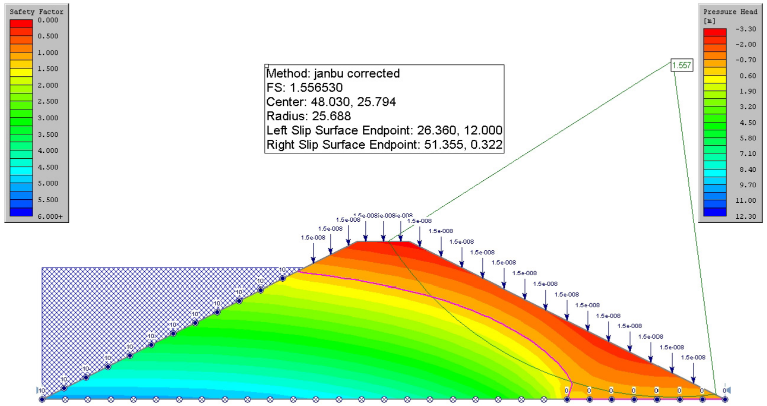
Static Slope Stability Analyses Before the Northridge Earthquake

- Prior to NE most slope stability analyses were performed by hand using calculators or stability charts (computer programs were just starting to be developed)
- Although the methods of static slope stability analysis that we use today existed prior to NE, most analyses were limited to simple method of slices calculations, because they had to be done by hand



Static Slope Stability Analyses Since the Northridge Earthquake

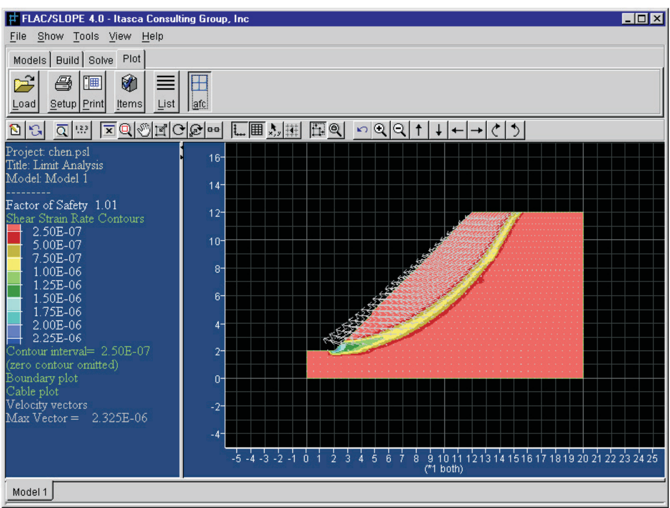
- Now all limit-eqiulibrium slope stability analyses are performed using sophisticated computer programs (e.g., SLOPE-W 2004, SLIDE 2000)
- Those programs allow the simultaneous use of multiple methods that satisfy both force and moment equilibrium
- They also allow for efficient searching of complex trial slip surfaces
- They allow use of stabilizing forces (e.g. tiebacks, piles, geogrid, etc.)
- Transient & steady-state seepage

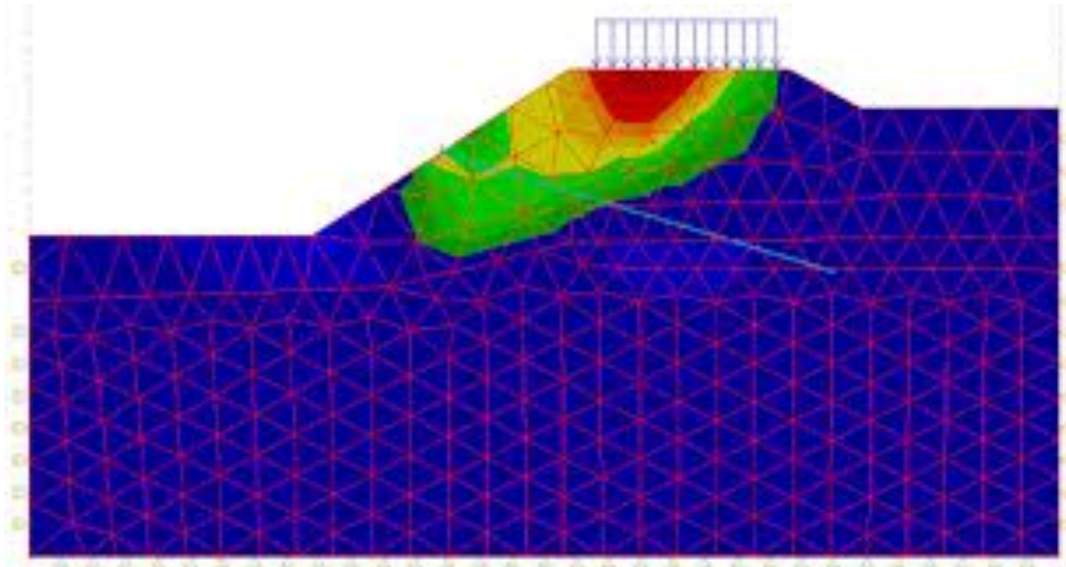


NORTHRIDGE 20 SYMPOSIUM

Static Slope Stability Analyses Since the Northridge Earthquake

- We can also perform slope stability analyses using finite element/finite difference programs using the shear strength reduction (SSR) technique (Dawson et al., 1999; Griffith & Lane, 1999; Hammah et al., 2004)
- FLAC-SLOPE, PHASE 2





Static Slope Stability Analyses Since the Northridge Earthquake

- FEM programs using SSR are not yet in common usage on small projects, but we are seeing their use more often on larger more significant projects
- One advantage: No trial surfaces; failure develops naturally
- Also, safety factor estimates are not sensitive to soil & rock stiffness properties, so just like limit-equlibrium methods

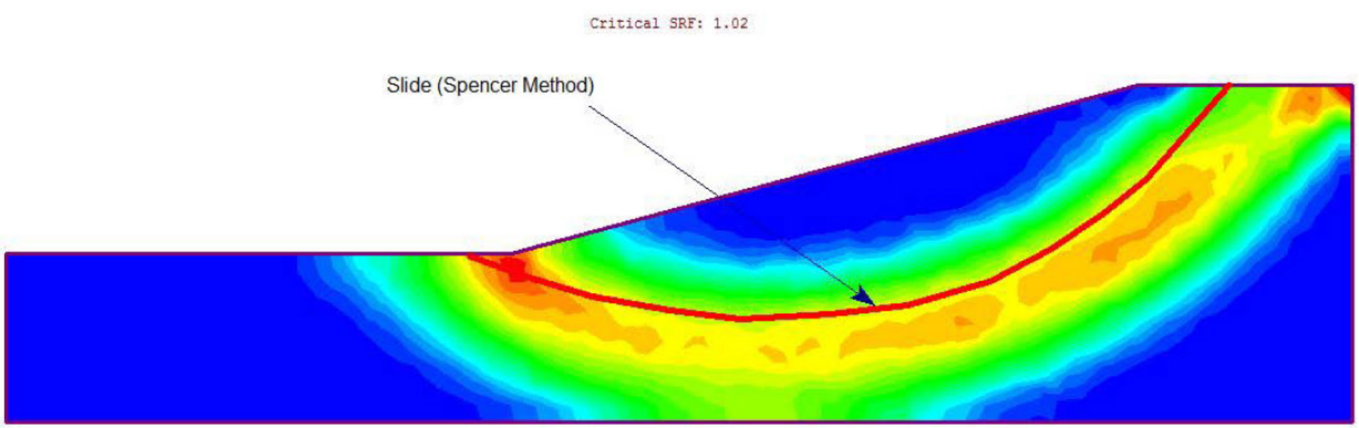


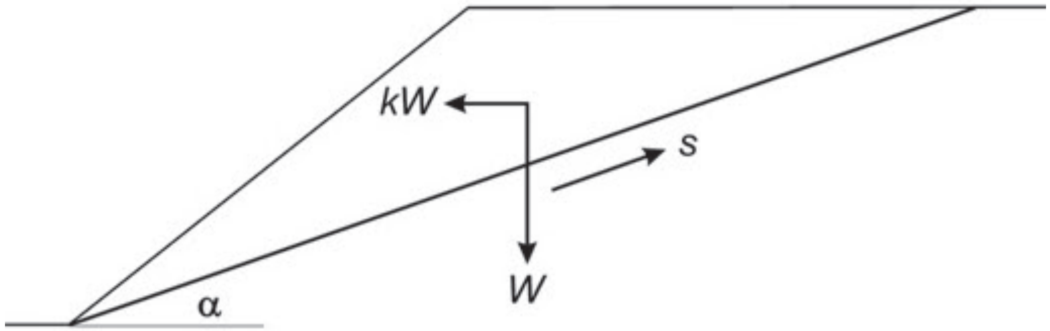
Figure 4 – Maximum Shear Strain Plot of Case 1

Seismic Slope Stability Analyses Before the Northridge Earthquake

- Before the NE, most EQ analyses were performed using presumptive pseudostatic methods
  - No hard and fast rules for selection of coefficient, but 0.15 with F.S. of 1.1 was common
- Various coefficients were proposed:
  - Terzhagi (1950) 0.1, 0.2, 0.5; depending on EQ Intens.
  - Seed (1979) 0.10, 0.15; depending on magnitude
  - Marcuson (1981) 0.33-0.50 x PGA
  - Hynes-Griffin & Franklin (1984) 0.5 x PGA
- Some were based on assumption of <1m displacement as being okay (from dams)

Seismic Slope Stability Analyses Since the Northridge Earthquake

- Since the NE most slope stability analyses still use the pseudostatic coefficient method
  - Still no hard and fast rules for selection of coefficient
  - Commonly used coefficient of about 0.15
  - Factor of safety of about 1.1
  - Most of the time the same coefficient is used everywhere regardless of proximity to seismic sources



Seismic Slope Stability Analyses Since the Northridge Earthquake

Pseudostatic coefficients from various studies.

Investigator	Recommended pseudostatic coefficient (k)	Recommended factor of safety (FS)	Calibration conditions
Terzhagi (1950)	0.1 (R-F = IX) 0.2 (R-F = X) 0.5 (R-F > X)	>1.0	Unspecified
Seed (1979)	0.10 (M = 6.50) 0.15 (M = 8.25)	>1.15	<1 m displacement in earth dams
Marcuson (1981)	0.33–0.50 × PGA/g	>1.0	Unspecified
Hynes-Griffin and Franklin (1984)	0.50 × PGA/g	>1.0	<1 m displacement in earth dams
California Division of Mines and Geology (1997)	0.15	>1.1	Unspecified; probably based on < 1 m displacement in dams

R-F is Rossi-Forel earthquake intensity scale.
M is earthquake magnitude.
PGA is peak ground acceleration.
g is acceleration of gravity.

From Jibson (2011)

Seismic Slope Stability Analyses Since the Northridge Earthquake

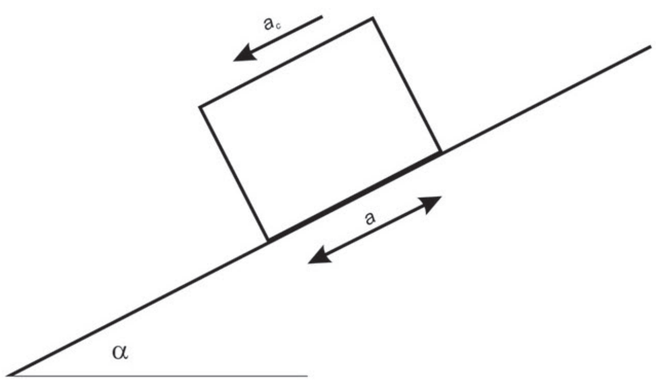
- However, displacement alternatives have been developed and are becoming more popular:
  - Calibrated pseudostatic approach
  - Semi-empirical Newmark displacement analyses
  - Rigorous Newmark-type displacement analyses
  - Rigorous finite element/finite difference analyses

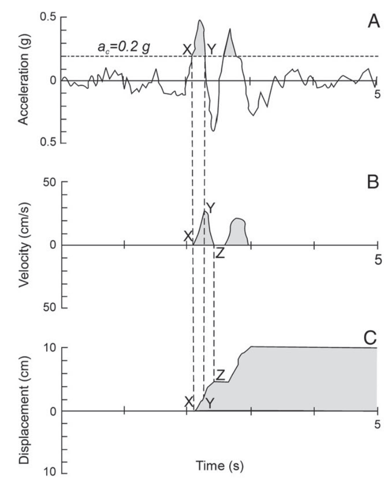
Seismic Slope Stability Analyses Since the Northridge Earthquake

- Before talking about Newmark displacement methods we need to understand the three types:
  - Rigid block
  - Decoupled
  - Fully coupled

Seismic Slope Stability Analyses Since the Northridge Earthquake

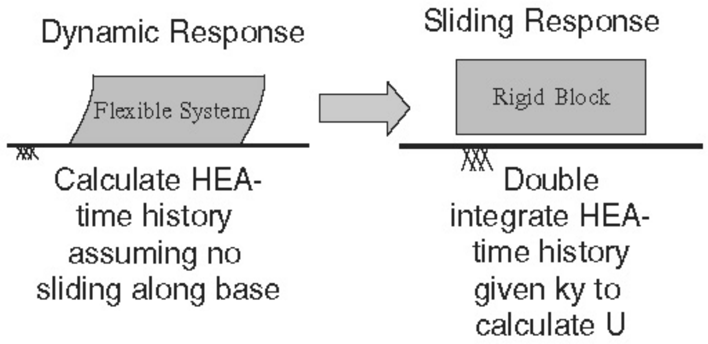
- Rigid block:
  - Assumes a rigid block sliding on a rigid inclined plane
  - Best results for stiffer, thinner slides
  - As slides get softer, thicker, the results can be either unconservative, conservative, or very conservative (i.e., unreliable)





Seismic Slope Stability Analyses Since the Northridge Earthquake

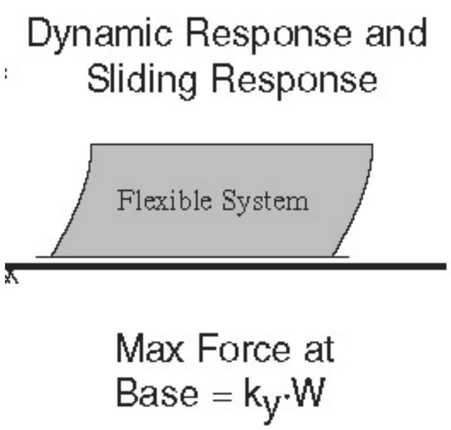
- Decoupled:
  - Assumes a deformable block sliding on a rigid inclined plane, with ground motion in block computed independently from displacement
  - Good results for stiffer, thinner slides (like rigid)
  - As slides get softer, thicker, the results can be conservative or very conservative, but also unconservative results are possible



HEA: Horizontal Equivalent Acceleration

Seismic Slope Stability Analyses Since the Northridge Earthquake

- Fully coupled:
  - Assumes a deformable block sliding on a rigid inclined plane, with ground motion in block computed simultaneously with displacement
  - Good results for softer, thicker slides
  - However, the results can become numerically unstable for rigid landslides
  - Assumption of slip along whole slide plane at once may not be satisfied for all real slides

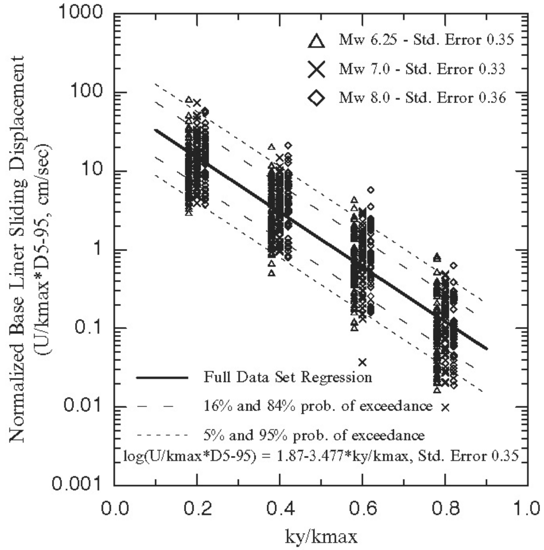


Seismic Slope Stability Analyses Since the Northridge Earthquake

- Therefore:
  - Use rigid block analysis methods for thin, stiff slides with Ts/Tm (site period/earthquake period) of <0.1
  - Use decoupled and fully coupled analysis methods for thicker, softer slides with Ts/Tm of >0.1

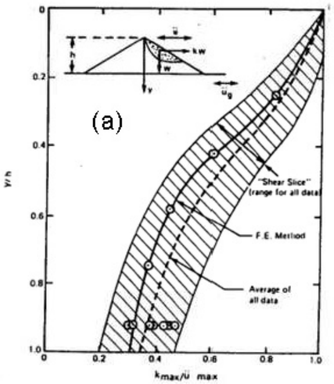
Seismic Slope Stability Analyses Since the Northridge Earthquake

- Calibrated pseudostatic:
  - Stewart et al. (2003) (based on Bray & Rathje, 1998) decoupled, now considered superseded by Bray
  - Bray & Travasarou (2009) (based on Bray & Travasarou, 2007) fully coupled
- Real value of method today is its use as a rapid screening tool



Seismic Slope Stability Analyses Since the Northridge Earthquake

- Semi-empirical Newmark displacement analyses:
  - Bray & Rathje (1998) (decoupled)
  - Bray & Travasarou (2007) (fully coupled)
  - Saygili & Rathje (2008) (rigid)
  - Rathje & Saygili (2009) (rigid)
  - Rathje & Antonokas (2011) (rigid & decoupled)
- Those methods had their roots before NE from analyses of dams:
  - Franklin & Chang (1977)
  - Makdisi & Seed (1978)
  - Yegian et al. (1991)

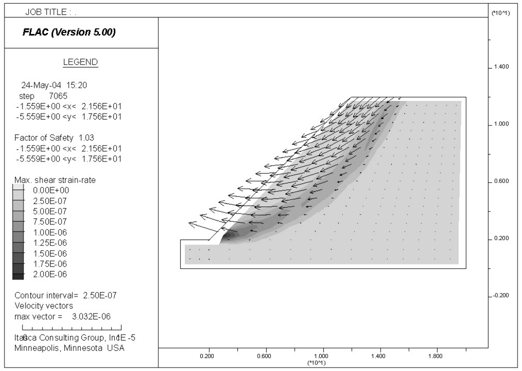


Seismic Slope Stability Analyses Since the Northridge Earthquake

- Rigorous Newmark-type displacement analyses:
  - Pyke (2002) Taga Software, TNMN (rigid block program)
  - Jibson & Jibson (2003) (rigid block program)
  - Jibson et al. (2013) SLAMMER (rigid, decoupled, and fully coupled program, with empirical methods included)
- SLAMMER analyses:
  - Properly selected records (this is critical step)
  - Need similar M, distance, & duration to target spectrum
  - Select records for both short and long period ranges
  - Use spectrally matched, scaled records (match geometric mean spectrum using Sigma Spectra or similar)

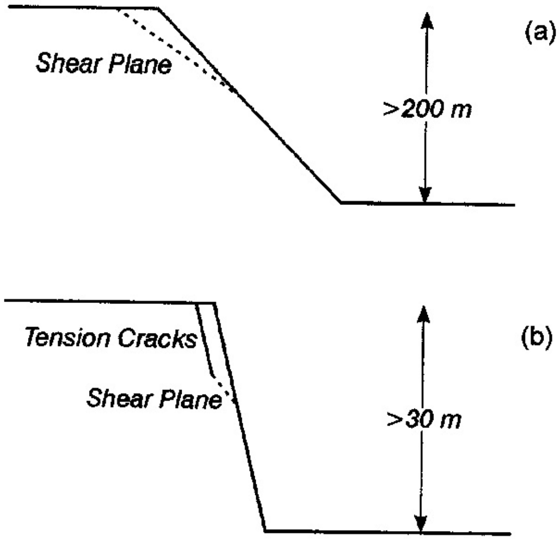
Seismic Slope Stability Analyses Since the Northridge Earthquake

- Rigorous finite element/finite difference analyses:
  - FLAC
  - PLAXIS
- Preferred method for single-site analyses where sufficient data exist to merit
- Used at critical facilities such as dams, or for embankments or slopes near critical structures
- Costly, time consuming, and requires above-normal experience and skill



Special case of steep slopes

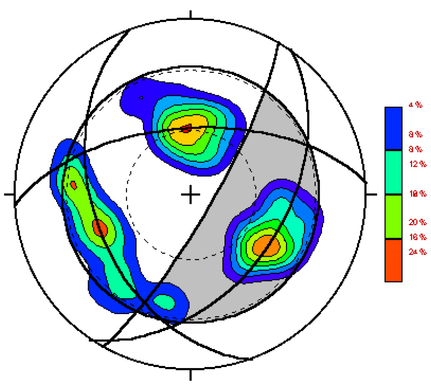
- Static stability of cemented steep slopes:
  - Collins & Sitar (2011) Developed a relatively simple approach that captures the typical mode of failure of steep bluffs
- Seismic stability of steep slopes:
  - Ashford & Sitar (2002) Developed a procedure that recognizes the ground motion amplification that develops near steep bluff slopes



From: Ashford & Sitar, 2002

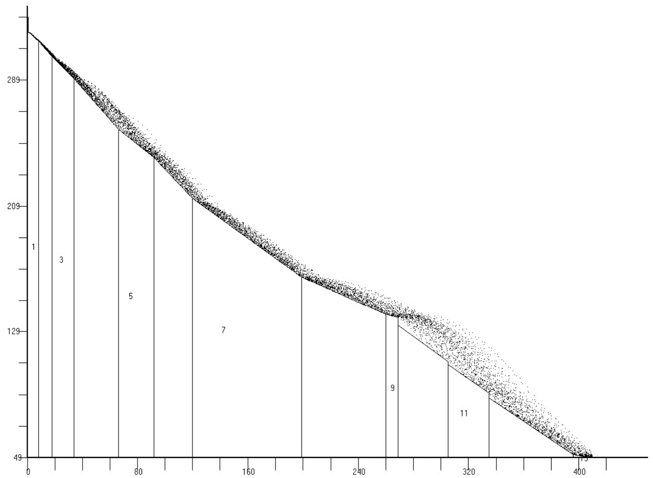
Rock-Wedge Slope Stability

- Rock-wedge slope stability analyses
  - ROCKPACK I & II (Skip Watts, 1987-1991)
  - ROCKPACK III (2001) ROCKPACK IV (2014)
  - SWEDGE (Rocscience, 2000)
  - RocPlane (Rocscience, 2001)
  - RocTopple (Rocscience, 2013)

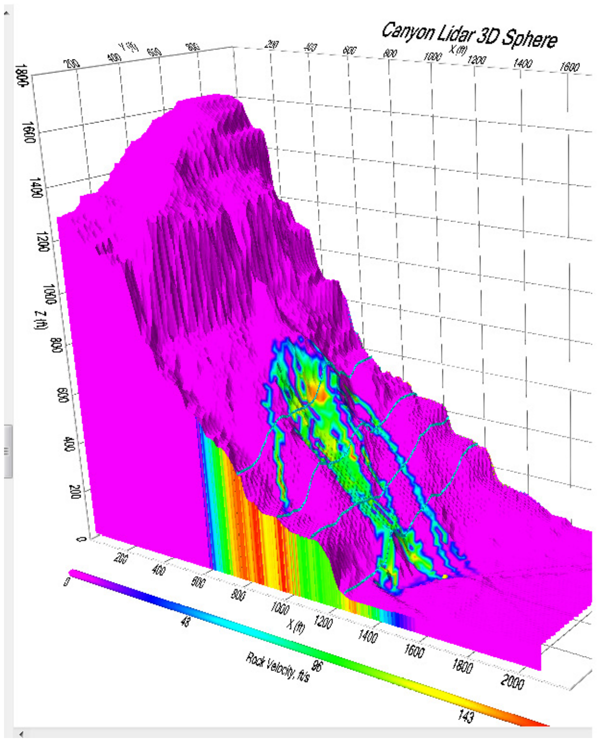


Rock-Fall Simulation

- Rock-fall simulation
  - Colorado Rockfall Simulation Program (CRSP) 2000
  - CRSP-3D now available (FHWA, 2012)
  - ROCFALL (Rocscience, 2000)

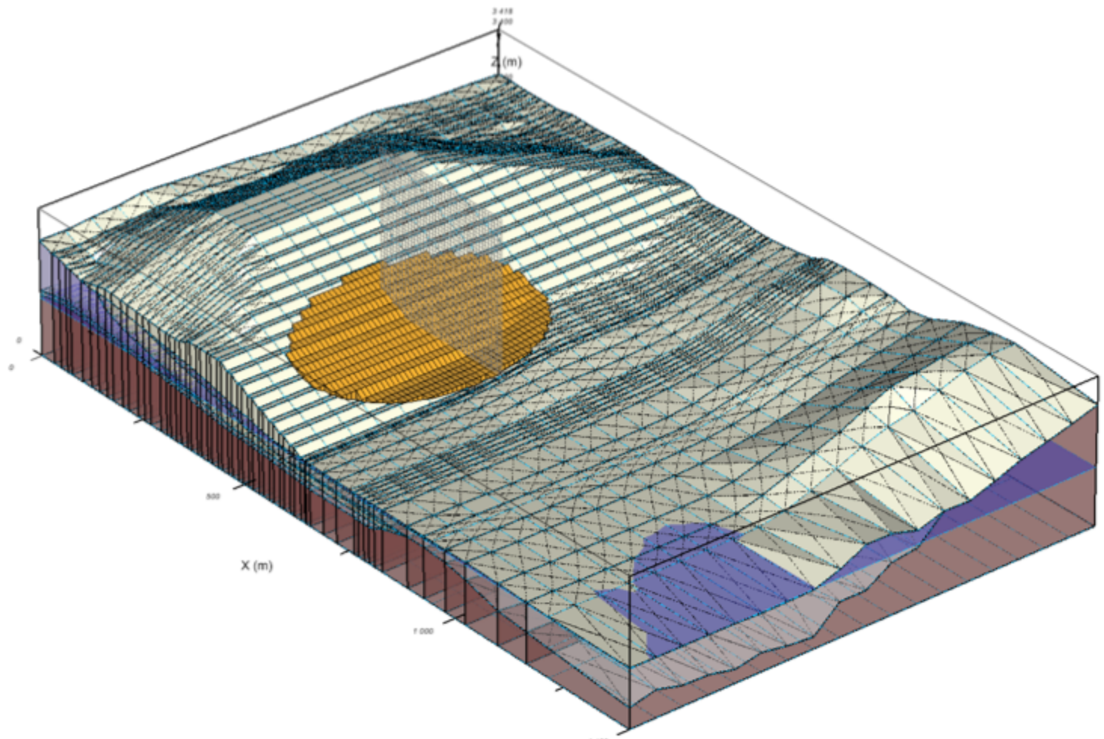


Rock Paths CRSP (Rifle example)



Three-Dimensional Slope Stability

- 3-D slope stability analyses
  - CLARA (early 1990s)
  - CLARA-W (2001) (No longer avail)
  - SVSLOPE-3D (Soilvision, 2012)



Conclusions

- Computer slope stability software is here to stay and it will keep getting more powerful and sophisticated
- Although they are still in common use, there is no real good reason to use presumptive pseudostatic analyses any more . . . Should use calibrated pseudostatic if a screening tool is needed
- Should perform displacement analyses using either semi-empirical or rigorous methods
  - Use rigid block methods for stiff, thin landslides
  - Use decoupled and fully coupled methods for softer, thicker landslides
- Because computers have gotten more powerful, we are likely to see more use of finite element programs using the SSR method in lieu of limit equilibrium methods or even full deformation analyses.

Something to Think About

In spite of the availability of sound technical approaches, the full implementation of those approaches in practice may still be limited by political pressure, as illustrated by the response to our 2002 SCEC Guidelines document.