Best Practices in Dam and Levee Safety Risk Analysis

IV-6. Seismic Risks for Embankments

2 April 2015

RECLAMATION
Managing Water in the West

US Army Corps of Engineers
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Outline

- Important case histories
- Steps for risk assessment
- Seismic potential failure modes
- Screening
- Event Tree
- Loading considerations
- Site characterization
- Likelihood of liquefaction
- Residual strength of liquefied soil
- Embankment deformation
- Overtopping
- Internal erosion through cracks

Failure due to Earthquakes

- Only about 1.5 percent of historical failures of embankment dams have been attributed to earthquakes.

Mode of failure	No. of cases		% failures (where known)		Average frequency of failure ($\times 10^{-3}$)	
	All failures	Failures in operation	All failures	Failures in operation	All failures	Failures in operation
Earthquake–liquefaction	2	2	1.6	1.7	0.18	0.18
Unknown mode	8	7				
Total no. of failures	136	124			12.2 (1.2%)	11.1 (1.1%)
Total no. of failures where mode of failure known	128	117				
No. of embankment dams	11 192	11 192				

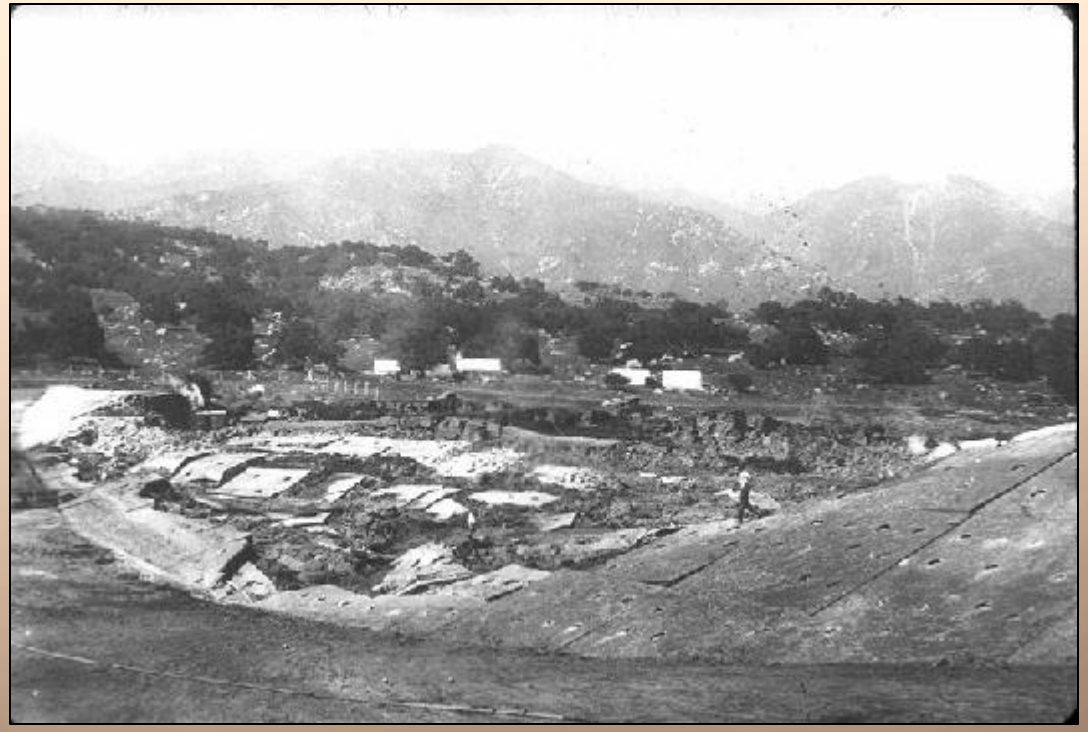
- The only known complete dam failures as a result of seismic shaking were tailings or hydraulic fill dams, or relatively small earthfill embankments of older and possibly inadequate design and construction.

Foster et. al (2000)

Sheffield Dam (1925)

(Courtesy of National Information Service for Earthquake Engineering, University of California, Berkeley, Karl Steinbrugge Collection)

Sheffield Dam (1925)



(Courtesy of National Information Service for Earthquake Engineering, University of California, Berkeley, Karl Steinbrugge Collection)

Lower San Fernando Dam (1971)

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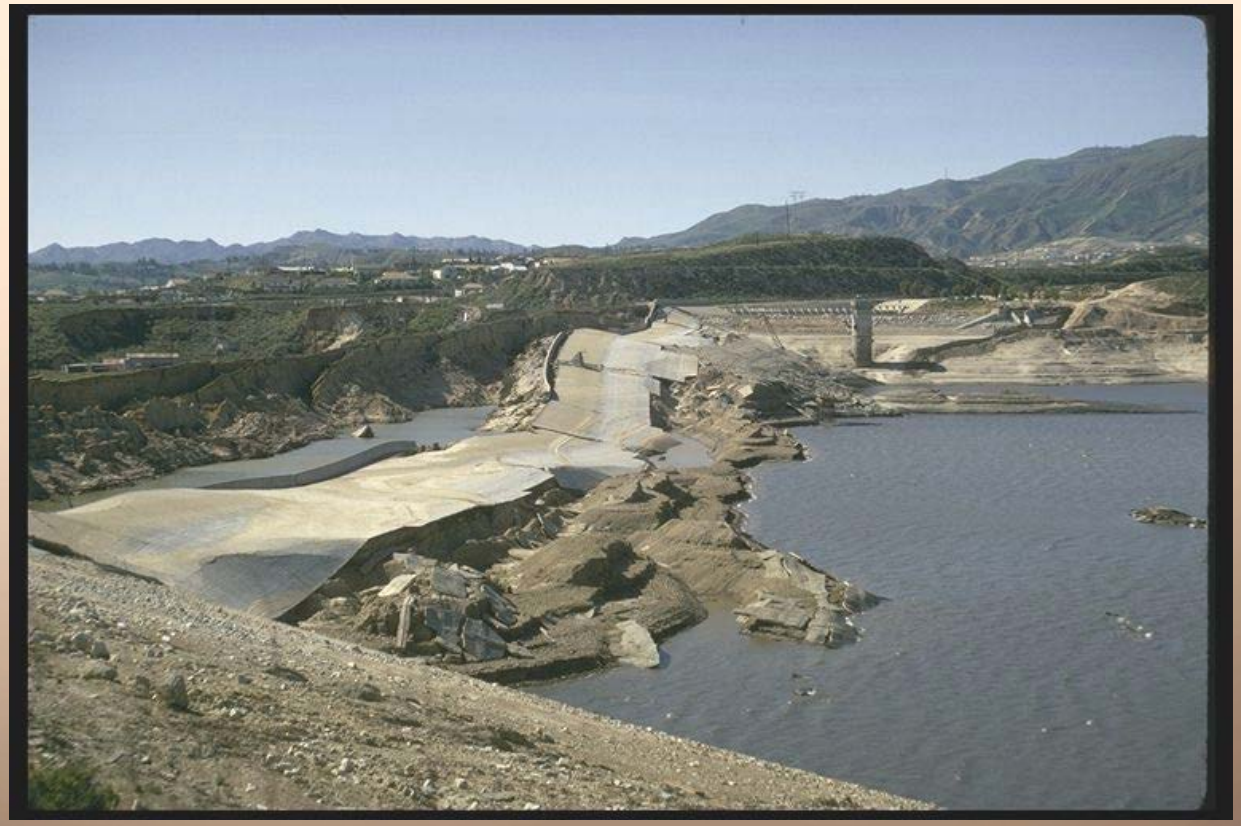

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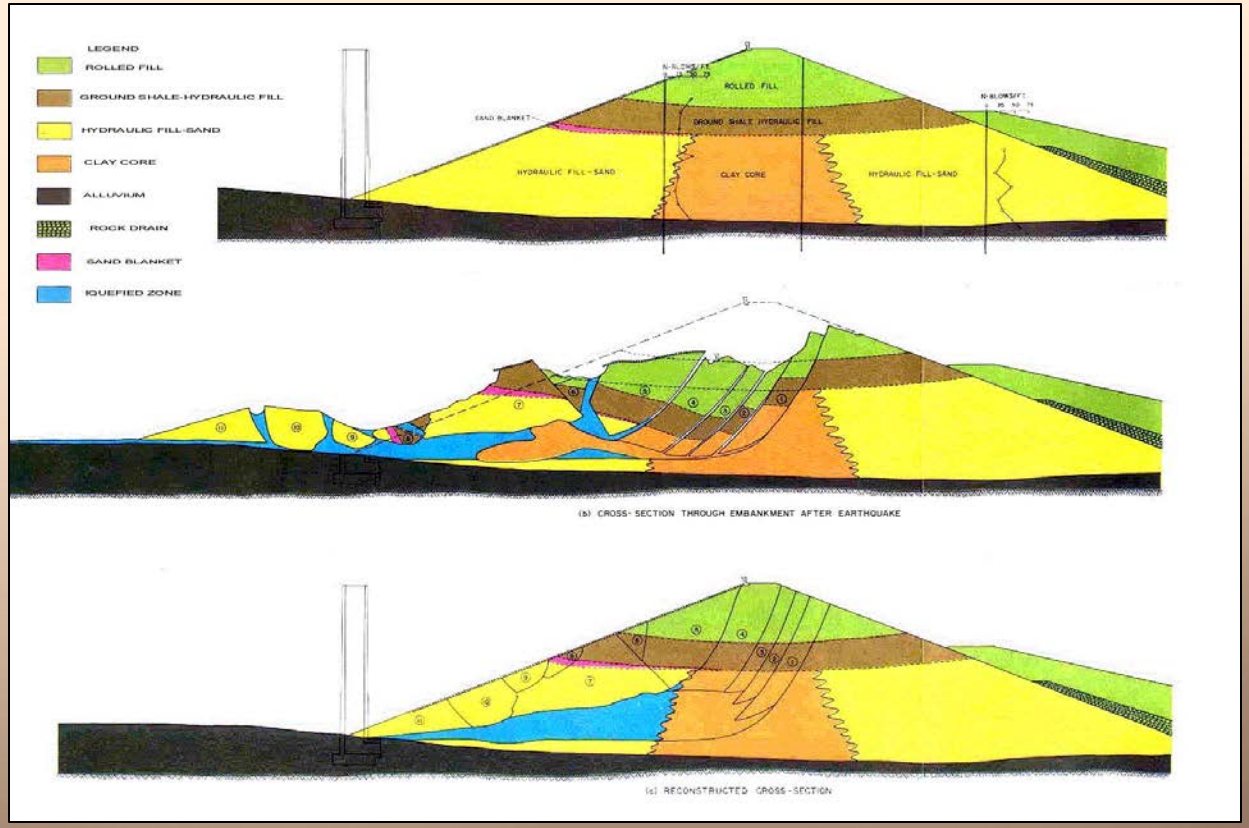
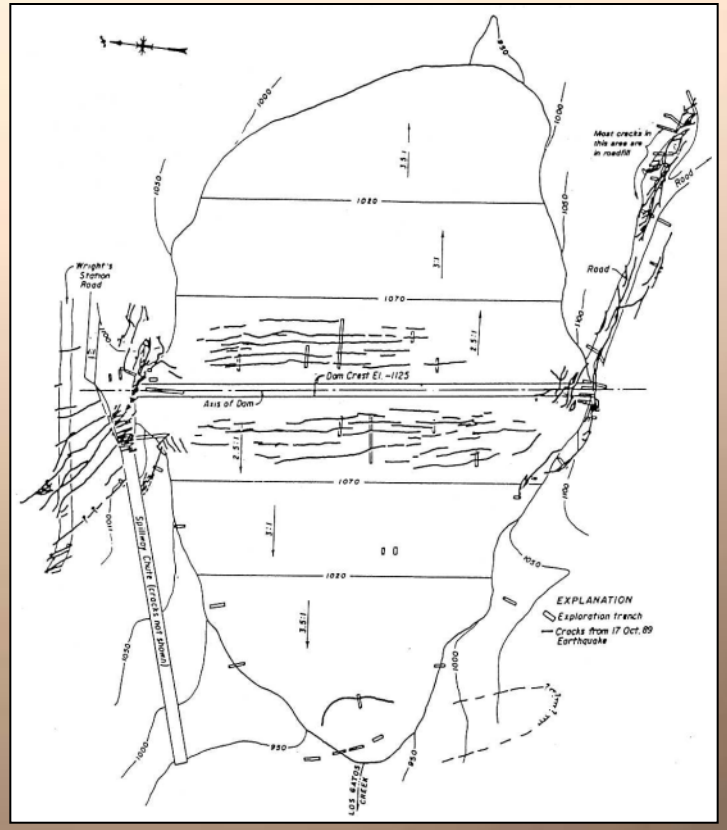
Lower San Fernando Dam (1971)



(Seed et al. 1975)

Austrian Dam (1989)

(Courtesy of Sal Todaro)



(Forster and MacDonald 1998)

Cautionary Note

- Given the lack of case history performance, the prediction of embankment behavior under earthquake loading generally has significant uncertainty.
- In spite of few historical cases, seismic failures are viewed as a legitimate threat, with a capability of sudden loss of a reservoir.

General Steps for Evaluation of Seismic Risks for Embankments

- Develop detailed site-specific failure modes
- Develop event trees to assess failure modes
- Establish loading conditions for earthquake ground motions and associated magnitudes, as well the coincident reservoir level
- Evaluate site conditions and develop representative characterization of the embankment and foundation materials
- Perform a screening by evaluating the load combinations and site characteristics to determine if seismic potential failure modes will be significant risk contributors

Steps for Evaluation of Seismic Potential Failure Modes

- Estimate the likelihood of liquefaction of any foundation or embankment materials
- Calculate the likelihood of no liquefaction (one minus the probability of liquefaction)
- Estimate the residual strength of the materials that may liquefy or may experience strength loss
- Estimate the deformation of the embankment given liquefaction
- Estimate the deformation of the embankment given no liquefaction occurs

Complete the Event Tree Similar to Static Potential Failure Modes

- For overtopping, assess the estimated deformation, and estimate a probability of overtopping for the various reservoir (freeboard) and earthquake combinations as described in Chapter IV-2 Flood Overtopping Failure.
- For cracking, assess the estimated deformation, determine the likelihood of developing transverse cracks, estimate the depth and width of the cracks, and estimate a probability of overtopping for the various reservoir (freeboard) and earthquake combinations as described in Chapter IV-4 Internal Erosion Risks for Embankments and Foundations.

Effects on Embankment Dams

- Embankment settlement and cracking, particularly near crest of dam
- Instability of upstream and downstream slopes of dam
- Reduction in freeboard due to settlement or instability which may result in overtopping of dam
- Differential movement between embankment, abutments, and spillway structures leading to cracks
- Internal erosion which may develop in cracks

Adapted from Fell (2005) *Geotechnical Engineering of Dams*

Effects on Embankment Dams

- Liquefaction and loss of shear strength due to increased pore pressures in embankment or its foundation
- Differential movements on faults in dam foundation
- Overtopping of dam in event of large tectonic movement in reservoir basin, by seiches induced upstream
- Overtopping of dam by waves due to earthquake-induced landslides into reservoir
- Damage to outlet works through embankment leading to leakage and potential internal erosion of embankment

Adapted from Fell (2005) *Geotechnical Engineering of Dams*

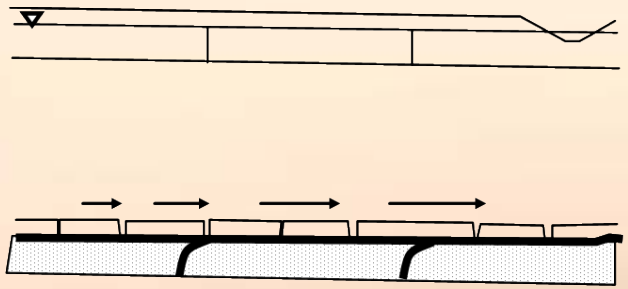
Typical Potential Failure Modes

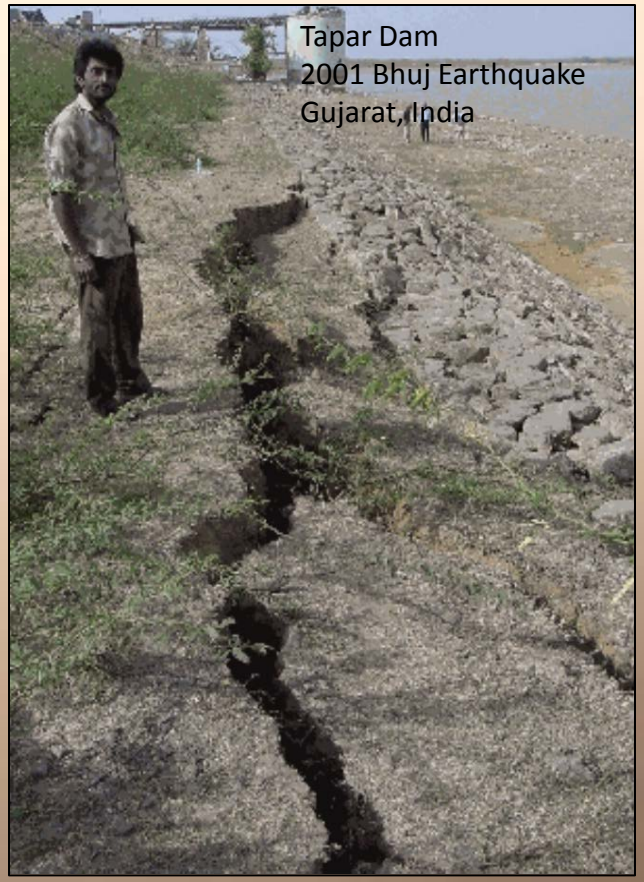
- Overtopping erosion due to deformation exceeding the available freeboard
  - Liquefaction and non-liquefaction
- Internal erosion due to transverse cracking
  - See characteristics susceptible to cracking described in Chapter 26 (Internal Erosion)
  - Liquefaction and sliding

Liquefaction

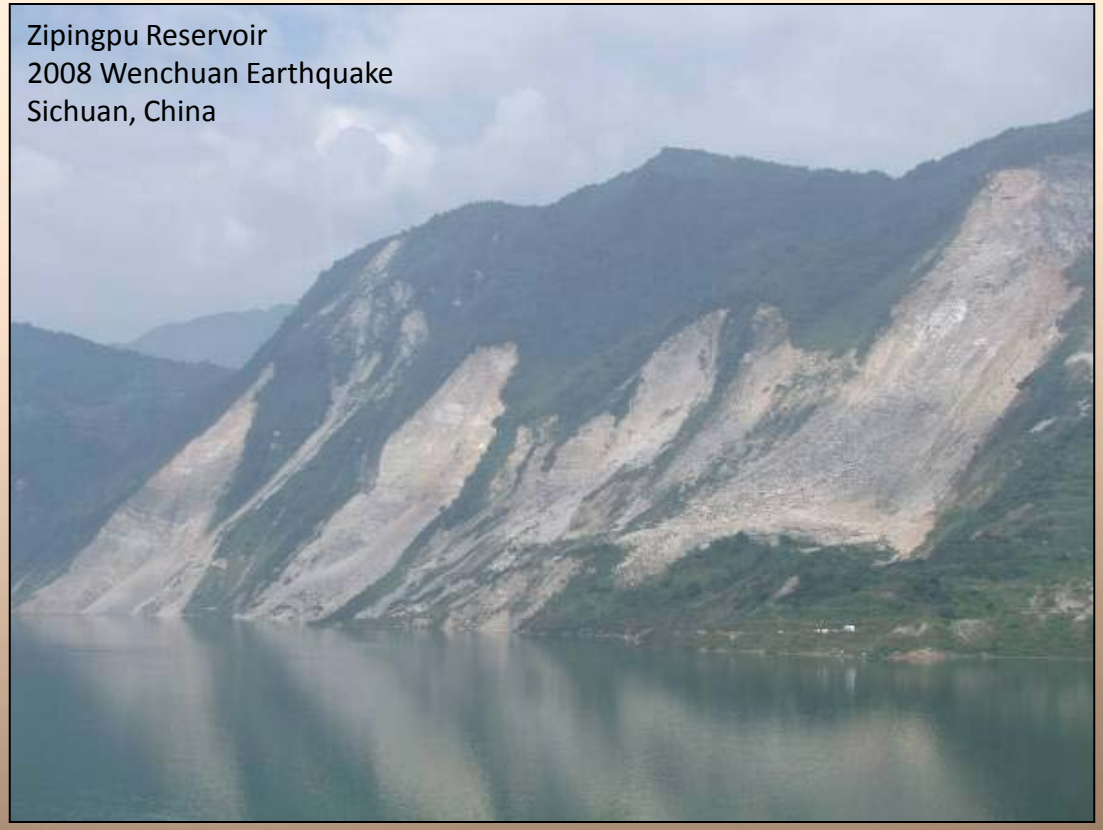
- Liquefaction occurs when earthquake shaking causes water pressure to increase in soils thus greatly reducing the shear strength of the soil.
- Saturated, clean, loose cohesionless or uncompacted materials are most susceptible.
- Liquefiable soils are common to alluvial valleys, where earth dams are typically built.

Lateral Spreading

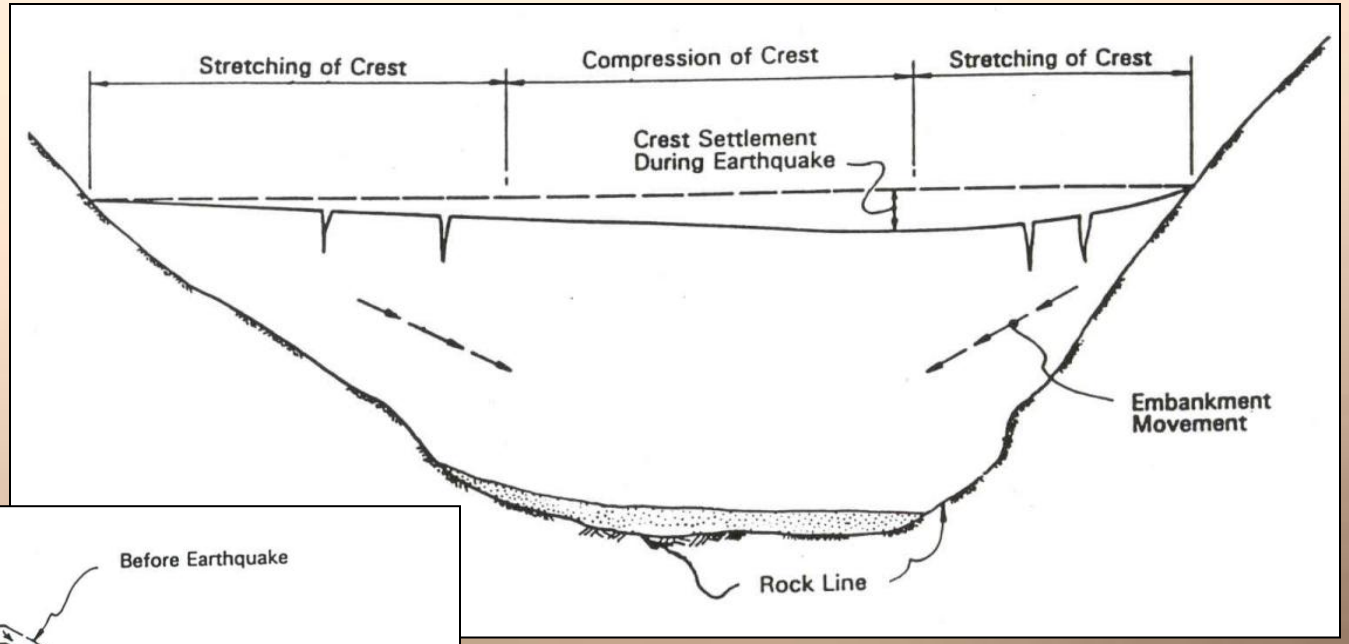


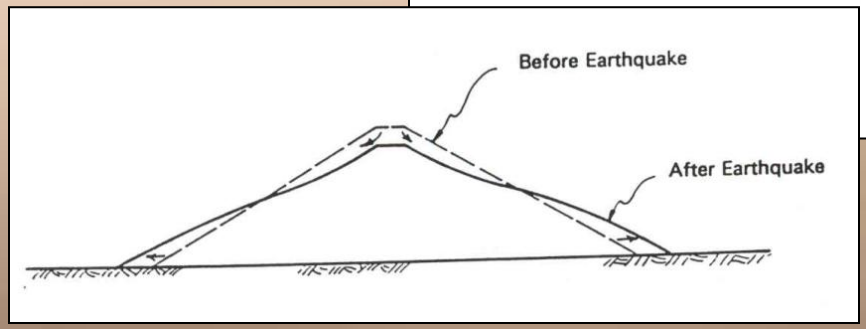


Mass Movements into Reservoir

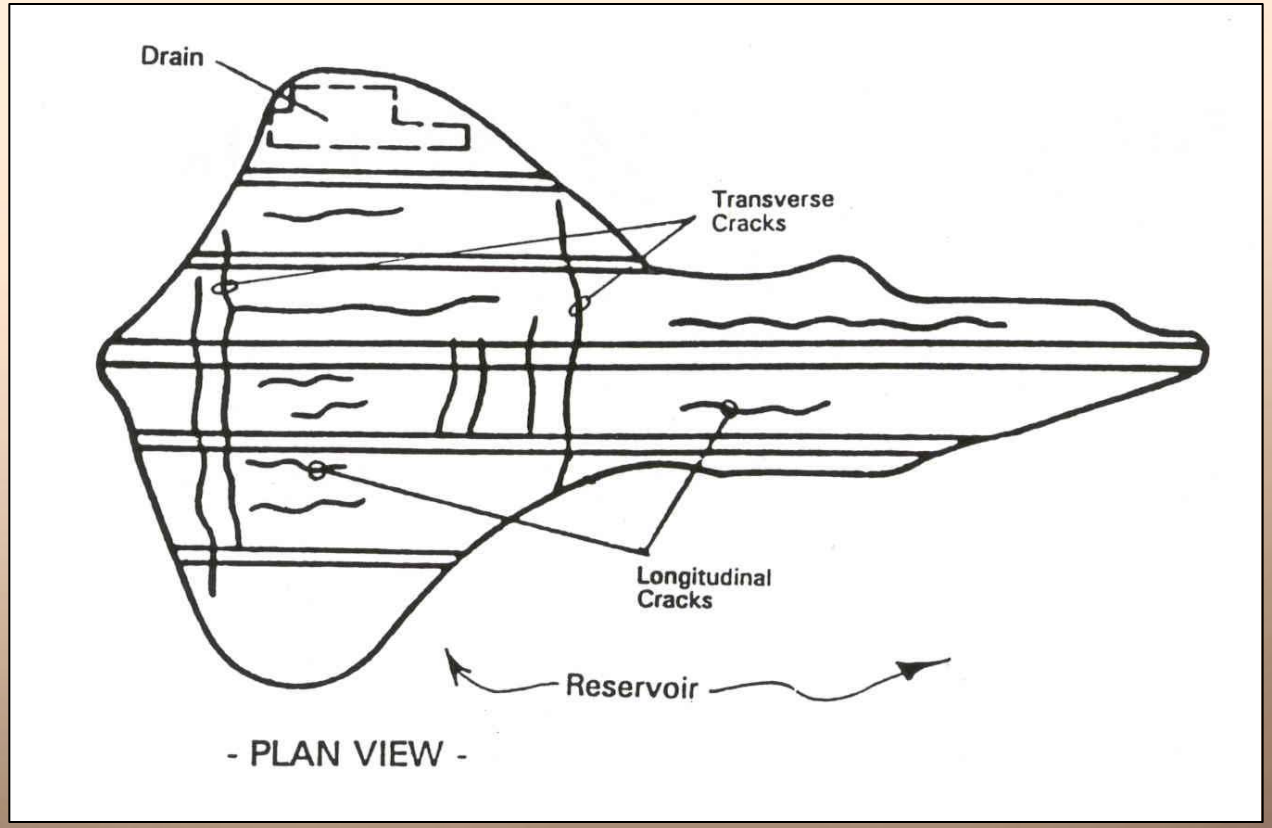


Crest Settlement and Cracking

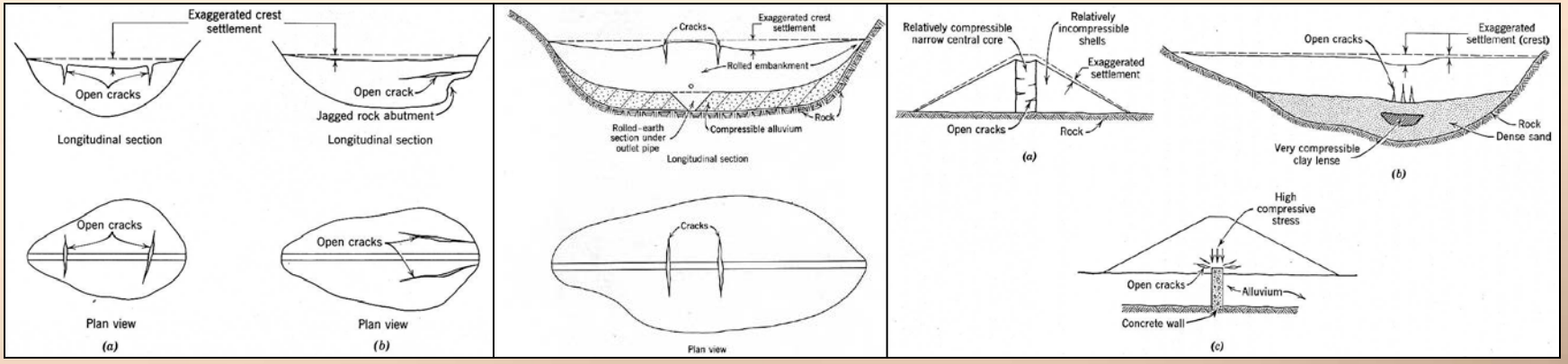




Types of Cracks



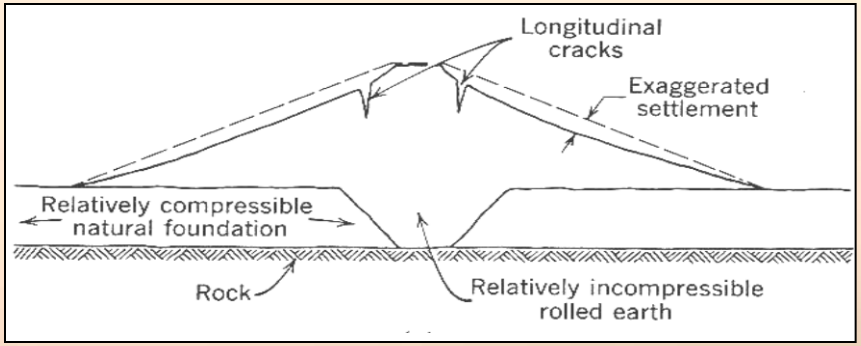
Transverse Cracking due to Differential Settlement

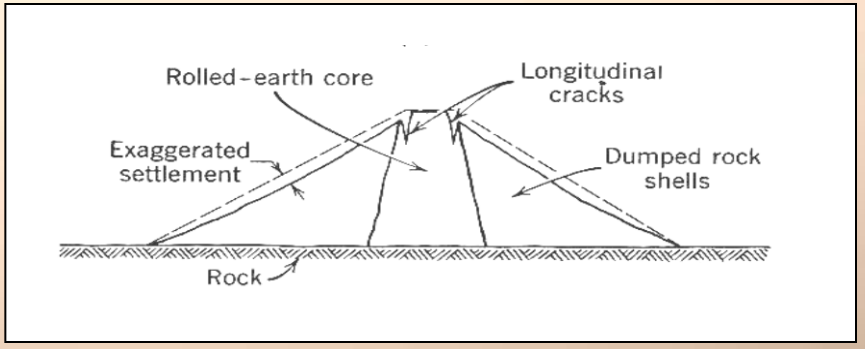


- Sudden changes in depths of embankment material the foundation.
- Highly stressed zones within the embankment.
- Differences in strength and modulus of embankment and foundation material.
- Difference in degree of compaction of embankment materials.

Source: Sherard (1963) *Earth and Earth-Rock Dams*

Longitudinal Cracking due to Differential Settlement



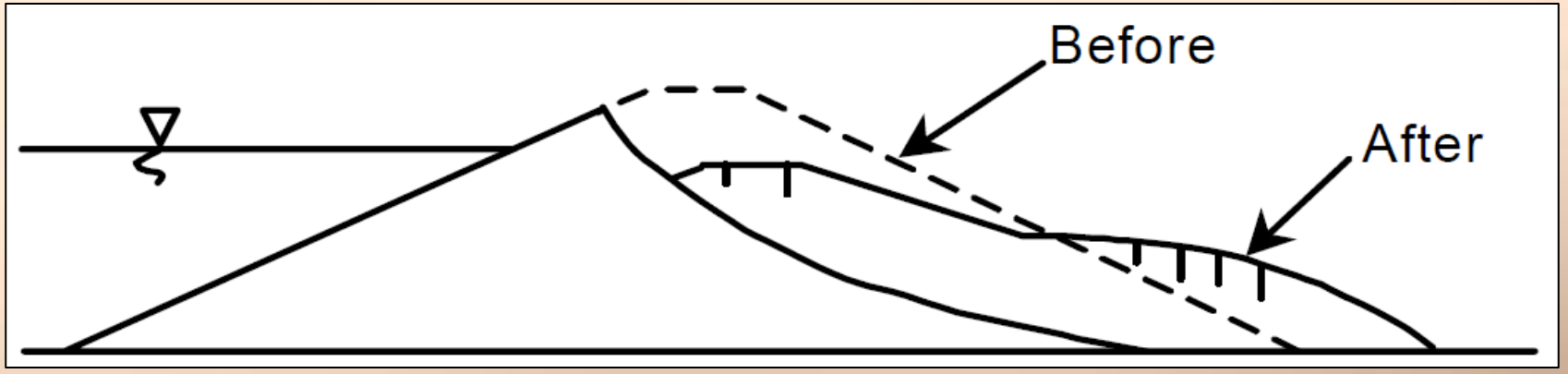


- Differential settlement over foundation discontinuities (e.g., localized liquefaction)
- Different settlement between embankment zones
- May occur in conjunction with other unseen cracks running transverse through the core.

Source: Sherard (1963) *Earth and Earth-Rock Dams*

Longitudinal Cracking

Cracking due to Non-Overtopping Slope Failure



- Often, but not always, associated with loss of embankment and/or foundation strength due to liquefaction.
- Failure surface creates a seepage path through the dam.
- Failure surface creates significant cracking in vicinity of failure surface.

Source: Resendriz et al. (1982)

Cracking due to Fault Rupture

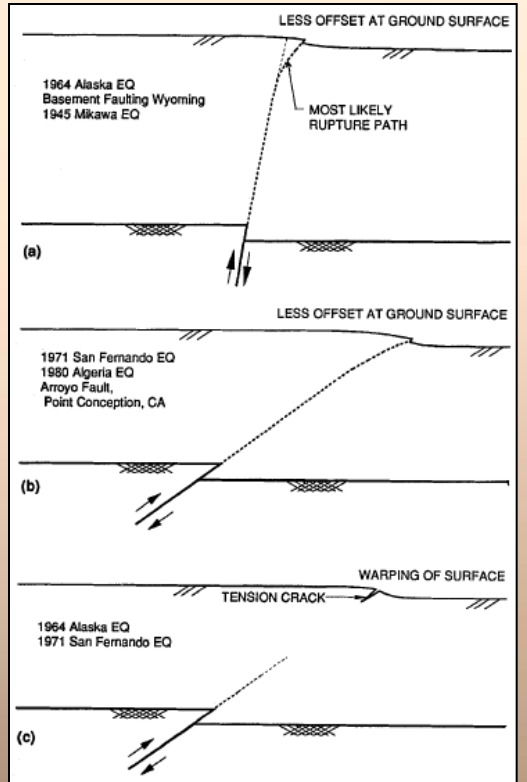


FIG. 6. Path of Reverse Fault Rupture through Soil: (a) Stiff Earth Materials, Stee Dip; (b) Stiff Earth Materials, Shallow Dip; (c) Ductile Earth Materials

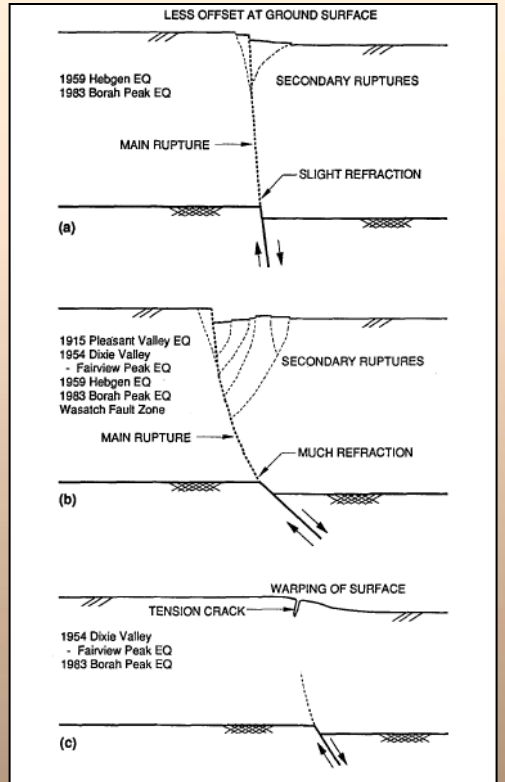


FIG. 7. Path of Normal Fault Rupture through Soil: (a) Stiff Earth Materials, Steep Dip; (b) Stiff Earth Materials, Shallow Dip; (c) Ductile Earth Materials

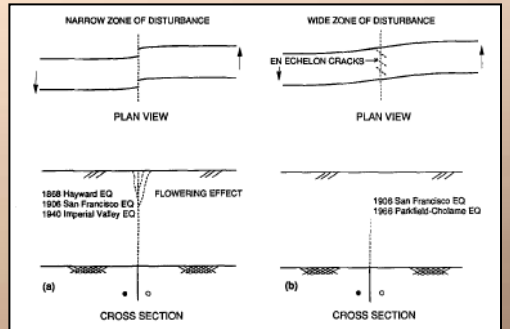


FIG. 8. Path of Strike-Slip Fault Rupture through Soil: (a) Stiff Earth Materials; (b) Ductile Earth Materials

Source: Bray et al. (1994)

San Andreas Dam, CA (1906)
Fault Rupture

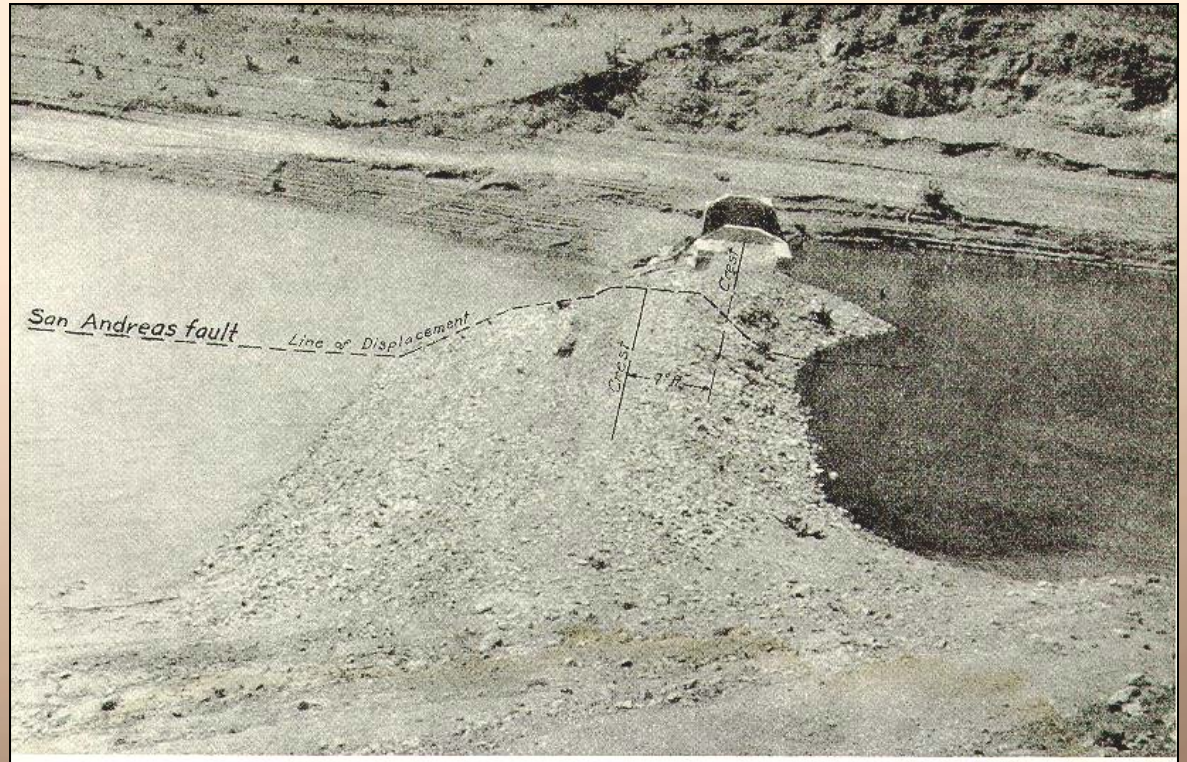


Photo by G. F. Engle, April 17, 1931

Fig. 2. View along the axis of the old dam in the San Andreas Valley (the same as fig. 1), showing the offset of about seven feet caused by the fault movement of April 18, 1906.

Cracking due to Embedded or Adjacent Structures

- At conduit contacts
  - Typically, located deep in the embankment and thus cracks may close due to confining pressures
- At spillway wall contacts
  - Separation in these areas observed in case histories
  - Typically, transverse orientation
- At concrete/embankment wrap-around sections
  - Similar behavior to the other structure contacts
  - Typically, more circuitous seepage path

PFM Screening: More Likely Factors for Damaging Deformation

- PGA greater than 0.2g
- Capable faults beneath the embankment
- Hydraulic fill embankments
- Saturated sand embankments
- Loose, saturated alluvial foundations
- Fine-grained soils susceptible to cyclic failure
- Thin impervious cores
- Thin filter zones
- Conduits embedded in embankment
- History of seismic damage
- Earth embankment-concrete section interface
- Small freeboard

adapted from Seed et al. (1978)

PFM Screening: Less Likely Factors for Damaging Deformation

- PGA less than 0.2g
- No capable faults beneath embankment
- Well-built, rolled/compacted embankment embankments (i.e., RC > 95% or D_r > 75%)
- Non-liquefiable embankment and foundation materials (i.e., embankment founded on rock, dense foundation soils with $(N_1)_{60}$ greater than 30 bpf, or foundation materials are non-sensitive clays)
- Unsaturated embankment and foundation soils
- Embankment slopes flatter than 3H:1V
- Large core and filter zones
- Rock fill shells
- Static FS greater than 1.5
- Freeboard greater than 3% to 5% of embankment height and low seismicity
- No embedded critical features that would be harmed during small embankment movements

adapted from Seed et al. (1978)

Example of Failure Mode Screening based on Joint Loading Probability

APF ≈ Σ (Annual frequency of an earthquake within PGA partition) (Fraction of a year for reservoir within partition) (Assumed SRP = 1)

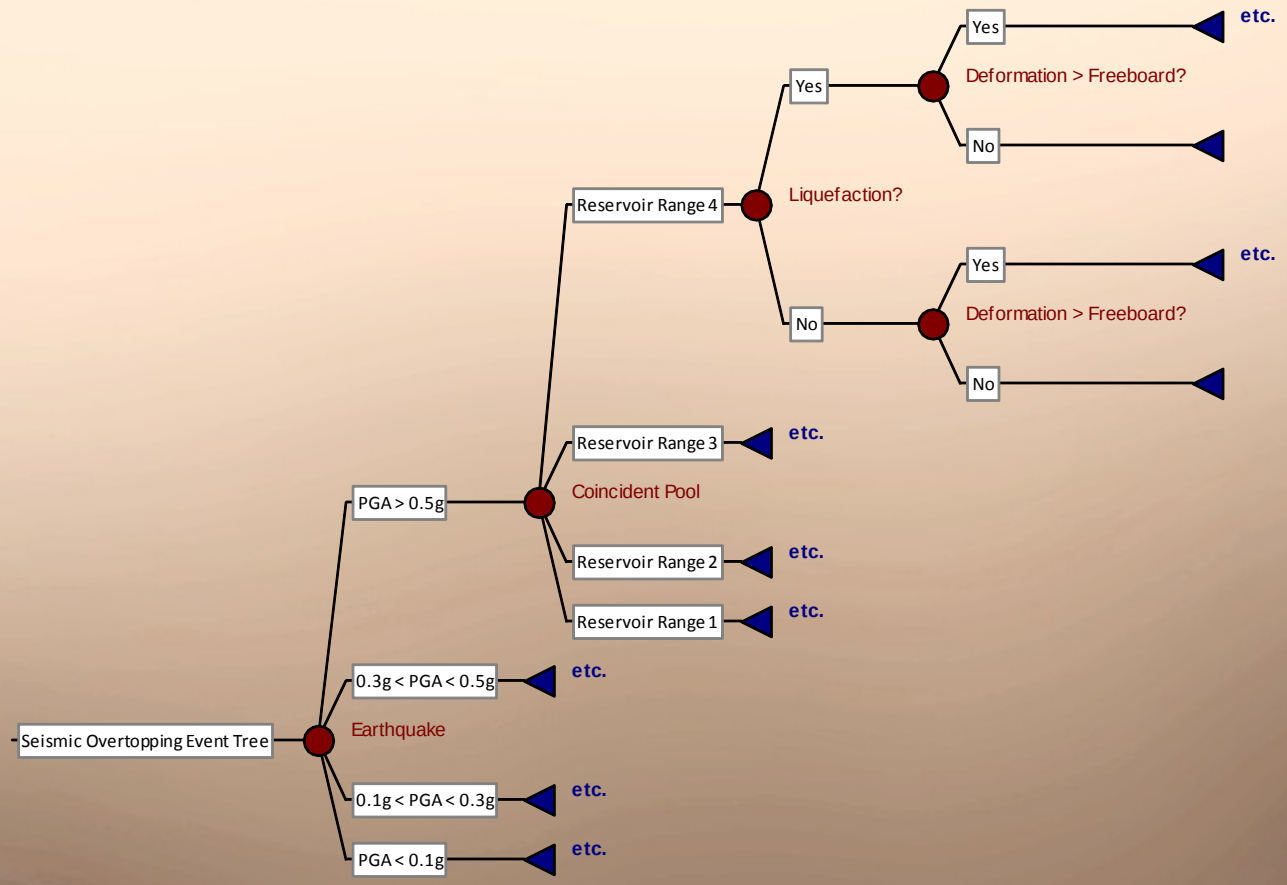
					184.0	189.0	197.5	200.0	205.0	216.5	228.5	228.6	234.0	$Pool_A$ (g)
					186.0	197.5	200.0	205.0	216.5	228.5	228.6	234.0	239.0	$Pool_B$ (g)
					1.00E+00	7.75E-02	1.91E-02	6.37E-03	2.40E-04	2.01E-05	1.51E-06	1.48E-06	4.63E-07	P_A
					2.11E-01	1.91E-02	6.37E-03	2.40E-04	2.01E-05	1.51E-06	1.48E-06	4.63E-07	1.57E-07	P_B
PGA_A (g)	PGA_B (g)	AEP_A	AEP_B	P_{AB}	7.89E-01	5.84E-02	1.27E-02	6.13E-03	2.20E-04	1.86E-05	3.23E-08	1.02E-06	3.05E-07	P_{AB}
0.000	0.050	9.26E-01	7.37E-02	8.53E-01	6.72E-01	4.98E-02	1.09E-02	5.23E-03	1.88E-04	1.59E-05	2.75E-08	8.69E-07	2.60E-07	
0.050	0.100	7.37E-02	3.04E-02	4.33E-02	3.41E-02	2.53E-03	5.52E-04	2.65E-04	9.53E-06	8.06E-07	1.40E-09	4.41E-08	1.32E-08	
0.100	0.150	3.04E-02	1.62E-02	1.41E-02	1.12E-02	8.27E-04	1.80E-04	8.67E-05	3.12E-06	2.64E-07	4.57E-10	1.44E-08	4.32E-09	
0.150	0.200	1.62E-02	9.98E-03	6.24E-03	4.92E-03	3.65E-04	7.96E-05	3.83E-05	1.38E-06	1.16E-07	2.02E-10	6.37E-09	1.91E-09	
0.200	0.250	9.98E-03	6.90E-03	3.08E-03	2.43E-03	1.80E-04	3.93E-05	1.89E-05	6.79E-07	5.74E-08	9.96E-11	3.14E-09	9.41E-10	
0.250	0.300	6.90E-03	4.95E-03	1.96E-03	1.54E-03	1.14E-04	2.49E-05	1.20E-05	4.31E-07	3.64E-08	6.32E-11	1.99E-09	5.97E-10	
0.300	0.400	4.95E-03	2.88E-03	2.07E-03	1.63E-03	1.21E-04	2.64E-05	1.27E-05	4.56E-07	3.85E-08	6.69E-11	2.11E-09	6.32E-10	
0.400	0.500	2.88E-03	1.86E-03	1.02E-03	8.02E-04	5.94E-05	1.30E-05	6.24E-06	2.24E-07	1.89E-08	3.29E-11	1.04E-09	3.10E-10	
0.500	0.600	1.86E-03	1.24E-03	6.24E-04	4.92E-04	3.64E-05	7.95E-06	3.82E-06	1.37E-07	1.16E-08	2.02E-11	6.36E-10	1.90E-10	
0.600	0.700	1.24E-03	8.52E-04	3.85E-04	3.04E-04	2.25E-05	4.91E-06	2.36E-06	8.48E-08	7.17E-09	1.24E-11	3.93E-10	1.18E-10	
0.700	0.800	8.52E-04	5.92E-04	2.60E-04	2.05E-04	1.52E-05	3.31E-06	1.59E-06	5.72E-08	4.84E-09	8.39E-12	2.65E-10	7.93E-11	
0.800	0.900	5.92E-04	4.26E-04	1.67E-04	1.32E-04	9.74E-06	2.13E-06	1.02E-06	3.67E-08	3.11E-09	5.39E-12	1.70E-10	5.09E-11	
0.900	1.000	4.26E-04	3.06E-04	1.20E-04	9.45E-05	7.00E-06	1.53E-06	7.35E-07	2.64E-08	2.23E-09	3.87E-12	1.22E-10	3.66E-11	
1.000	1.250	3.06E-04	1.41E-04	1.65E-04	1.30E-04	9.62E-06	2.10E-06	1.01E-06	3.63E-08	3.07E-09	5.32E-12	1.68E-10	5.03E-11	
1.250	1.500	1.41E-04	6.69E-05	7.40E-05	5.84E-05	4.32E-06	9.43E-07	4.54E-07	1.63E-08	1.38E-09	2.39E-12	7.55E-11	2.26E-11	
1.500	1.750	6.69E-05	3.34E-05	3.35E-05	2.64E-05	1.96E-06	4.27E-07	2.05E-07	7.37E-09	6.23E-10	1.08E-12	3.41E-11	1.02E-11	
1.750	2.000	3.34E-05	1.68E-05	1.67E-05	1.31E-05	9.73E-07	2.12E-07	1.02E-07	3.67E-09	3.10E-10	5.38E-13	1.70E-11	5.08E-12	
2.000	2.250	1.68E-05		#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
2.250	2.500			#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	**Total**
2.500	3.000			#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	**APF**
					7.31E-01	5.41E-02	1.18E-02	5.68E-03	2.04E-04	1.73E-05	2.99E-08	9.45E-07	2.83E-07	**8.02E-01**

Example of Failure Mode Screening based on Joint Loading Probability

APF ≈ Σ (Annual frequency of an earthquake within PGA partition) (Fraction of a year for reservoir within partition) (Assumed SRP = 1)

					184.0	189.0	197.5	200.0	205.0	216.5	228.5	228.6	234.0	$Pool_A$ (g)
					186.0	197.5	200.0	205.0	216.5	228.5	228.6	234.0	239.0	$Pool_B$ (g)
					1.00E+00	7.75E-02	1.91E-02	6.37E-03	2.40E-04	2.01E-05	1.51E-06	1.48E-06	4.63E-07	P_A
					2.11E-01	1.91E-02	6.37E-03	2.40E-04	2.01E-05	1.51E-06	1.48E-06	4.63E-07	1.57E-07	P_B
PGA_A (g)	PGA_B (g)	AEP_A	AEP_B	P_{AB}	7.89E-01	5.84E-02	1.27E-02	6.13E-03	2.20E-04	1.86E-05	3.23E-08	1.02E-06	3.05E-07	P_{AB}
0.000	0.050	9.26E-01	7.37E-02	8.53E-01										
0.050	0.100	7.37E-02	3.04E-02	4.33E-02										
0.100	0.150	3.04E-02	1.62E-02	1.41E-02										
0.150	0.200	1.62E-02	9.98E-03	6.24E-03										
0.200	0.250	9.98E-03	6.90E-03	3.08E-03										
0.250	0.300	6.90E-03	4.95E-03	1.96E-03										
0.300	0.400	4.95E-03	2.88E-03	2.07E-03					4.56E-07	3.85E-08	6.69E-11	2.11E-09	6.32E-10	
0.400	0.500	2.88E-03	1.86E-03	1.02E-03					2.24E-07	1.89E-08	3.29E-11	1.04E-09	3.10E-10	
0.500	0.600	1.86E-03	1.24E-03	6.24E-04					1.37E-07	1.16E-08	2.02E-11	6.36E-10	1.90E-10	
0.600	0.700	1.24E-03	8.52E-04	3.85E-04					8.48E-08	7.17E-09	1.24E-11	3.93E-10	1.18E-10	
0.700	0.800	8.52E-04	5.92E-04	2.60E-04					5.72E-08	4.84E-09	8.39E-12	2.65E-10	7.93E-11	
0.800	0.900	5.92E-04	4.26E-04	1.67E-04					3.67E-08	3.11E-09	5.39E-12	1.70E-10	5.09E-11	
0.900	1.000	4.26E-04	3.06E-04	1.20E-04					2.64E-08	2.23E-09	3.87E-12	1.22E-10	3.66E-11	
1.000	1.250	3.06E-04	1.41E-04	1.65E-04					3.63E-08	3.07E-09	5.32E-12	1.68E-10	5.03E-11	
1.250	1.500	1.41E-04	6.69E-05	7.40E-05					1.63E-08	1.38E-09	2.39E-12	7.55E-11	2.26E-11	
1.500	1.750	6.69E-05	3.34E-05	3.35E-05					7.37E-09	6.23E-10	1.08E-12	3.41E-11	1.02E-11	
1.750	2.000	3.34E-05	1.68E-05	1.67E-05					3.67E-09	3.10E-10	5.38E-13	1.70E-11	5.08E-12	
2.000	2.250	1.68E-05		#VALUE!										
2.250	2.500			#VALUE!										**Total**
2.500	3.000			#VALUE!										**APF**
					#N/A	#N/A	#N/A	#N/A	1.09E-06	9.18E-08	1.59E-10	5.03E-09	1.50E-09	**1.18E-06**

Sample Event Tree for Seismic Crest Deformation



Seismic Loading Considerations

- AEP relationship for either peak horizontal ground acceleration (PGA) or spectral acceleration (SA) at a specified period of range of periods
- Acceleration time histories also used
- Deaggregations needed for magnitude with greatest contribution to the loading partition.
  - USGS has a number of useful tools

Reservoir Loading Considerations

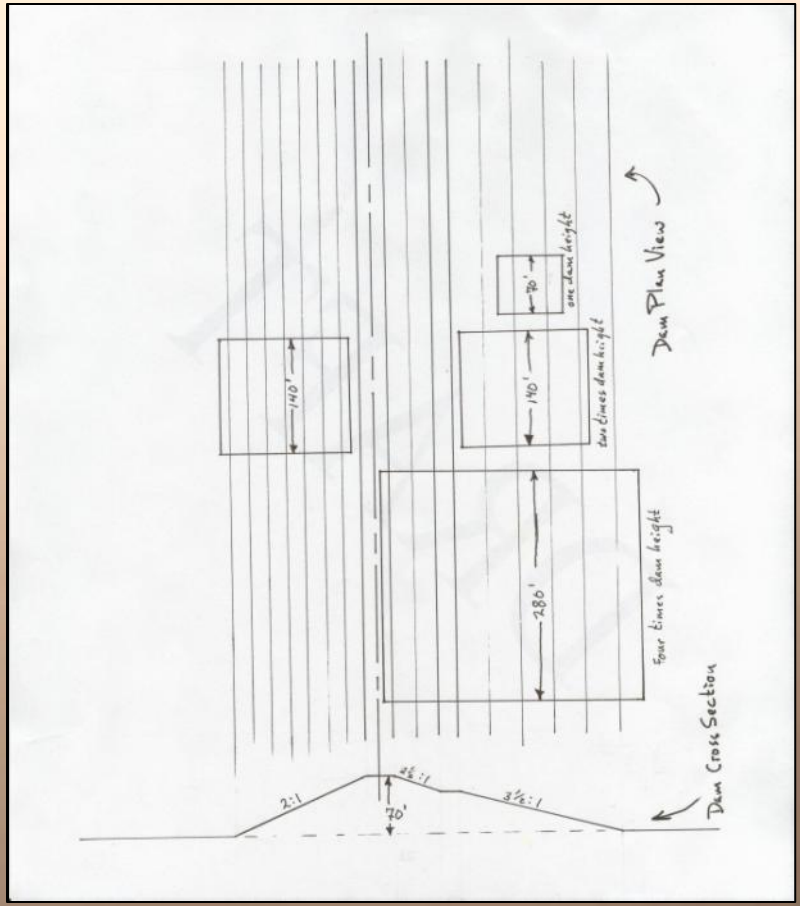
- For water supply dams with a relatively constant reservoir level, consider the normal operating level or percentage of time above a threshold level.
- For flood control dams with large fluctuations in reservoir level, failure modes are also a function of the coincident reservoir level
  - Use stage-duration relationship for frequencies
  - SRP = f(PGA or M_w, Coincident Pool)

Characterization

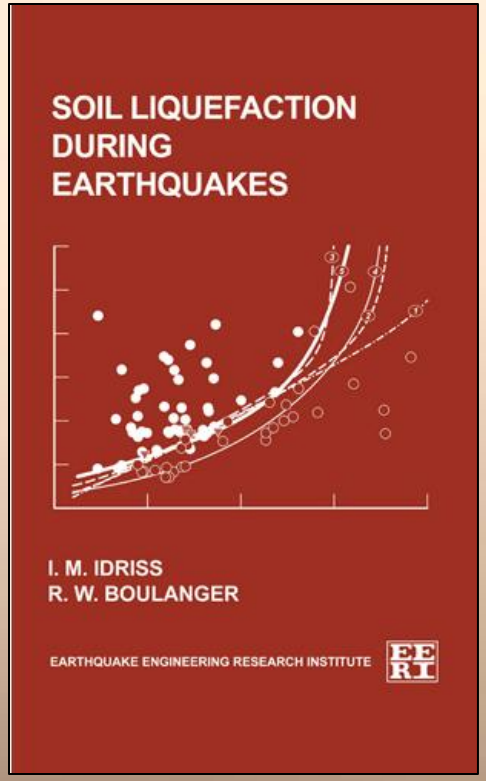
- Likelihood of a continuous layer or zone of potentially liquefiable materials.
  - Informed by borehole test data (SPT, CPT, BPT, shear waves, etc.)
  - Assign “representative” values for field and laboratory test data

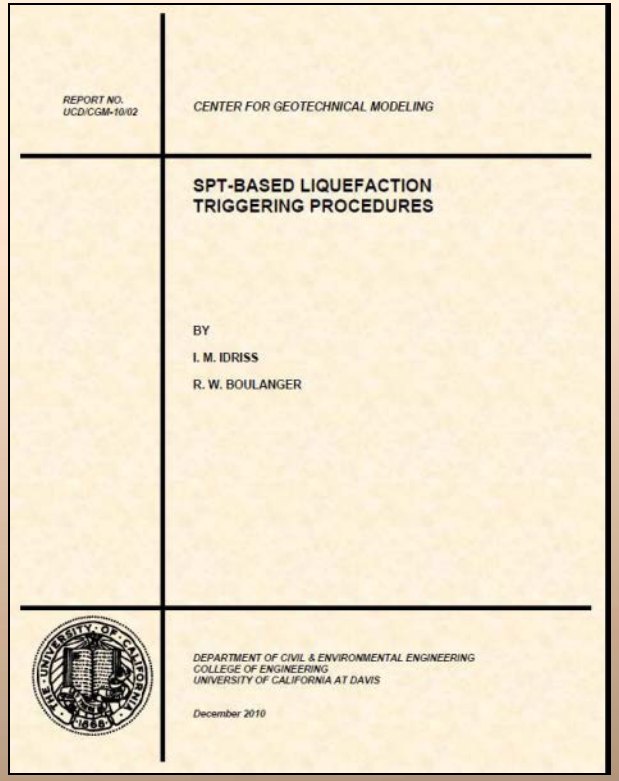
“Representative” Blow Count

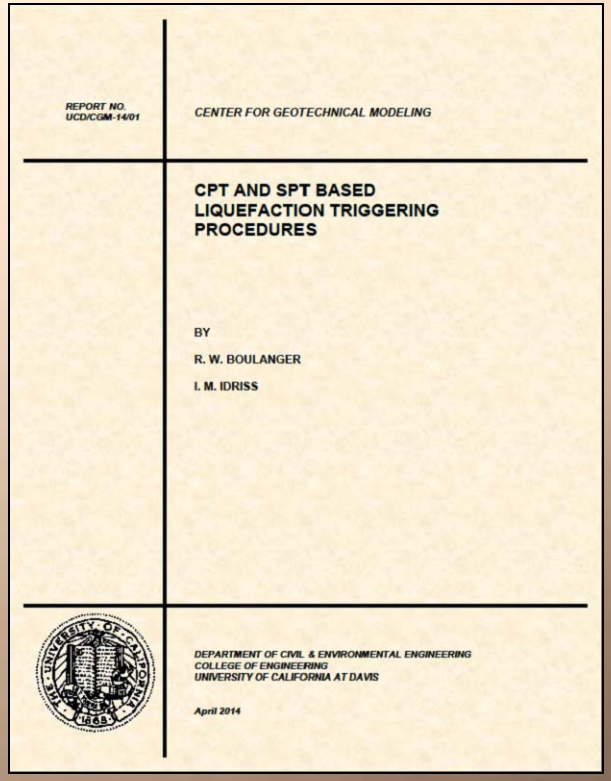
Consider whether there is a weaker layer that controls the response, and what area the liquefiable materials cover.



Likelihood of Liquefaction







Probability of Liquefaction

Boulanger and Idriss (2010):

$$CSR_{M=7.5,\sigma'_v=1atm} = 0.65\frac{\sigma_v}{\sigma'_v}\frac{a_{max}}{g}r_d\frac{1}{MSF}\frac{1}{K_\sigma}$$

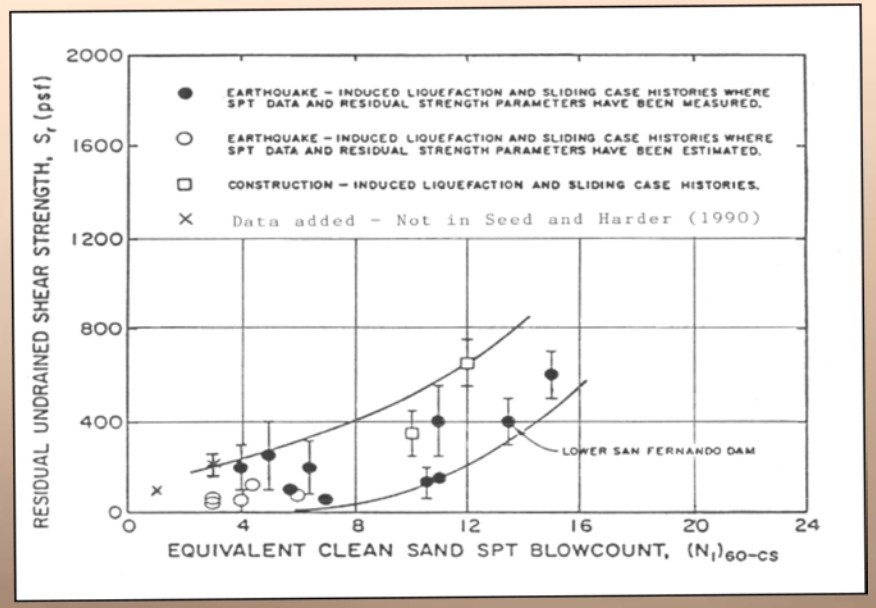
$$P_L\left((N_1)_{60cs}, CSR_{M=7.5,\sigma'_v=1atm}\right) = \left[\frac{\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.67 - ln\left(CSR_{M=7.5,\sigma'_v=1atm}\right)}{0.13}\right]$$

Probability of no liquefaction: $P_{NL} = 1 - P_L$

Residual Shear Strength of Liquefied Soil

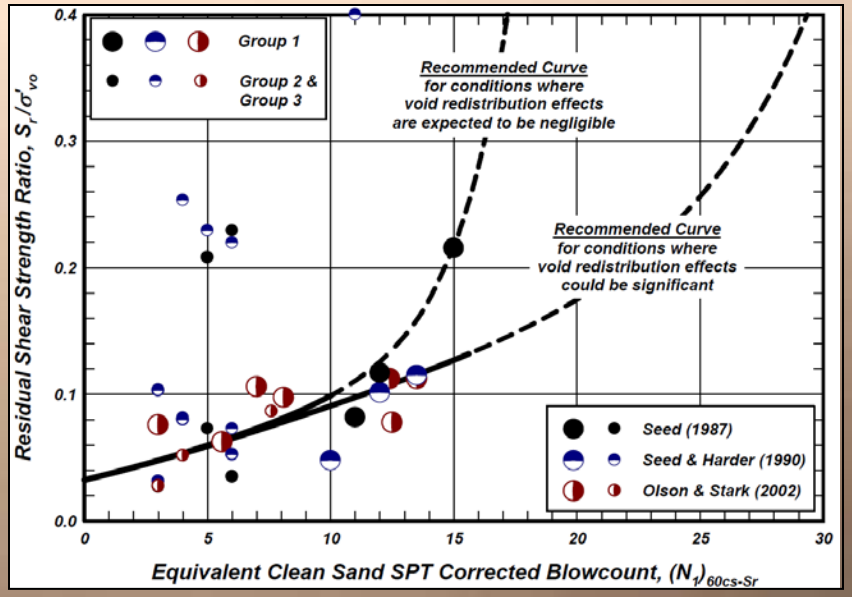
Seed and Harder (1990)

$S_r = f((N_1)_{60cs})$



Idriss and Boulanger (2008)

$S_r/\sigma'_{vc} = f((N_1)_{60\text{-}Sr})$



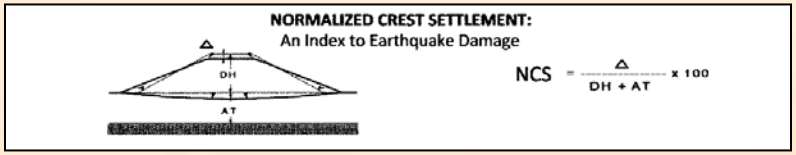
Embankment Deformation

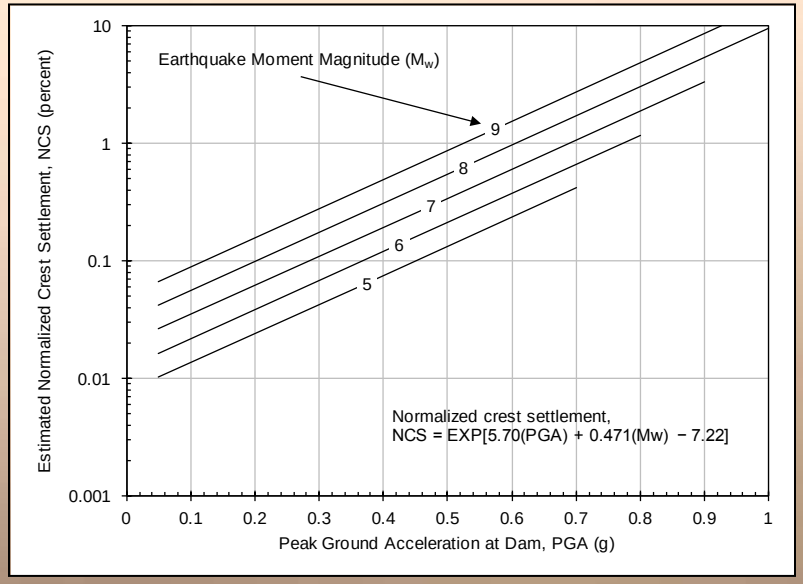
- There are numerous methods to estimate seismic deformations.
  - Unfortunately none of the methods, accurately predict actual deformation shape and magnitudes.
  - Risk assessment team must be familiar with the assumptions and limitations of the methods used and apply significant judgment when assessing the probabilities.

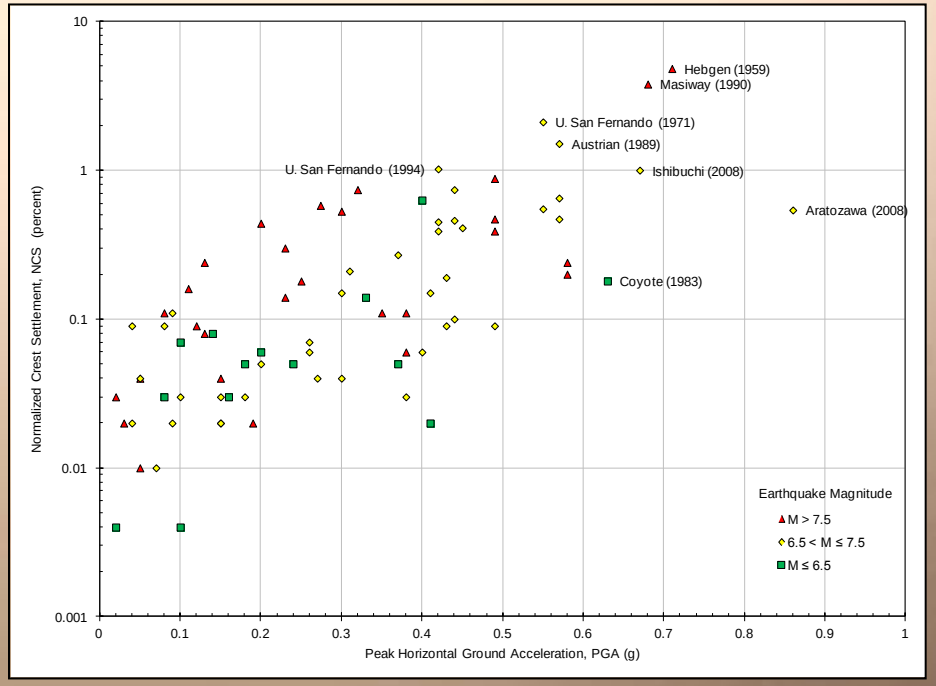
Embankment Deformation (cont.)

- Use simplified methods for screening.
- More refined studies (FLAC) may be justified.
  - Loss of freeboard as a function of loading
  - Loss of freeboard as a function of undrained residual shear strength of the liquefied materials.

Empirical Deformation (No Liquefaction occurs)



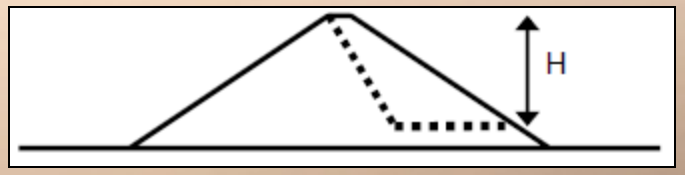




Swaisgood (1998, 2003, 2014)

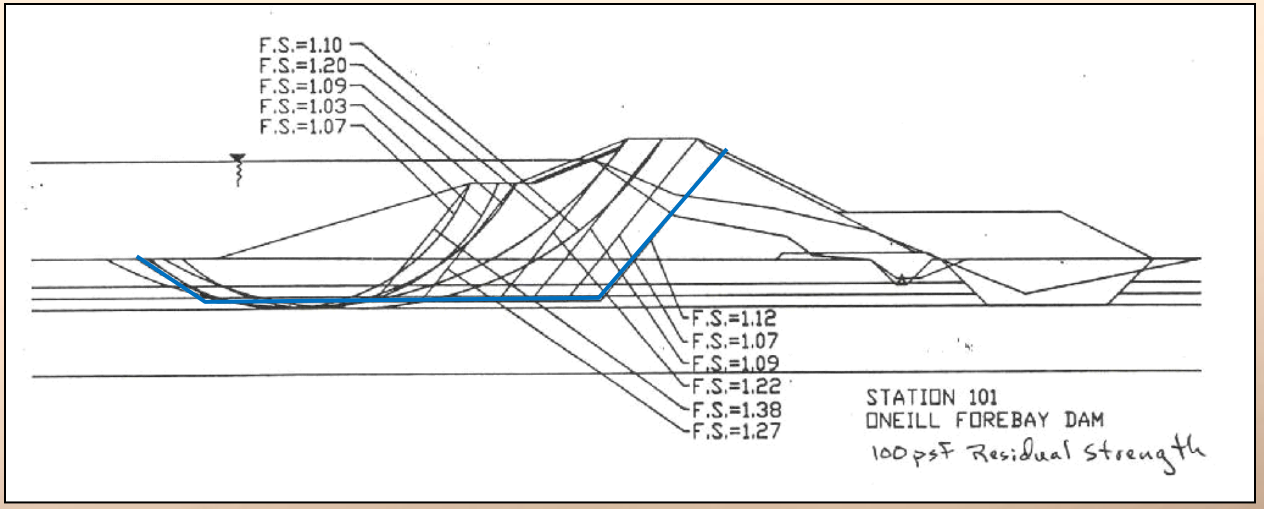
Simplified Dynamic Sliding Mass Deformation

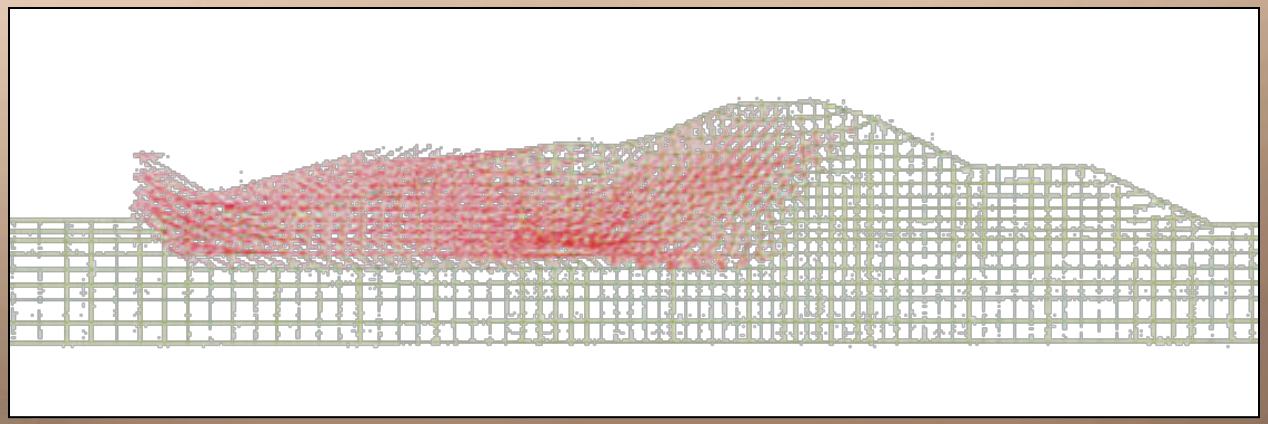
- Newmark (1965) and modified and updated by
  - Makdisi and Seed (1978)
  - Watson-Lamprey and Abrahamson (2006)
  - Bray and Travasarou (2007)



- Limitations include:
  - Deformation assumed along sliding mass, not entire embankment
  - Deformation assumed to only occur during shaking
  - Only valid for non-liquefied embankment materials

Post-Earthquake Stability Analysis

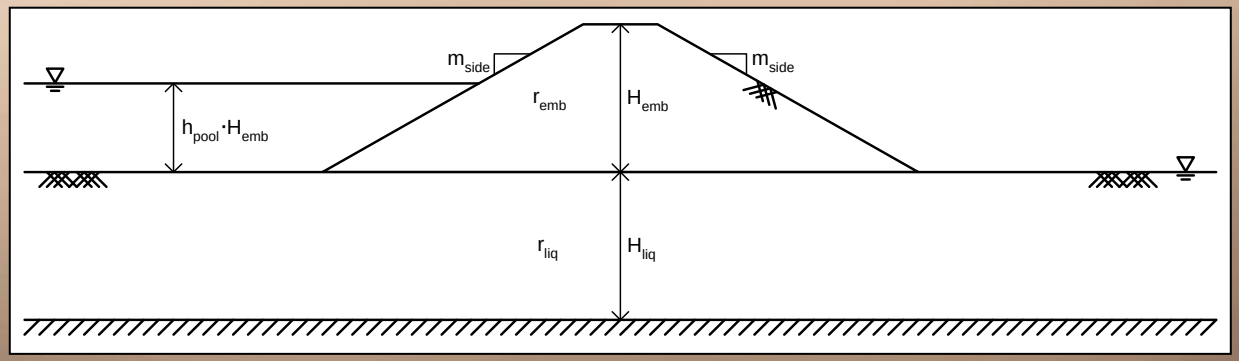




Simplified Post-Earthquake Deformation Screening

- FMSM (2007) performed a parametric study of over 20,000 cases using FLAC with 8,612 converged solutions.

$$\log_{10}(\Delta) = -6.399 \cdot H_{emb}^{-1} - 0.6023 \cdot \log_{10}(r_{emb}) + 1.581 \cdot \log_{10}(m_{side})$$
$$- 4.689 \cdot h_{pool} H_{emb}^{-1} + 0.9123 h_{pool}^{3} - 6.256 \cdot H_{liq}^{-1} - 8.428 \cdot r_{liq} + 2.620$$

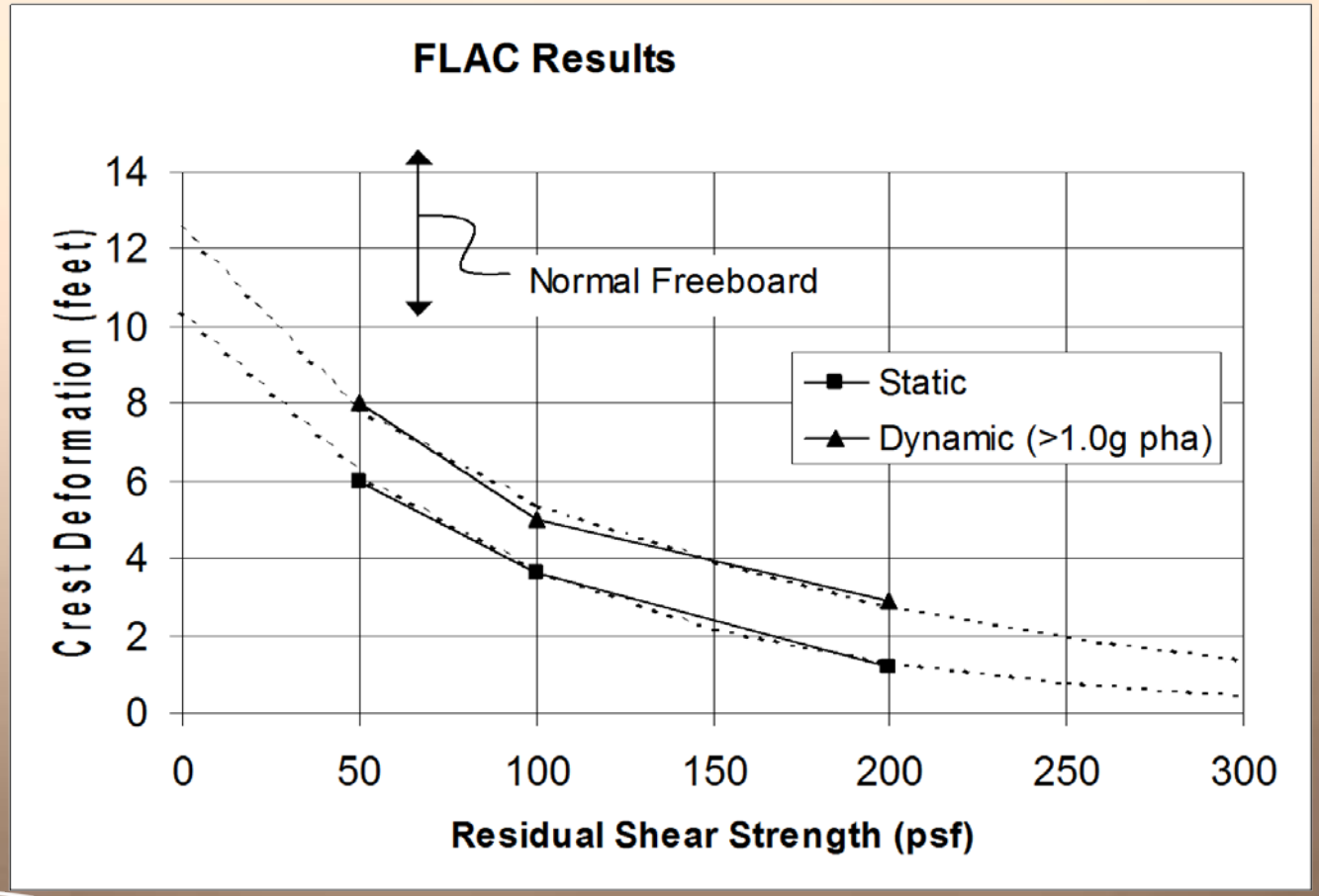


$R^2 = 0.803$

Numerical Post-Earthquake Deformation

- Use a computer program such as FLAC
  - Model potentially liquefiable materials using residual undrained shear strengths
  - Evaluate deformed shape and displacement magnitudes from applied gravity loading only
- Neglects dynamic deformations that could occur during shaking

Numerical Dynamic and Post-Earthquake Deformation



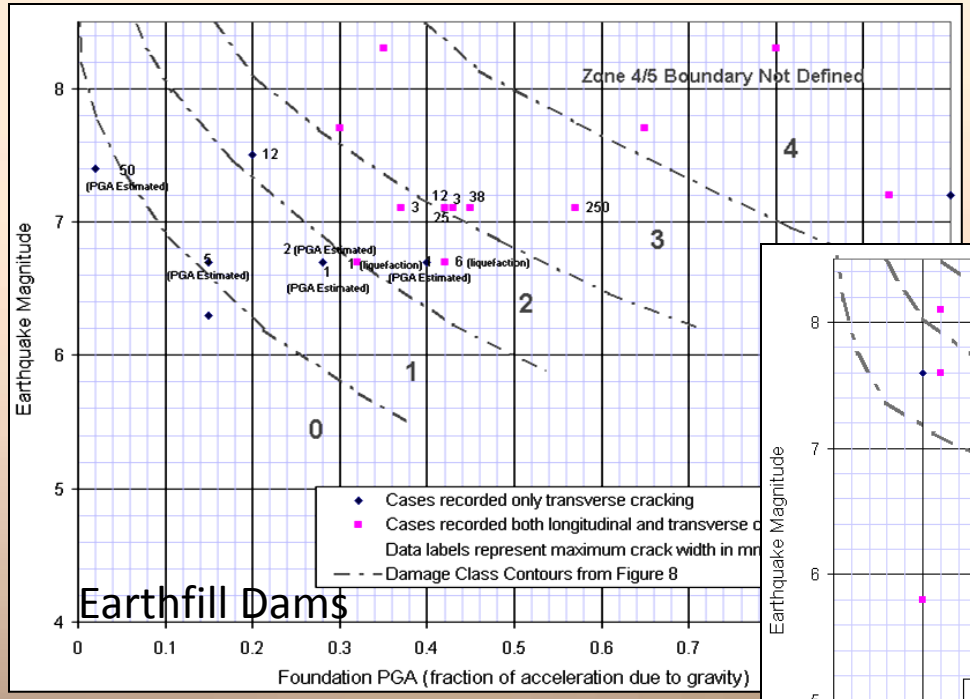
Internal Erosion through Cracks

- Estimate damage class from deaggregation of seismic hazard for each seismic load partition
  - Assume Damage Class 3 or 4 if liquefaction occurs
- Estimate maximum likely crest settlement.
  - Cracking begins at settled crest elevation
- Estimate probability of transverse cracking
  - Use expert elicitation and Fell et al. (2008) as guide

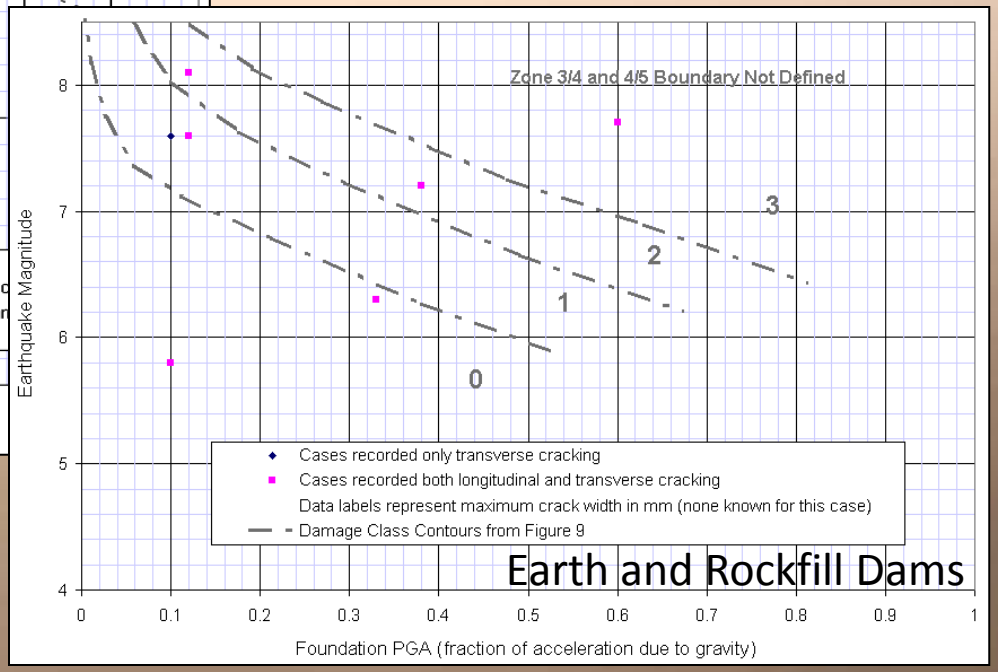
Internal Erosion through Cracks (cont.)

- Estimate maximum likely crack width at the crest using Fell et al. (2008) as guide
- Estimate maximum likely crack depth.
- Estimate probability of initiation of concentrated leak erosion for reservoir partitions
  - See Chapter IV-4 Internal Erosion

Damage Class = f (PGA, M_w)



PGA-M_w pairs can be obtained from seismic hazard deaggregation



Pells and Fell (2002, 2003)

Probability of Transverse Cracking

Damage Class		Maximum Longitudinal Crack Width (1) (mm)	Maximum Relative Crest Settlement (2) (percent)
Number	Description		
0	No or Slight	< 10	< 0.03
1	Minor	10 to 30	0.03 to 0.2
2	Moderate	30 to 80	0.2 to 0.5
3	Major	80 to 150	0.5 to 1.5
4	Severe	150 to 500	1.5 to 5
5	Collapse	> 500	> 5

Notes: (1) Maximum likely crack width is taken as the maximum width of any longitudinal crack that occurs.
(2) Maximum relative crest settlement is expressed as a percentage of the structural height.

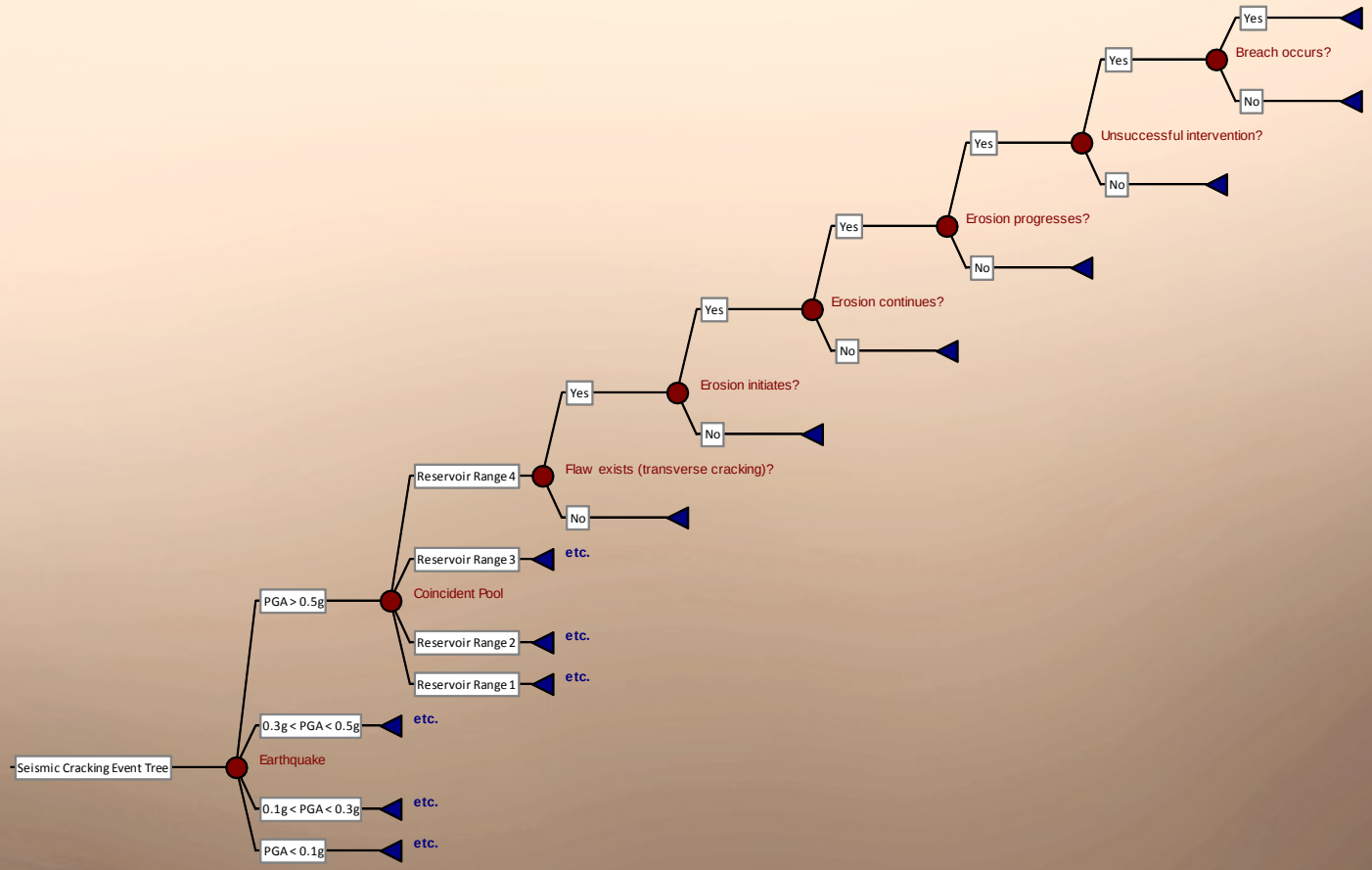
Damage Class		Probability of Transverse Cracking	Maximum Likely Crack Width at the Crest (mm)
Number	Description		
0	No or Slight	0.001 to 0.01	5 to 20
1	Minor	0.01 to 0.05	20 to 50
2	Moderate	0.05 to 0.10	50 to 75
3	Major	0.2 to 0.25	100 to 125
4	Severe	0.5 to 0.6	150 to 175

Main Issues to Consider

- Defensive measures of dam: filters to prevent or control internal erosion of the dam and its foundation; zones of good drainage capacity (e.g., free-draining rockfill)
- Embankment stability during and immediately after the earthquake
- Earthquake-induced deformations (i.e., settlement and cracking) and dam freeboard
- Liquefaction potential of saturated sandy and silty soils and some gravels with a sand and silt matrix in the foundation, and possibly in the embankment

Adapted from Fell (2005) *Geotechnical Engineering of Dams*

Exercise

- Using the event tree in Figure IV-6-6 as a guide develop an event tree to assess the probability of failure for deformation leading to transverse cracking and internal erosion through the cracks

Possible Exercise Solution