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Engineers & Economists

EERI Liquefaction Short Course
Salt Lake City, Utah
April 9, 2014

Examples of Accommodating Liquefaction Induced Failure Modes In the Risk Assessment of Dams

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Introduction

- Focus today on Risk Assessment for Failure Modes associated with Earthquake Induced Liquefaction
- Risk Assessment Process
- Risk Assessment Criteria
- Examples involving liquefaction
- Conclusions

Risk Assessment Process

- Loading Conditions – Consider a Full Range of Loading
  - Flood
  - Earthquake
  - Normal operating (may be included with Flood Loading)
- Potential Failure Modes Analysis
  - Identify Credible and Significant PFMs
  - Must understand the Failure Mode
  - Detailed description
- Event Tree Risk Model
- Probability and Consequences of Failure
- Evaluate against criteria
- Repeat for all Risk Reduction Measures

USACE Tolerable Risk Guidelines

- Existing Dams

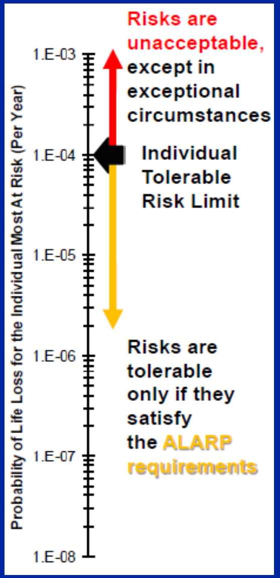
A) LIMIT GUIDELINES that should not be exceeded regardless of cost except in exceptional circumstances:

1) Annual Probability of Failure (APF) < 1 in 10,000 per yr

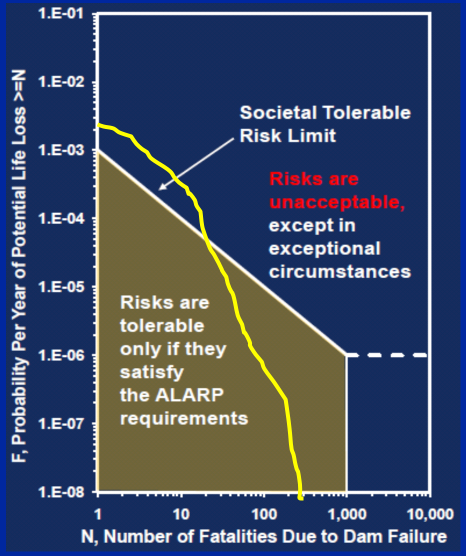
2) Individual Risk (IR)

- Probability of life loss for the most exposed individual

= APF if assume 24x7 presence below dam



3) Societal Risk (SR) - A probability distribution (F-N chart) of the number of fatalities from entire PAR



4) Annualized Life Loss (ALL) – Av. annual life loss < 0.001 lives/yr

B) ALARP (As Low As Reasonably Practicable) considerations:

1) Level of risk compared with Limit Guidelines; 2&3) Cost effectiveness of further risk reduction below the Limit Guidelines (BCR, CSSL, Disproportionality); 4) Essential USACE guidelines; and 5) Consultation.

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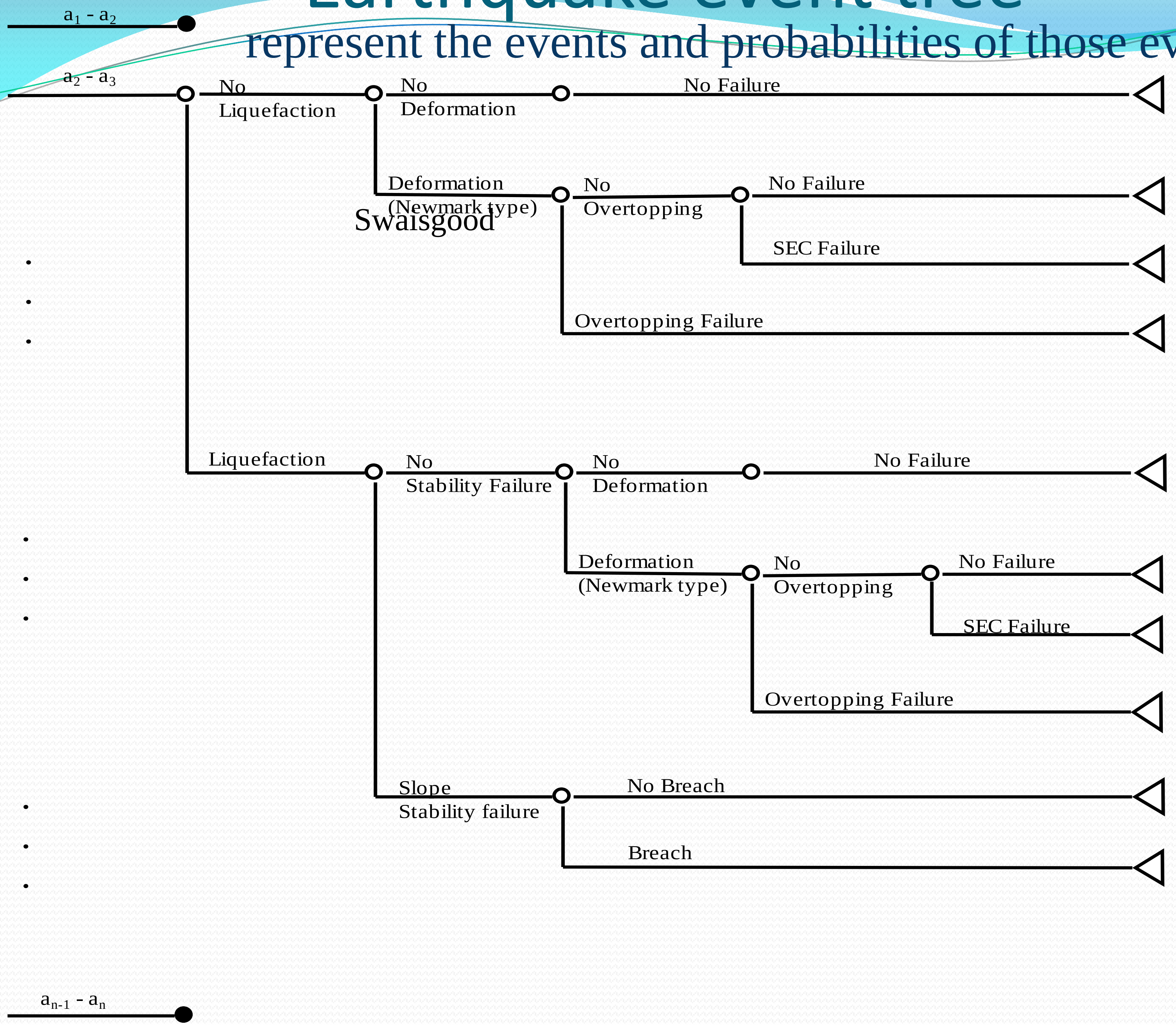
Portfolio Risk Assessment

Earthquake event tree

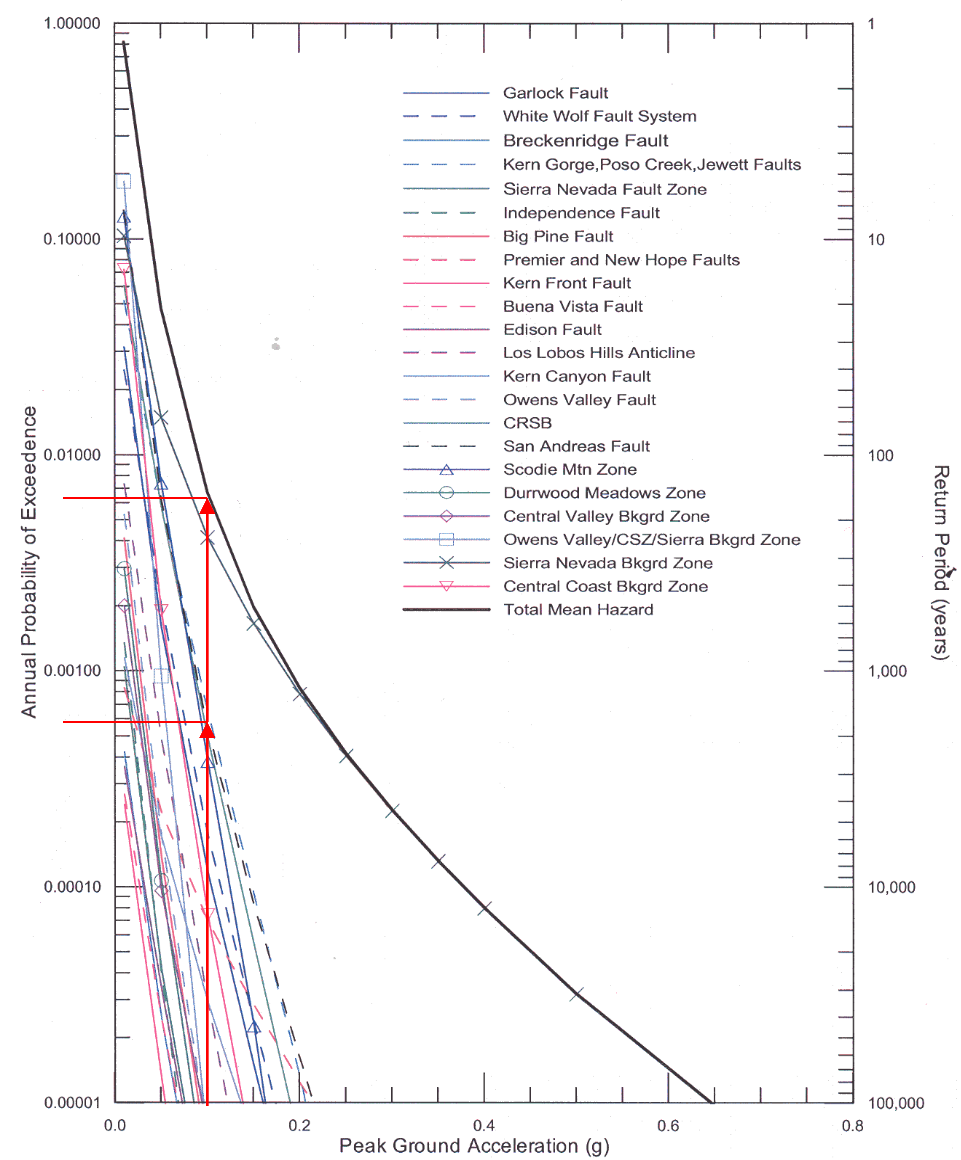
represent the events and probabilities of those events



Seismic Loading

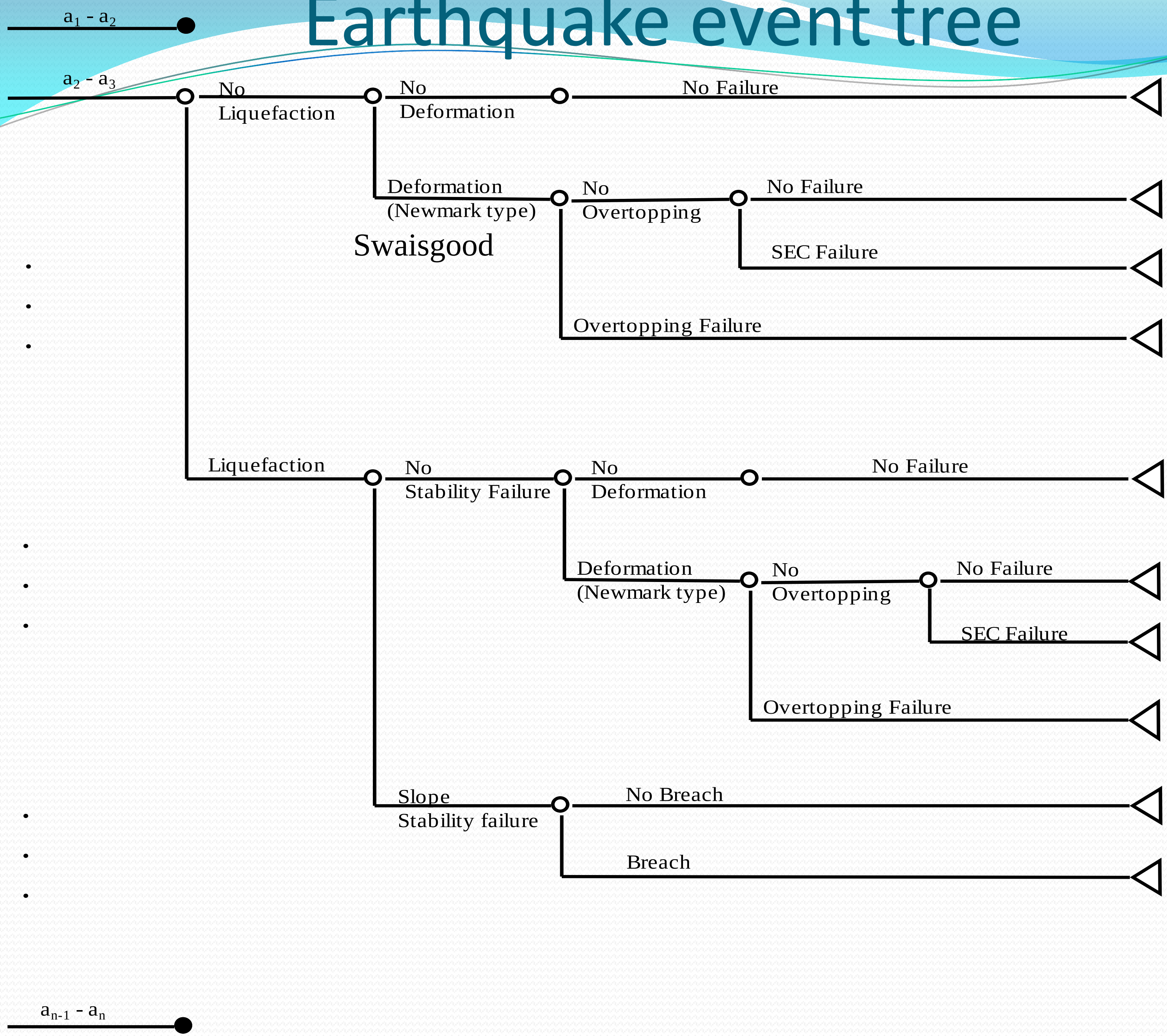
- Consider two magnitude ranges
  - M 5.75 (background)
  - M 8.0 (San Andreas & others)

Earthquake Loading			
Event Probability			
pga	Total Haz	San Andreas	Background
(g)			
0.05	0.05	0.007	0.043
0.1	0.007	0.00052	0.00648
0.15	0.002	0.000083	0.001917
0.2	0.00082	0.000016	0.000804
0.25	0.00041		0.00041
0.3	0.00022		0.00022



URS	Project No. 26814237 Success Dam	SEISMIC SOURCE CONTRIBUTIONS TO MEAN PEAK HORIZONTAL ACCELERATION HAZARD	Figure 16

Earthquake event tree



Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils[a]

By T. L. Youd,[1] Chair, Member, ASCE, I. M. Idriss,[2] Co-Chair, Fellow, ASCE, Ronald D. Andrus,[3] Ignacio Arango,[4] Gonzalo Castro,[5] John T. Christian,[6] Richardo Dobry,[7] W. D. Liam Finn,[8] Leslie F. Harder Jr.,[9] Mary Ellen Hynes,[10] Kenji Ishihara,[11] Joseph P. Koester,[12] Sam S. C. Liao,[13] William F. Marcuson III,[14] Geoffrey R. Martin,[15] James K. Mitchell,[16] Yoshiharu Moriwaki,[17] Maurice S. Power,[18] Peter K. Robertson,[19] Raymond B. Seed,[20] and Kenneth H. Stokoe II[21]

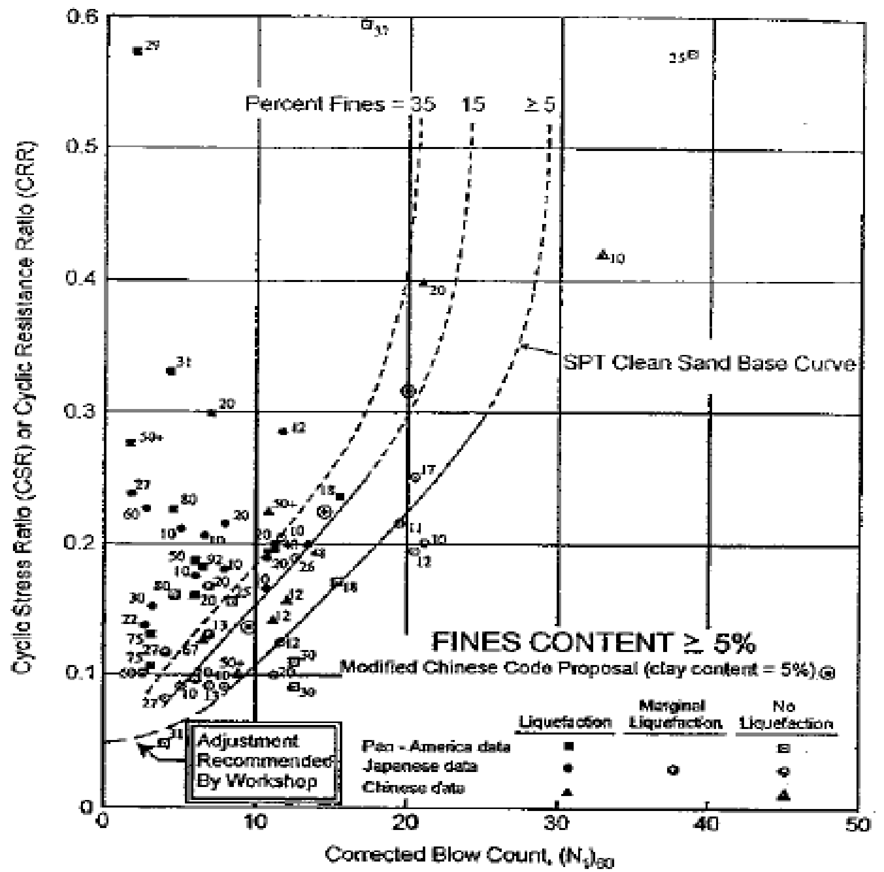


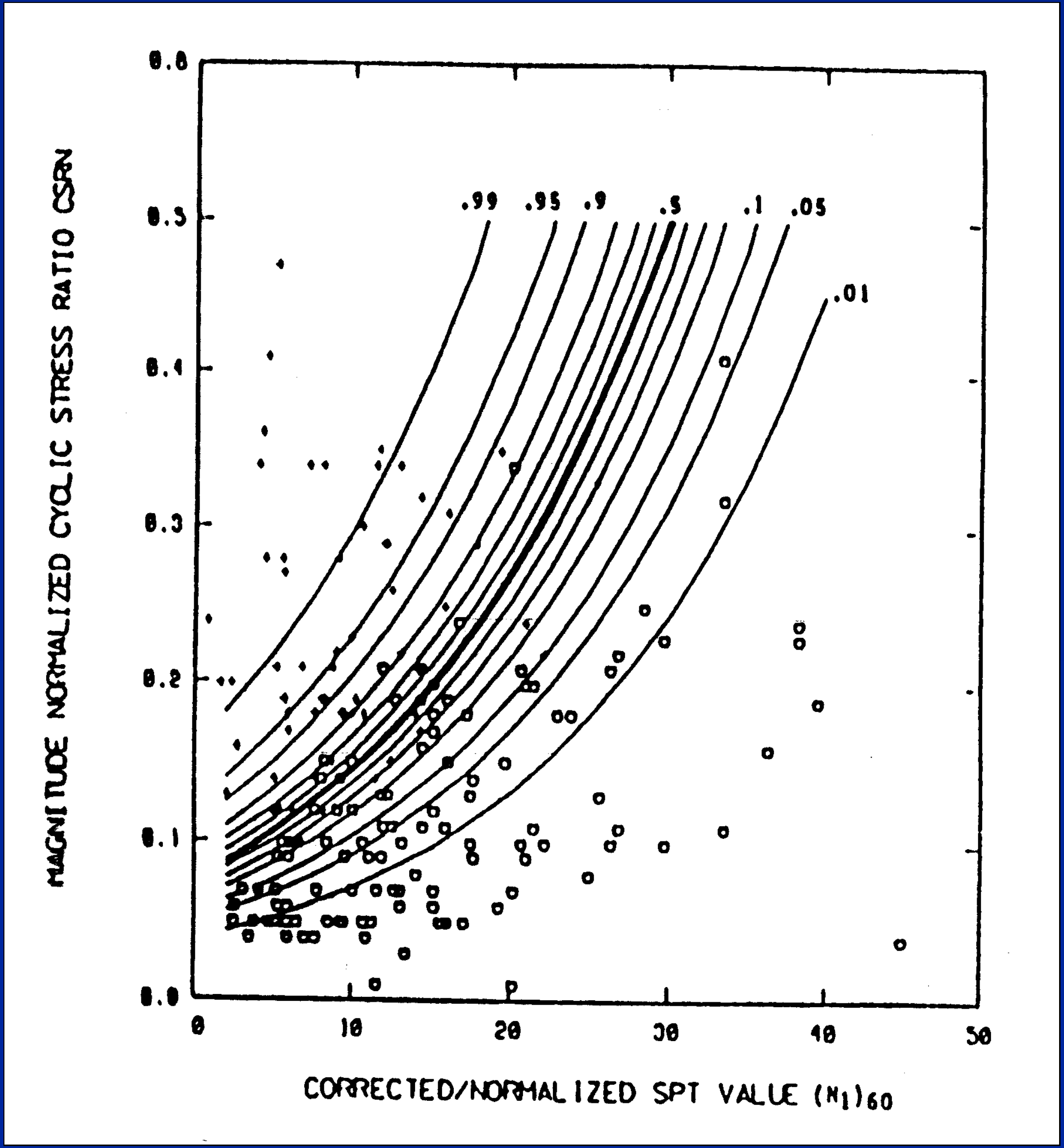
FIG. 2. SPT Clean-Sand Base Curve for Magnitude 7.5 Earthquakes with Data from Liquefaction Case Histories (Modified from Seed et al. 1985)

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

$$FS = (CRR_{7.5}/CSR)MSF$$

Probability of Liquefaction

- Liao, et al (1988)
- Youd and Noble (1998)
- Seed, et al. (2001)
- Sequence leading to breach
  - Liquefaction
  - Stability
  - Breach



Liquefaction Models

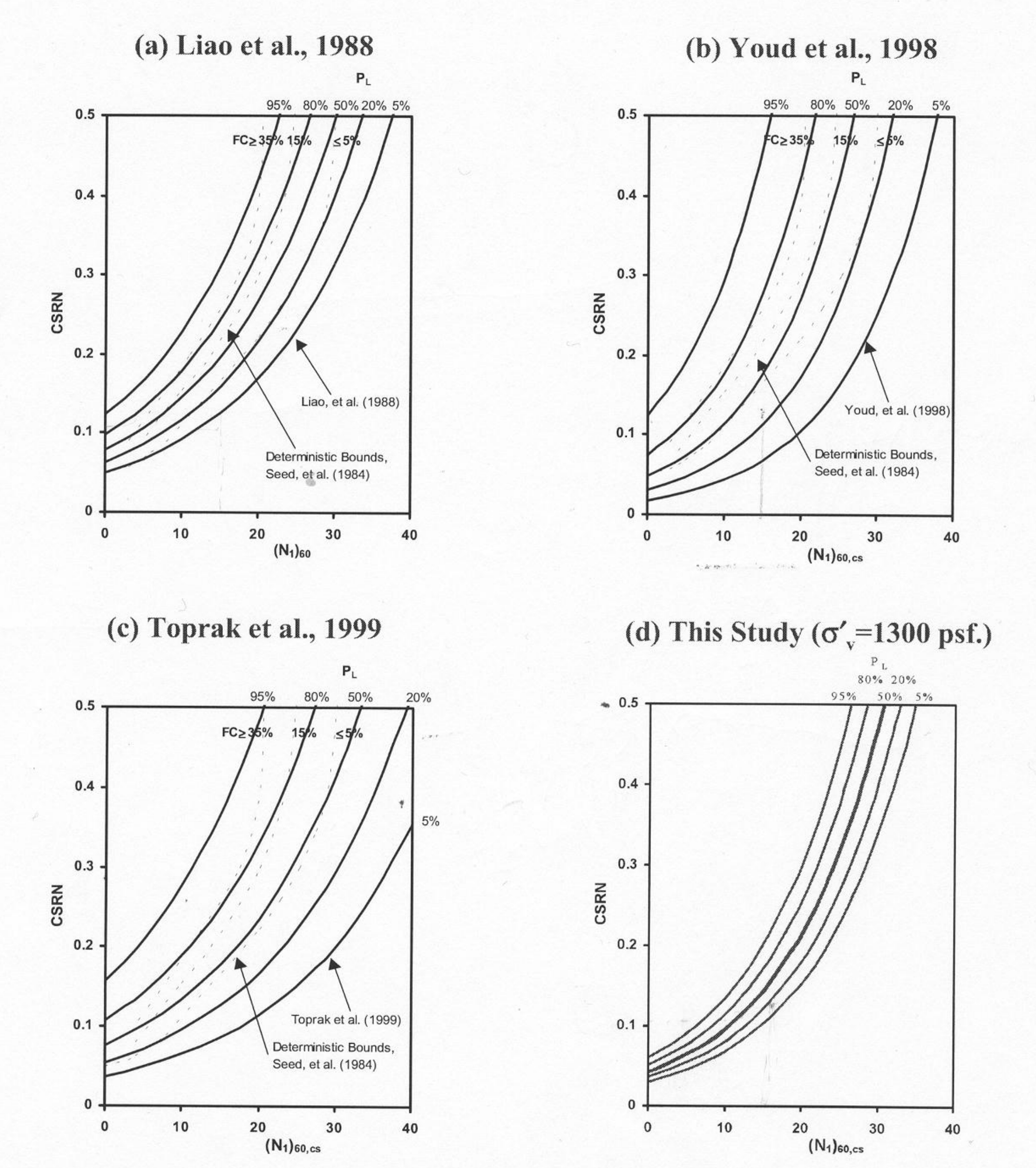


Fig. 5: Comparison of Best Available Probabilistic Correlations for Evaluation of Liquefaction Potential (All Plotted for M_w=7.5, σ_v' = 1300 psf, and Fines Content ≤ 5%)

Liquefaction Spread Sheet

Annual Probability of Liquefaction Calculations

CSR parameters

r_d =	0.9		$(N1)_{60}$ =	33.1	For Silty Sand $(N1)_{60}$ must be corrected
Stress Ratio =	1.35		M_w =	6.5	Magnitude is only directly considered in the equation by Youd and Noble
			MCF =	1.19	Magnitude Correction Factor applied to CSR for Liao method MCF = 1.0 for M7.5, 1.19 for M6.5

						Youd and Noble (1996) Equation				Liao et al. (1988) Equation modified for Magnitude using the MCF			
Loading (pga)	Return Perio	Annual Exceedance Prob	Probability Interval	Average pga	CSR	ln[PL/(1-PL)]	PL/(1-PL)	$P_{L/E}$	$P_{L\ per\ year}$	Modified CSR	Q_L	$P_{L/E}$	$P_{L\ per\ year}$
0.010	144	0.006944444											
			0.004839	0.0188	0.014847	-14.5423313	4.83E-07	4.83443E-07	2.3395E-09	0.012477	-25.0048	1.38213E-11	6.68839E-14
0.027	475	0.002105263											
			0.00108	0.0352	0.027799	-12.60117	3.37E-06	3.36806E-06	3.6362E-09	0.023361	-20.953	7.94763E-10	8.58043E-13
0.043	975	0.001025641											
			0.000622	0.0595	0.04699	-10.976502	1.71E-05	1.70985E-05	1.0628E-08	0.039488	-17.5618	2.36059E-08	1.46734E-11
0.076	2475	0.00040404											
			0.000286	0.1129	0.089163	-8.99406267	0.000124	0.000124129	3.5515E-08	0.074927	-13.4238	1.47954E-06	4.23319E-10
0.150	8480	0.000117925											
			0.000118	0.15	0.118463	-8.11466674	0.000299	0.00029903	3.5263E-08	0.099548	-11.5882	9.27483E-06	1.09373E-09

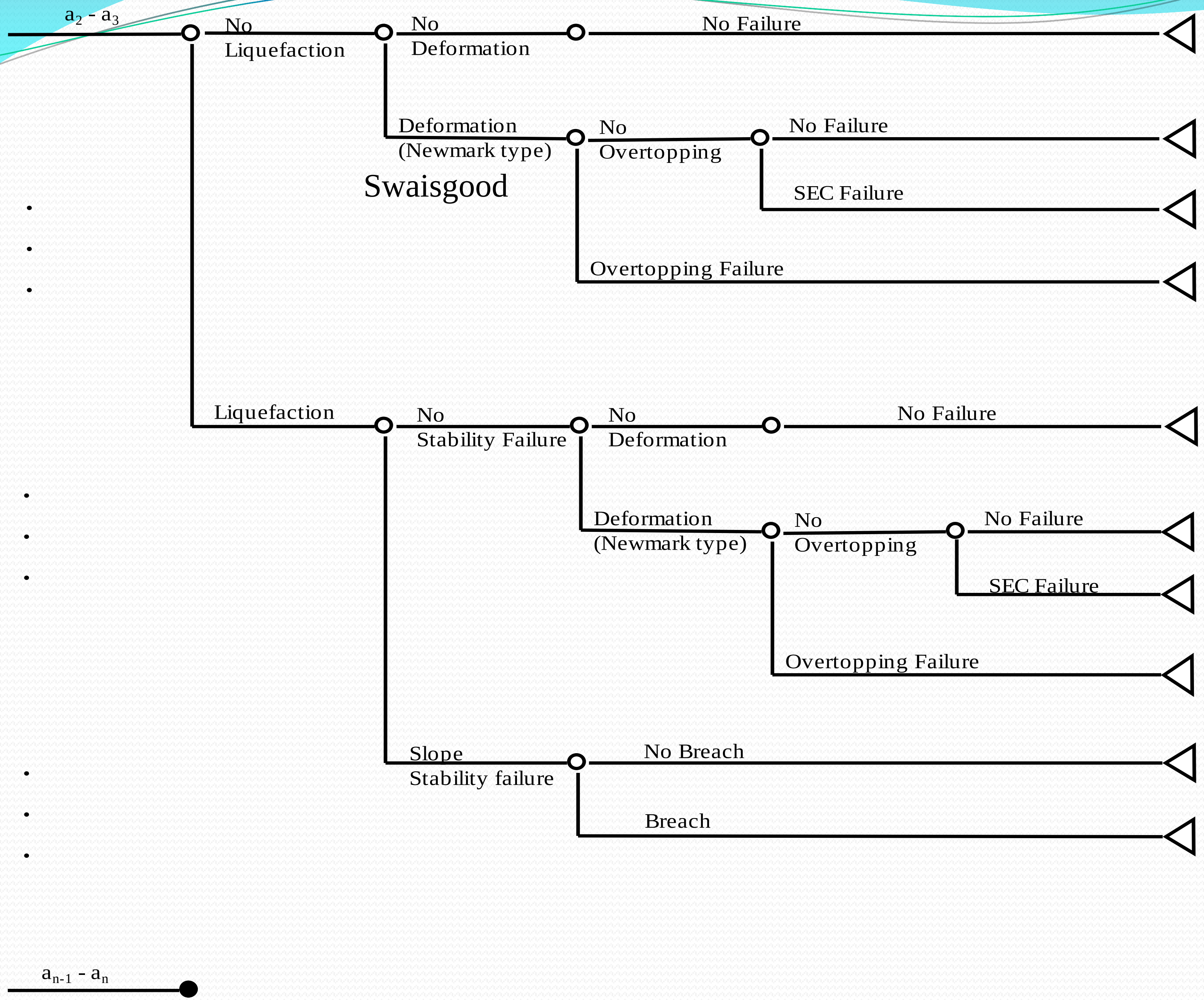
Sum $P_{L\ Youd}$ =	**8.74E-08**			**Sum $P_{L\ Liao}$ =**	**1.53E-09**
		Parameters Used			
		$(N1)_{60}$ =	33.1		
		M_w =	6.5		
		MCF =	1.19		

Delaware Lake		
RP	PGA	AEP
144	0.010	0.006944444
475	0.027	0.002105263
975	0.043	0.001025641
2475	0.076	0.00040404

PGA	SRP
0.0188	4.83E-07
0.0352	3.37E-06
0.0595	1.71E-05
0.1129	1.24E-04
0.15	2.99E-04

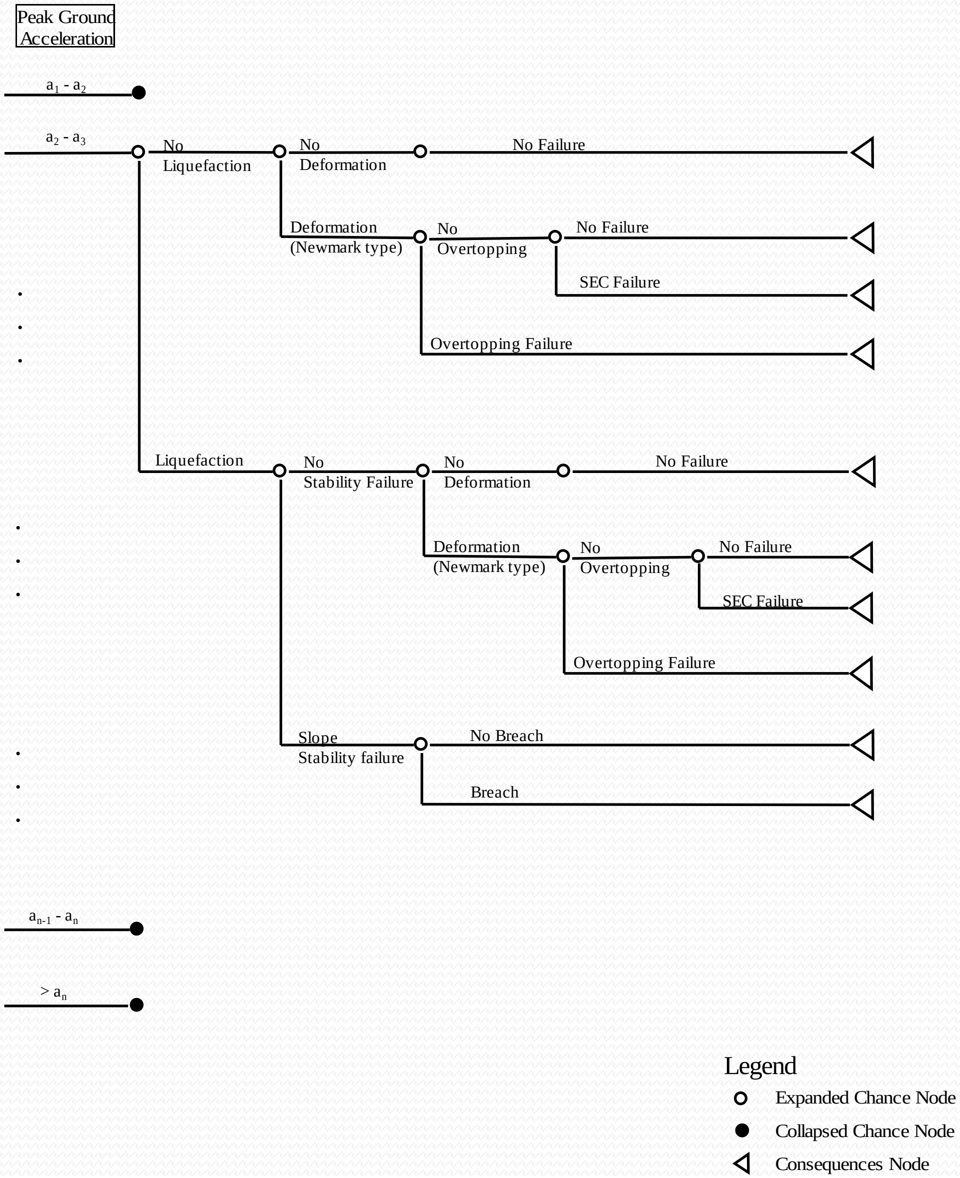
PGA	AEP
0.010	6.94E-03
0.0272	2.11E-03
0.0432	1.03E-03
0.0758	4.04E-04
0.15	1.18E-04

Earthquake event tree



Earthquake event tree

1. Annual Probability for a given PGA range
2. Given the PGA range the conditional probability of liquefaction can be determined
3. Given Liquefaction determine the conditional probability of a slope failure
4. Given the slope failure determine the conditional probability of a breach
5. Repeat for all PGA ranges



Risk Assessment of Success Dam, California

- Evaluation of Operating Restrictions as an Interim Measure to Mitigate Earthquake Risk
- Flood Related Potential Failure Modes
- Earthquake Induced Potential Failure Modes

RAC Engineers & Economists
David Bowles
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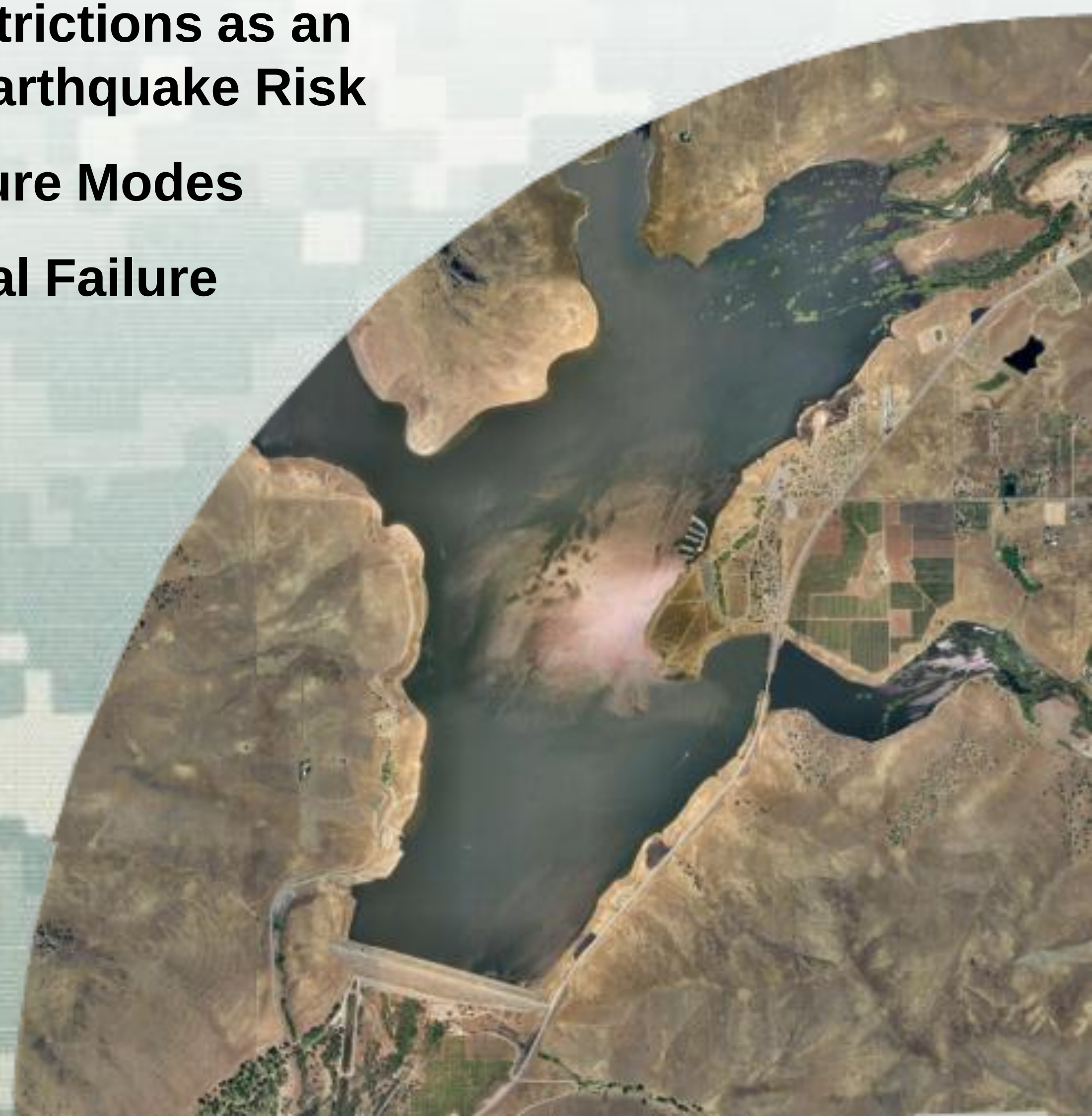
Beaty Engineering
Michael Beaty

Michael Ruthford
Vlad Perlea
David Serafini
Jack Montgomery

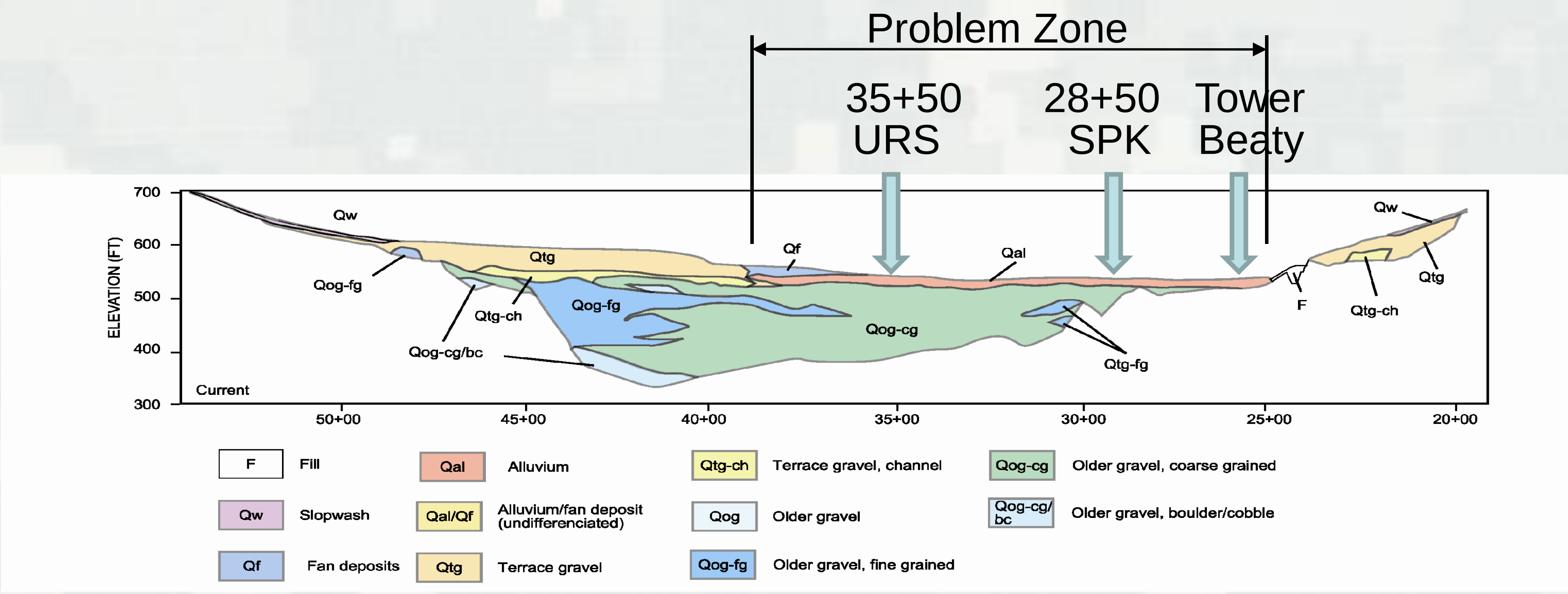
US Army Corps of Engineers
BUILDING STRONG®



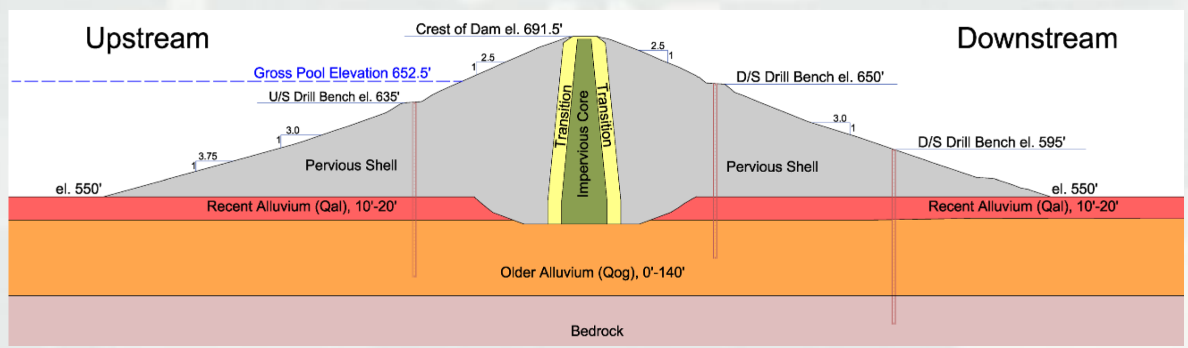
SUCCESS DAM CALIFORNIA

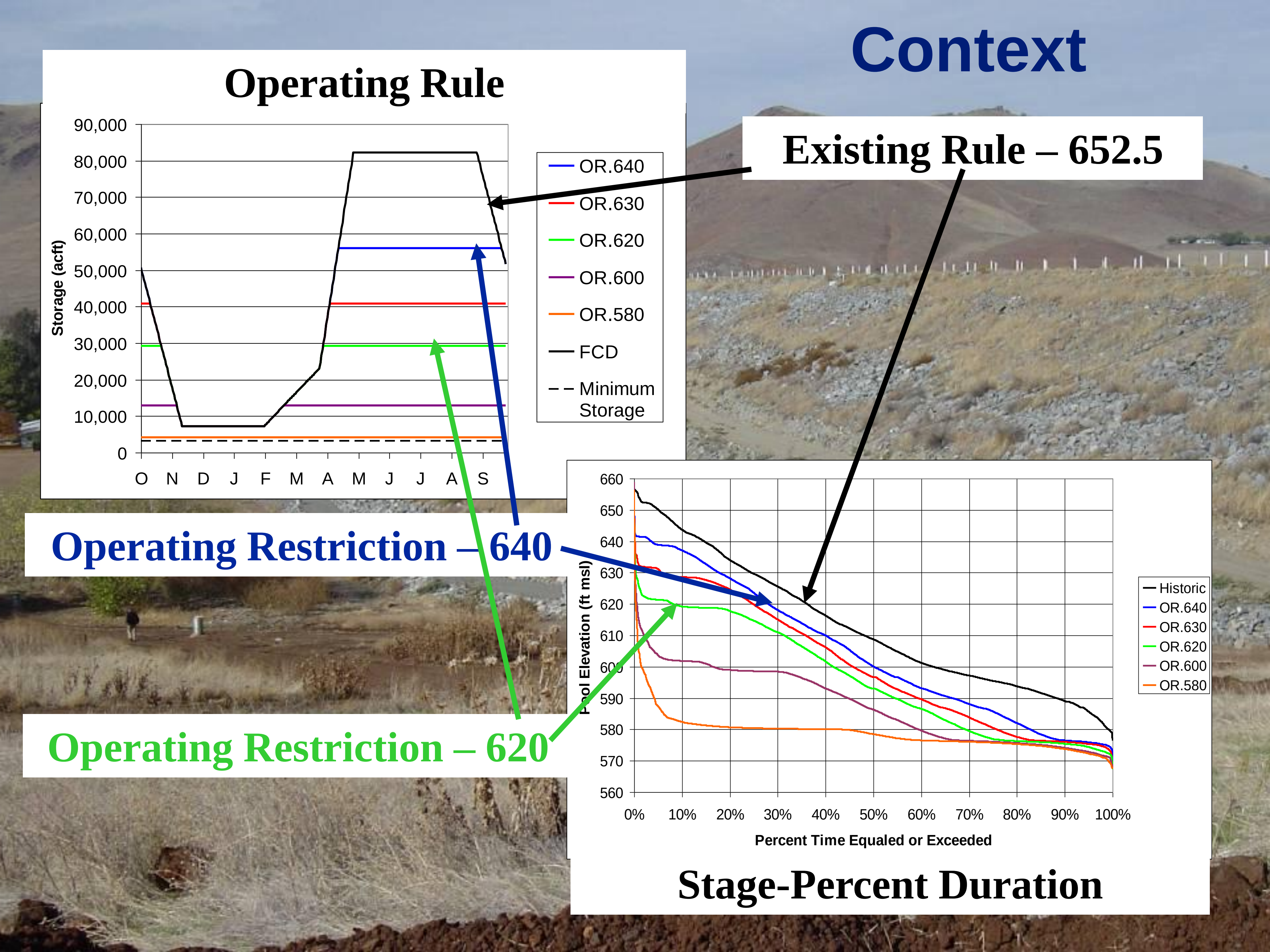
Embankment dam 144 feet (44 m) high
Central clayey core, pervious shells
Founded on alluvial deposit

Cross-Valley Geologic Profile



Typical Embankment Cross Section





Context
Operating Rule
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Storage (acft)
O N D J F M A M J J A S
OR.640
OR.630
OR.620
OR.600
OR.580
FCD
Minimum Storage
Existing Rule – 652.5
Operating Restriction – 640
Operating Restriction – 620
660
650
640
630
620
610
590
580
570
560
Pool Elevation (ft msl)
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Percent Time Equaled or Exceeded
Historic
OR.640
OR.630
OR.620
OR.600
OR.580
Stage-Percent Duration

Context: Impact Cost of Operating Restrictions in 2004$

1) Agricultural losses associated with reductions in irrigation water
2) Increased flood damages in an historic terminal lake, Tulare Lake agricultural area.
3) Net recreational losses, allowing for shifts to other lakes in the region

    $2.1 m for OR.630 and OR.640

    $2.8 m for OR.580, OR.600 and OR.620

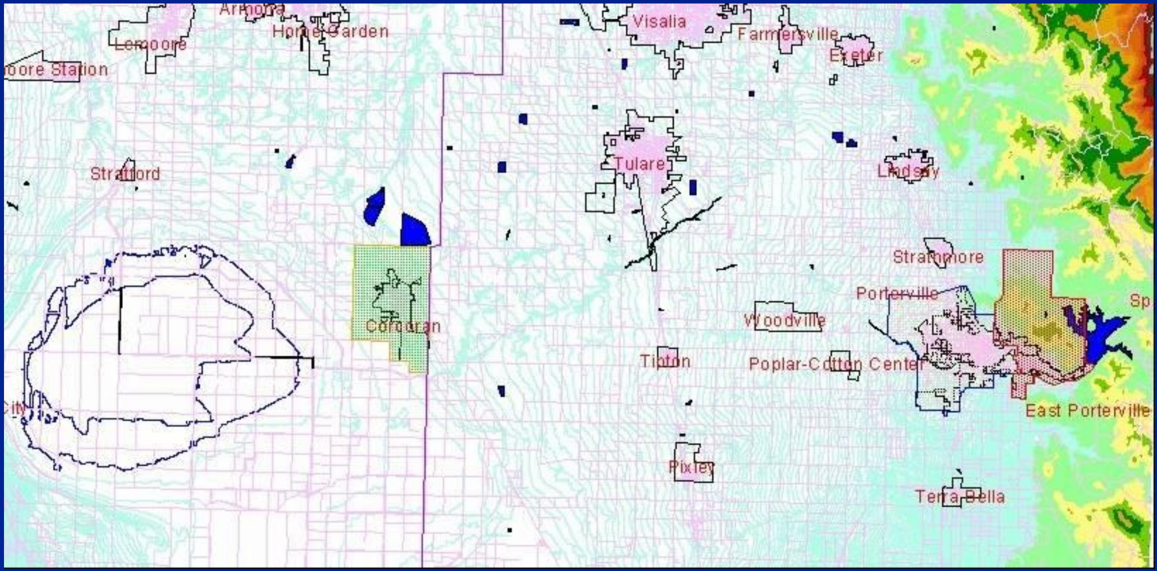


Table 1. Estimated Economic Losses to Downstream Agricultural Interests

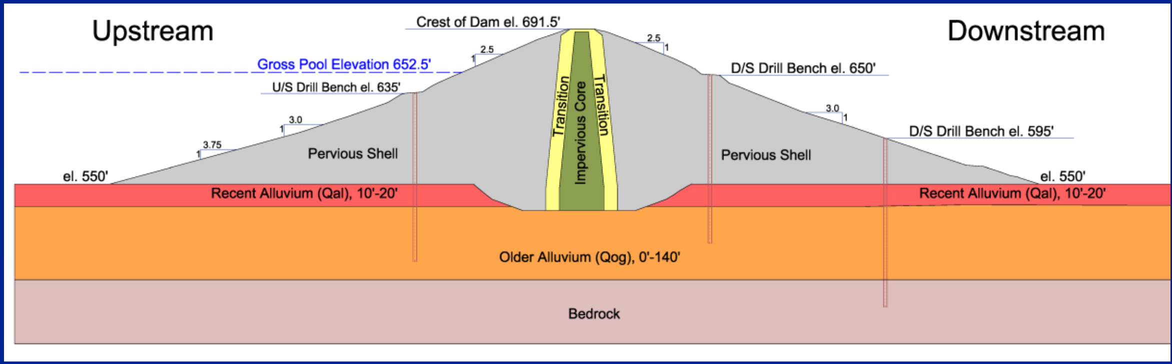
Potential Operating Restriction	Representative Water Year: Very Dry 1976	Dry 1964	Below Average 1985	Average 1996	Wet 1980	Average Annual Economic Losses ($/year)
OR 640	$0	$0	$0	$940,660	$1,065,050	$401,142
OR 630	$0	$0	$635,810	$2,014,530	$2,152,920	$960,652
OR 620	$0	$0	$1,420,440	$2,836,050	$2,952,250	$1,441,748
OR 600	$878,220	$1,038,240	$2,590,700	$3,940,300	$3,797,220	$2,448,936

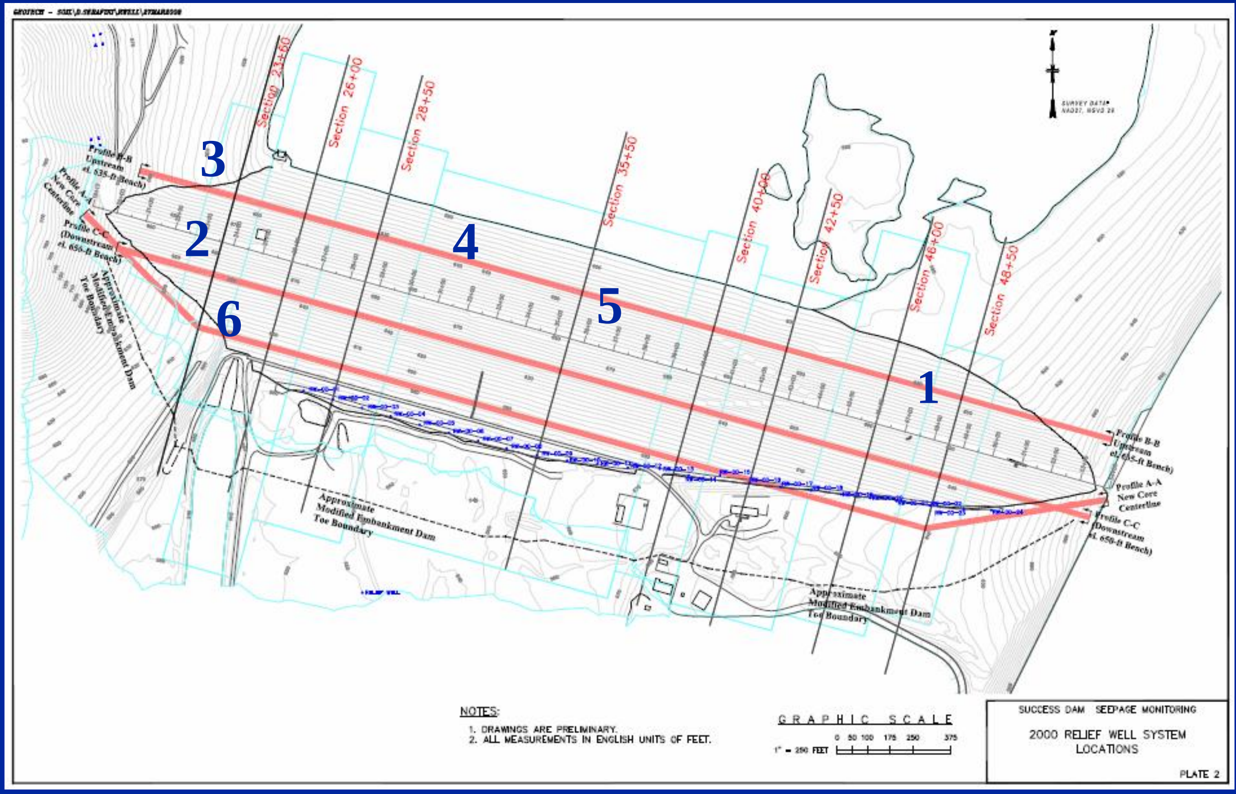
Table 2. Estimated Additional Flood Damages to Agricultural Lands in Tulare Lakebed

Potential Operating Restriction	Representative Water Year: Very Dry 1976	Dry 1964	Below Average 1985	Average 1996	Wet 1980	Average Annual Additional Flood Damages ($/year)
OR 640	$0	$0	$0	$0	$3,100,000	$620,000
OR 630	$0	$0	$0	$0	$3,100,000	$620,000
OR 620	$0	$0	$0	$0	$3,200,000	$640,000
OR 600	$0	$0	$0	$0	$7,500,000	$1,500,000

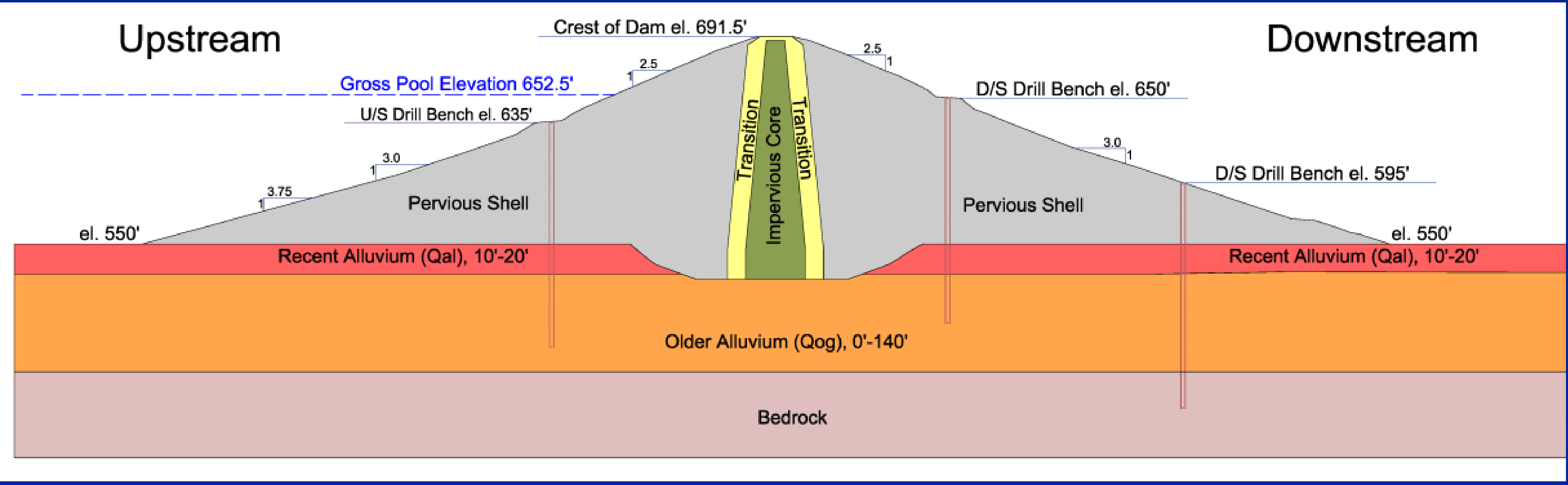
Seepage and Piping Failure Modes

1. Piping into Terrace Deposits Left Abutment Failure
2. Piping into Rock Right Abutment Failure
3. Piping through Rock Foundation Failure
4. Piping through Embankment Failure
5. Piping through Foundation in Older Alluvium Failure
6. Embankment Piping along Outlet Works Failure





Earthquake Failure Modes
- Liquefaction in Recent Alluvium and Upstream Shell



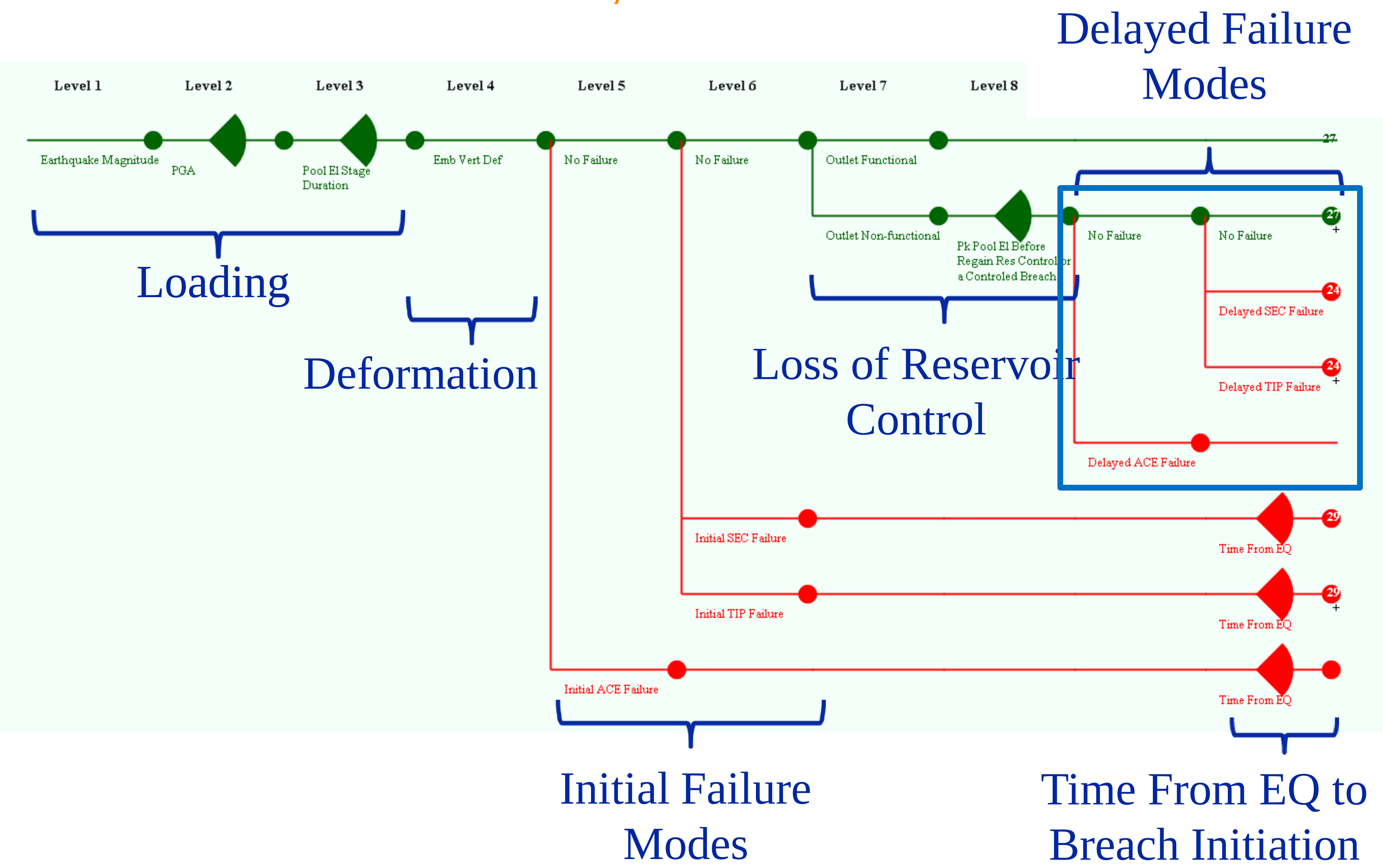
Earthquake Failure Modes

1) Liquefaction leading to vertical crest deformation and failure by Above-Core Erosion (ACE) of the dam.
2) Liquefaction leading to embankment deformation and failure by Seepage Erosion through Cracks (SEC).
3) Liquefaction leading to embankment and tower deformation resulting in failure by piping into a rupture in the control tower - outlet works system, referred to as a Tower-induced Piping (TIP) failure.

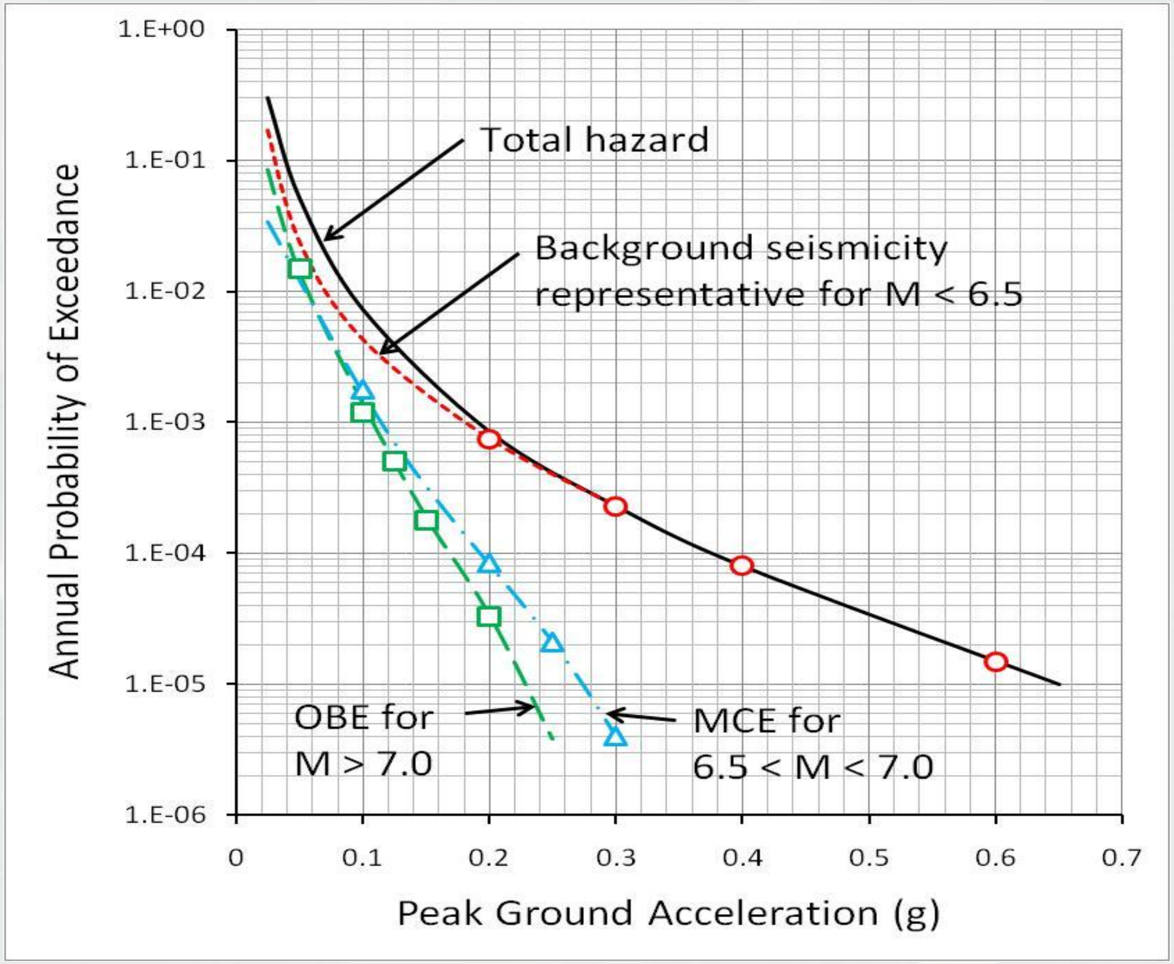
Delayed failure from loss of outlet works

Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



Results of Probabilistic Seismic Hazard Analysis



Method of Analysis

FLAC 6.00.387

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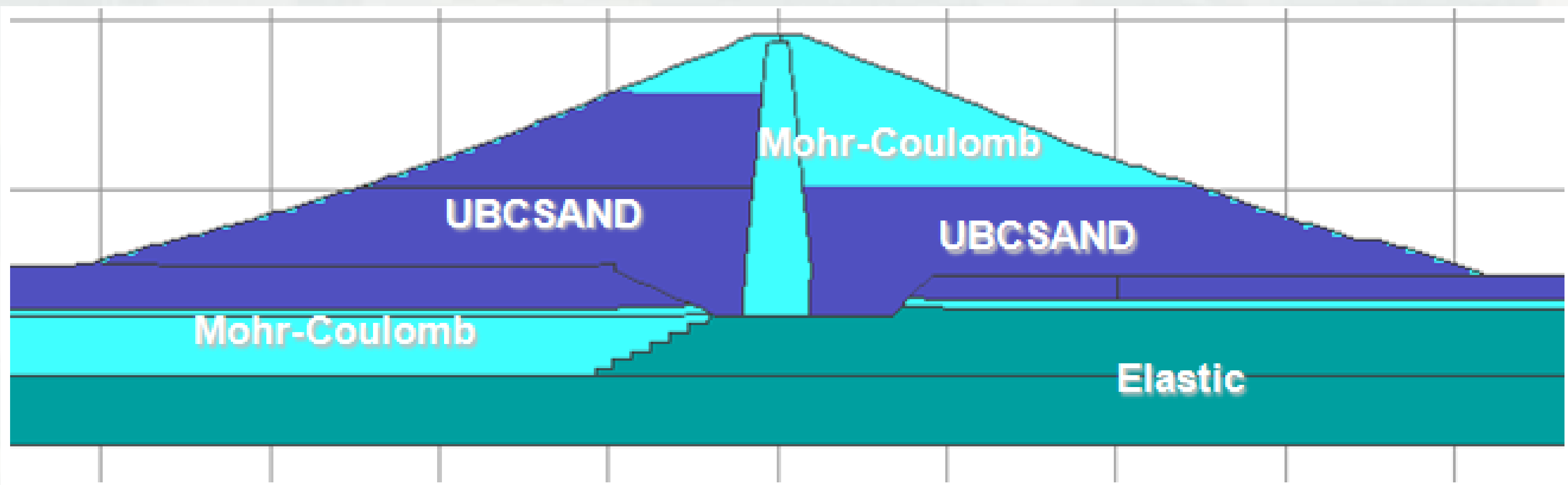
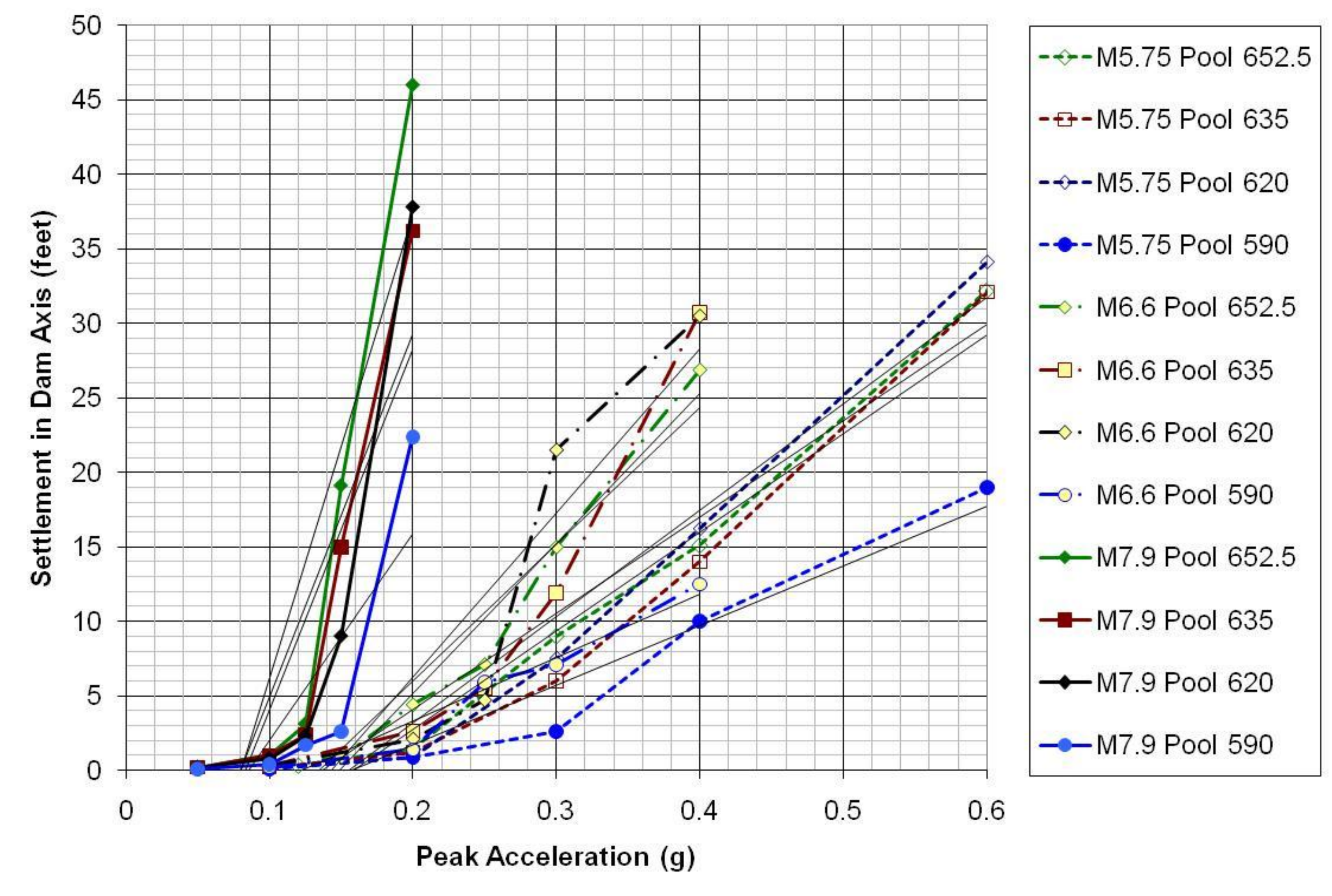
Fast **L**agrangian **A**nalysis of **C**ontinua

Models used in the dynamic shaking simulation

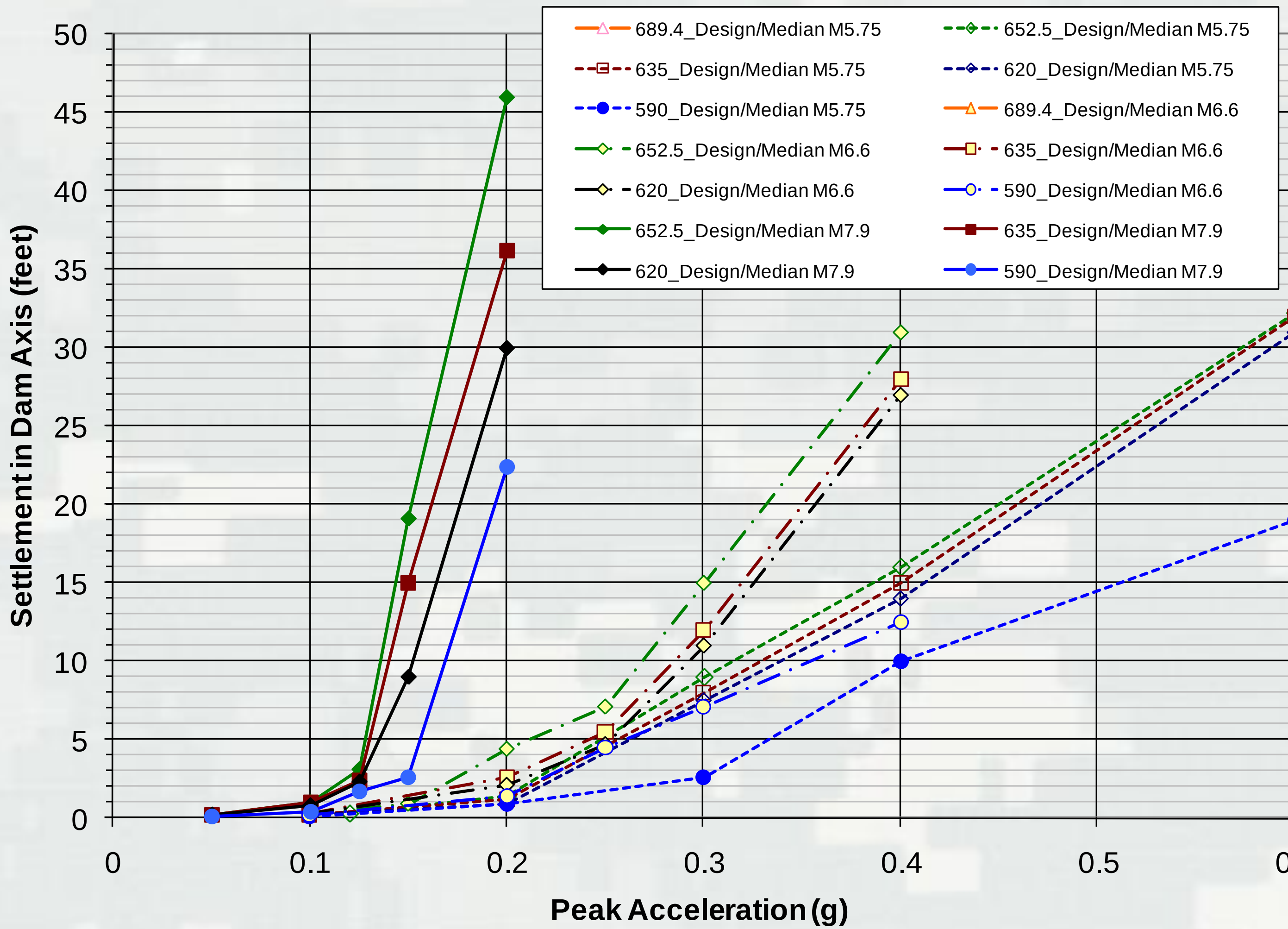


Selected parameter to represent earthquake damage: Seismic settlement at crest

as a function of: PGA, M, and pool elevation



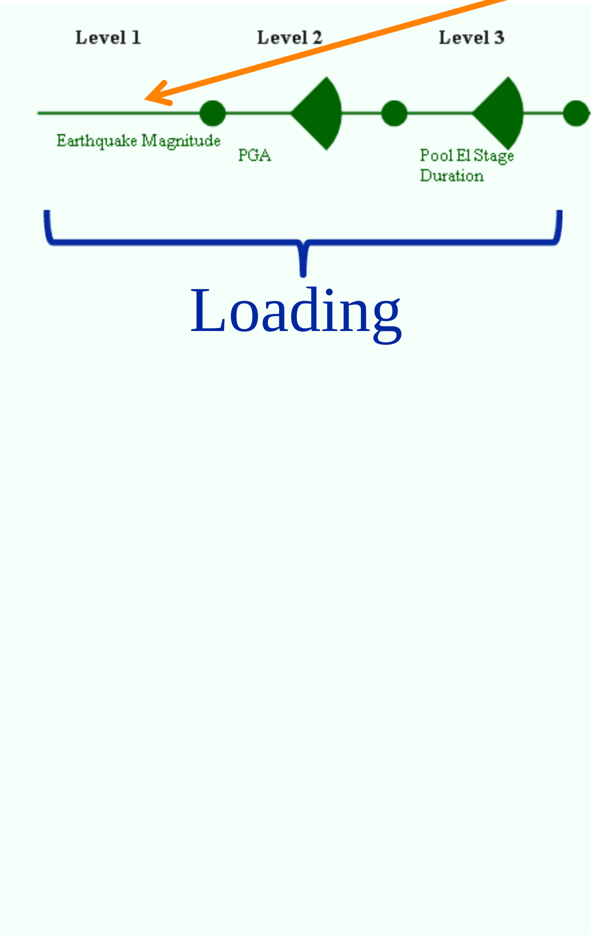
Smoothed Seismic settlement at crest
as a function of: PGA, M, and pool elevation



RAC Adjusted Values (2/24/09)

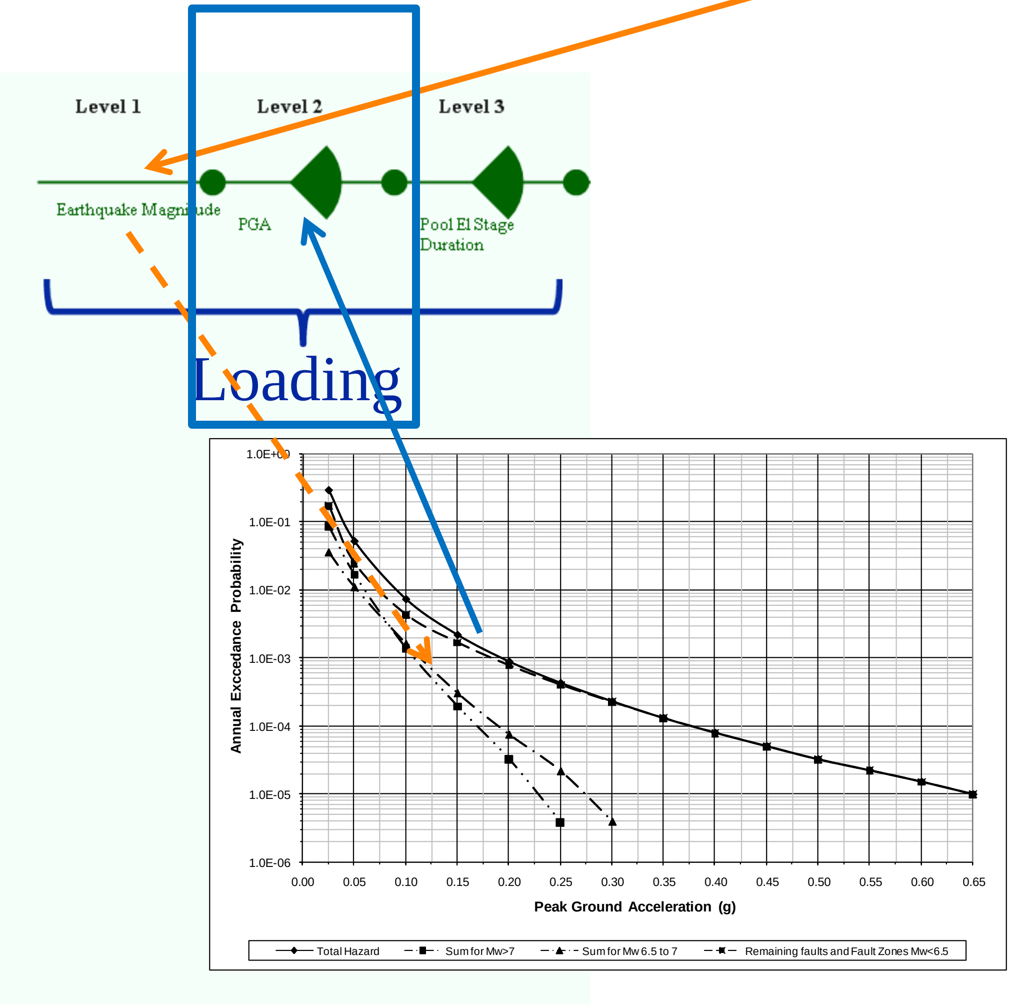
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



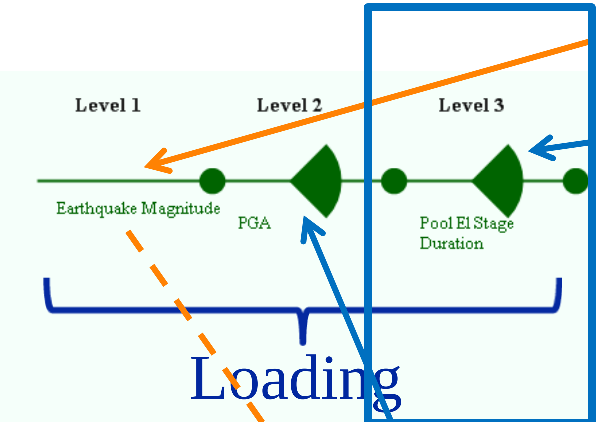
Earthquake Event Tree

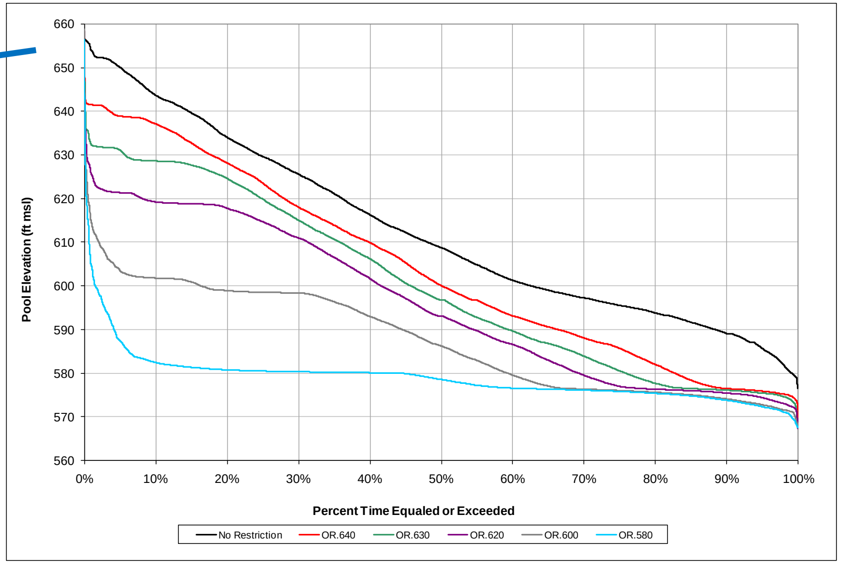
For < M6.5, M6.5 – 7 & > M7

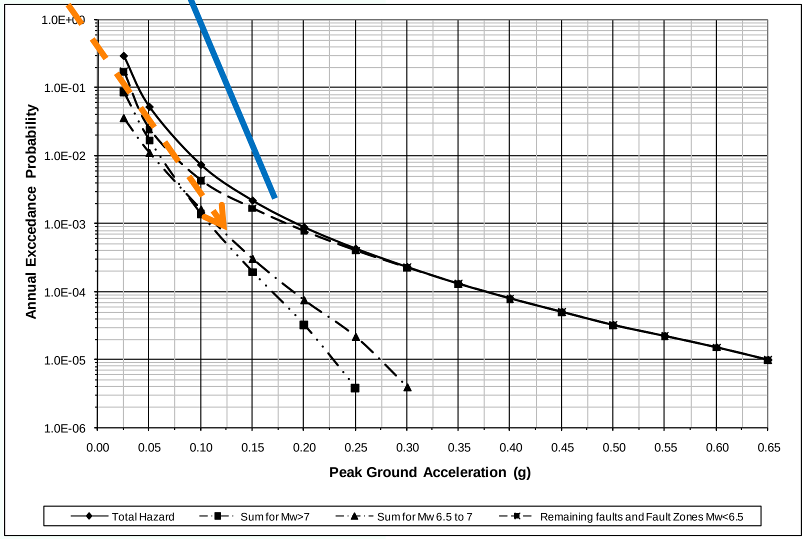


Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7

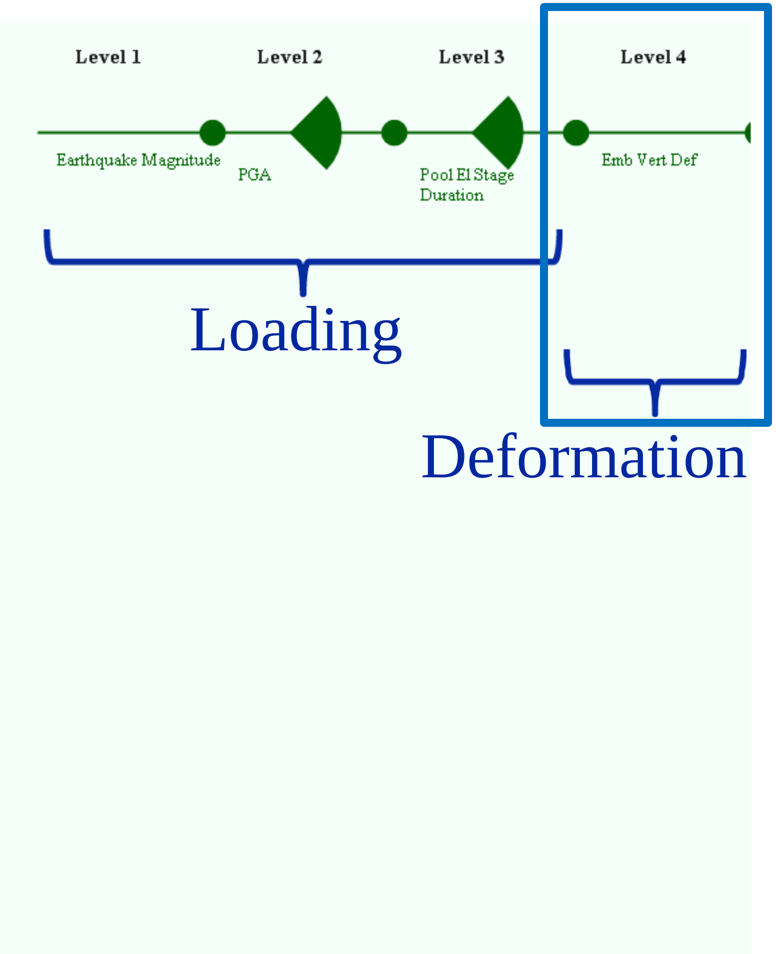






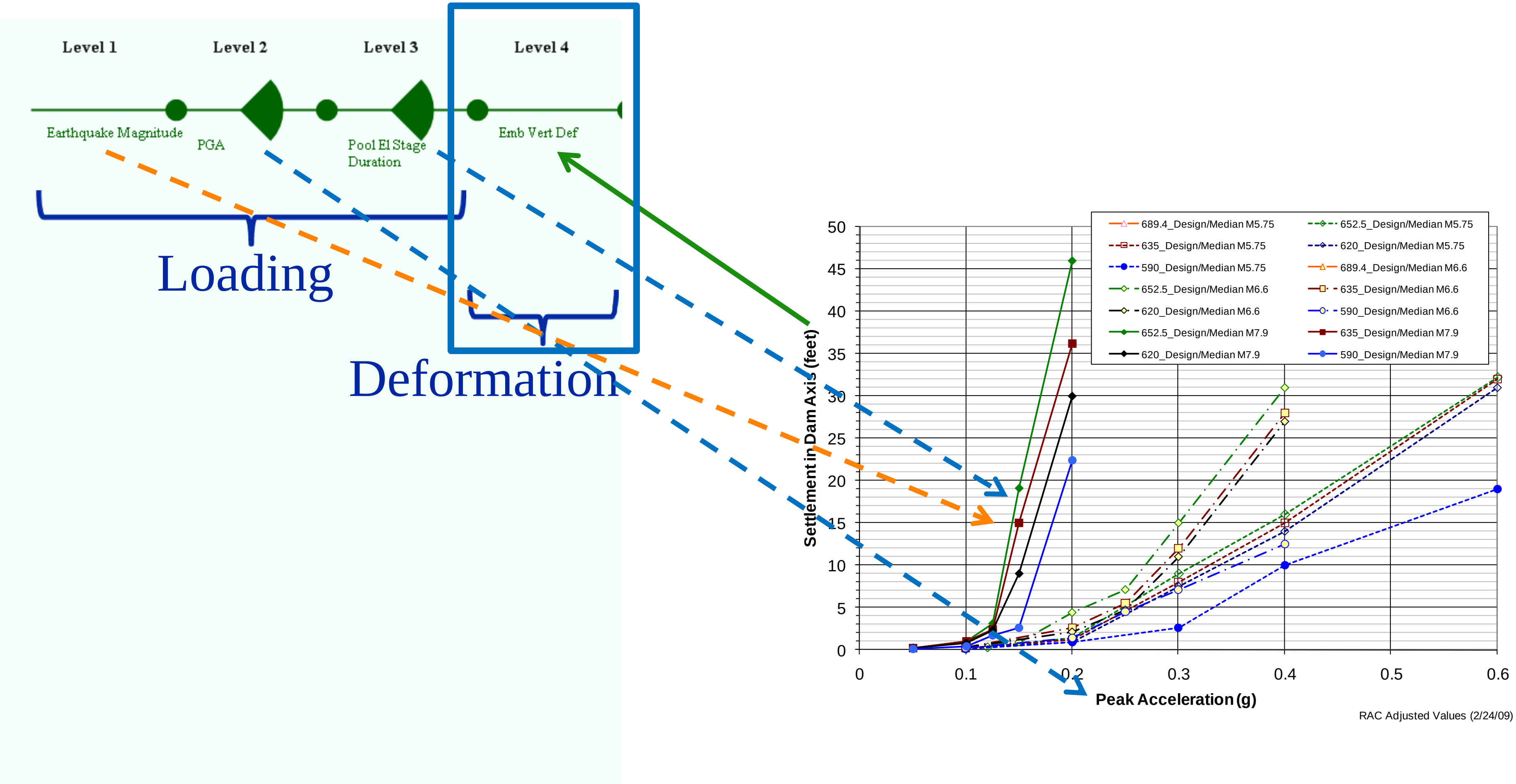
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7

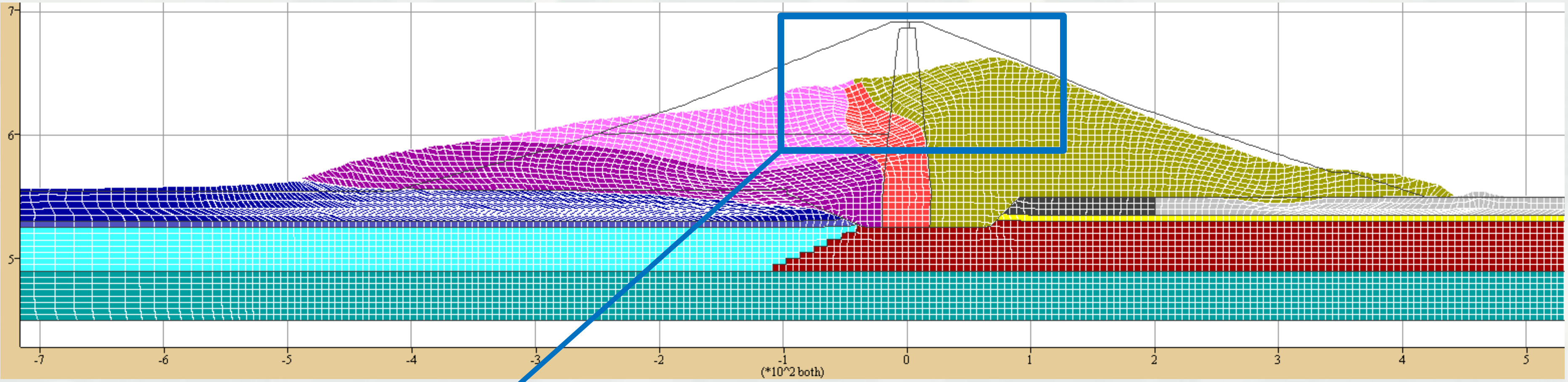


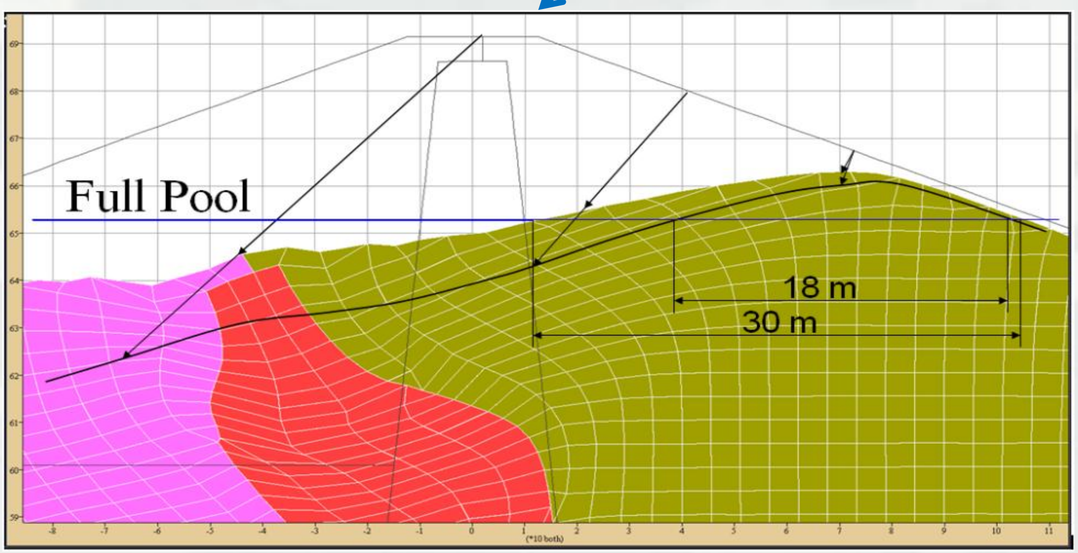
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



Above-Core Erosion (ACE) Failure Mode





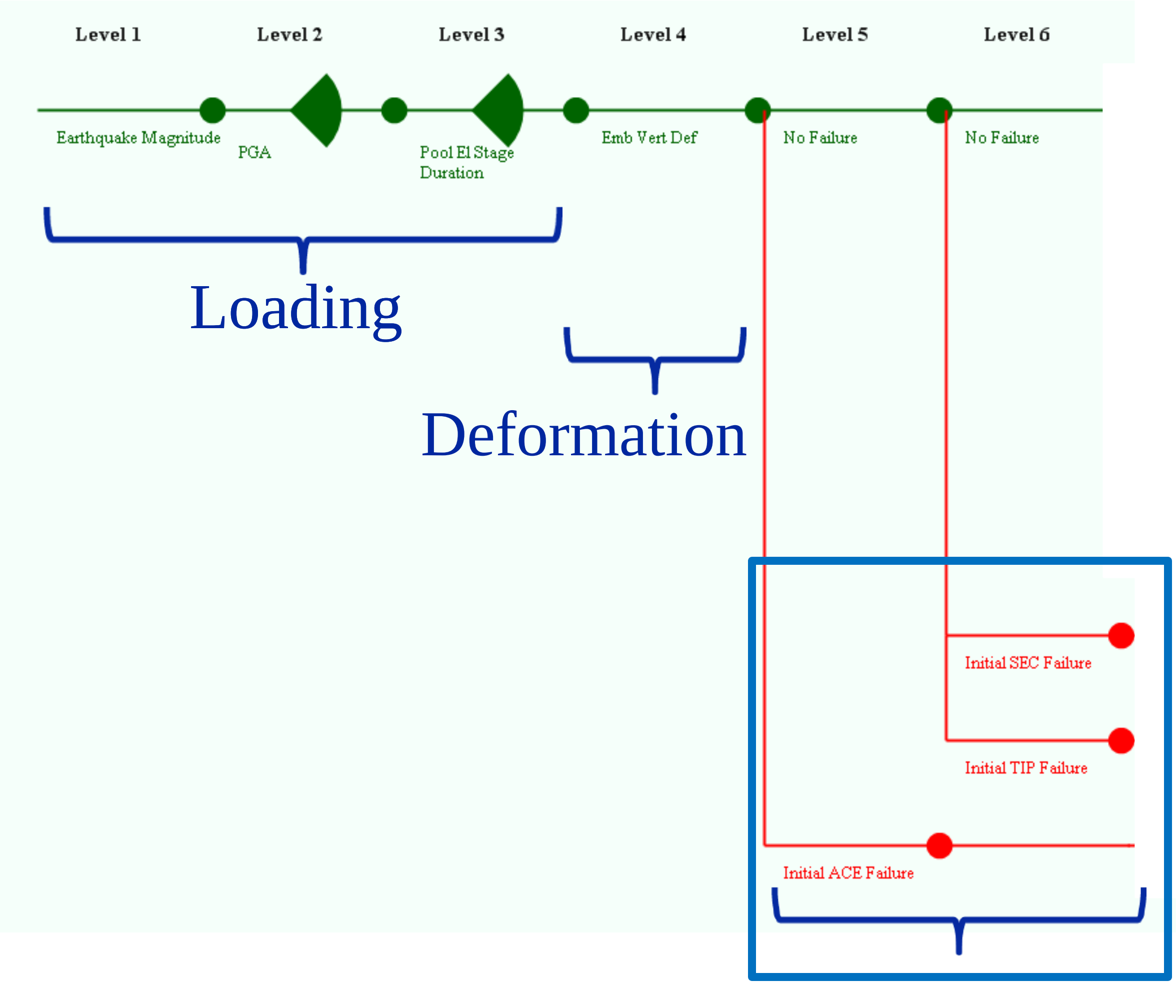
Failure Path:

•The embankment deforms due to strength loss of the foundation due to liquefaction.

•The top of the core is lowered below the pool elevation leading to saturation of the downstream shell.

Earthquake Event Tree

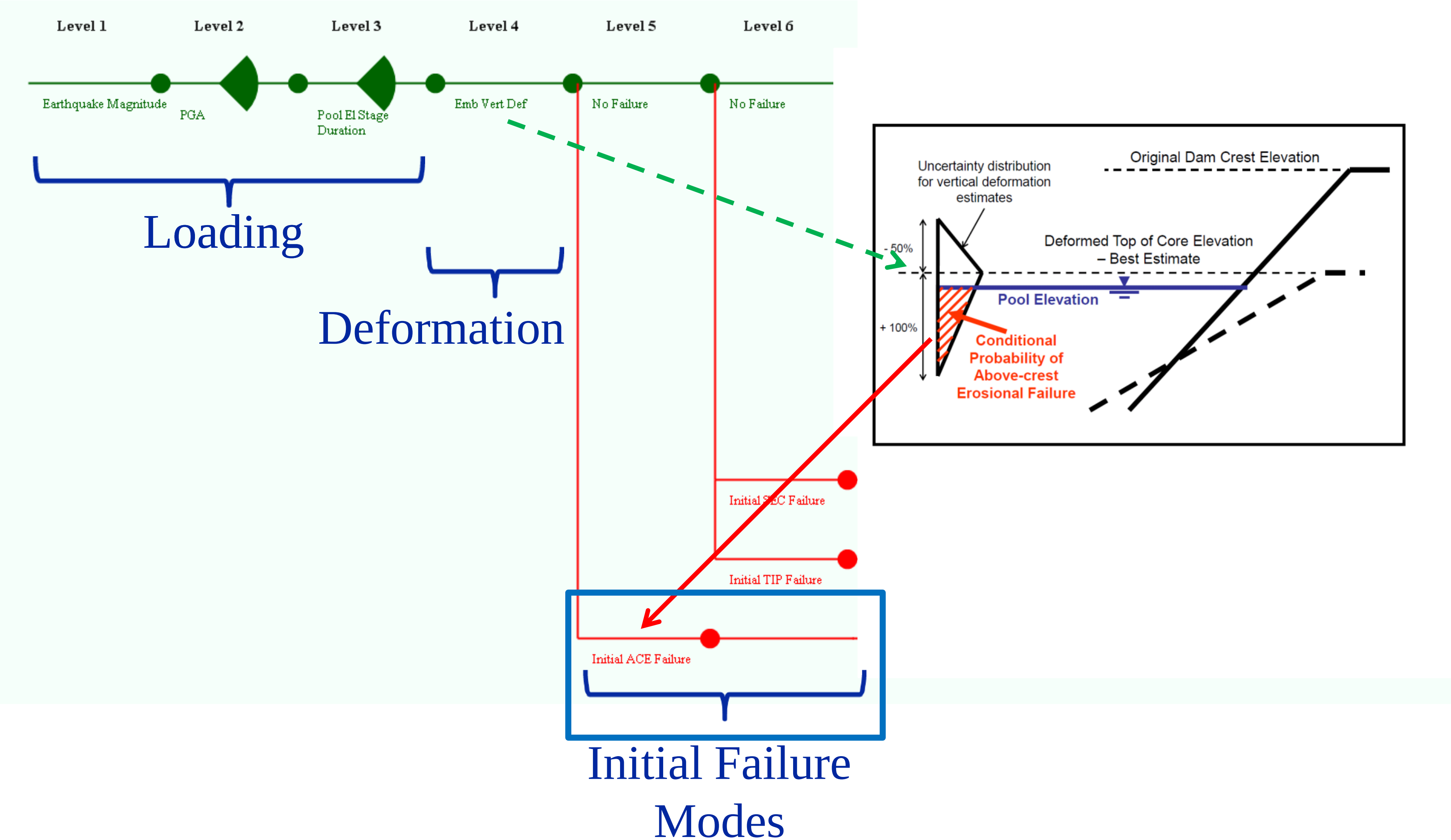
For < M6.5, M6.5 – 7 & > M7



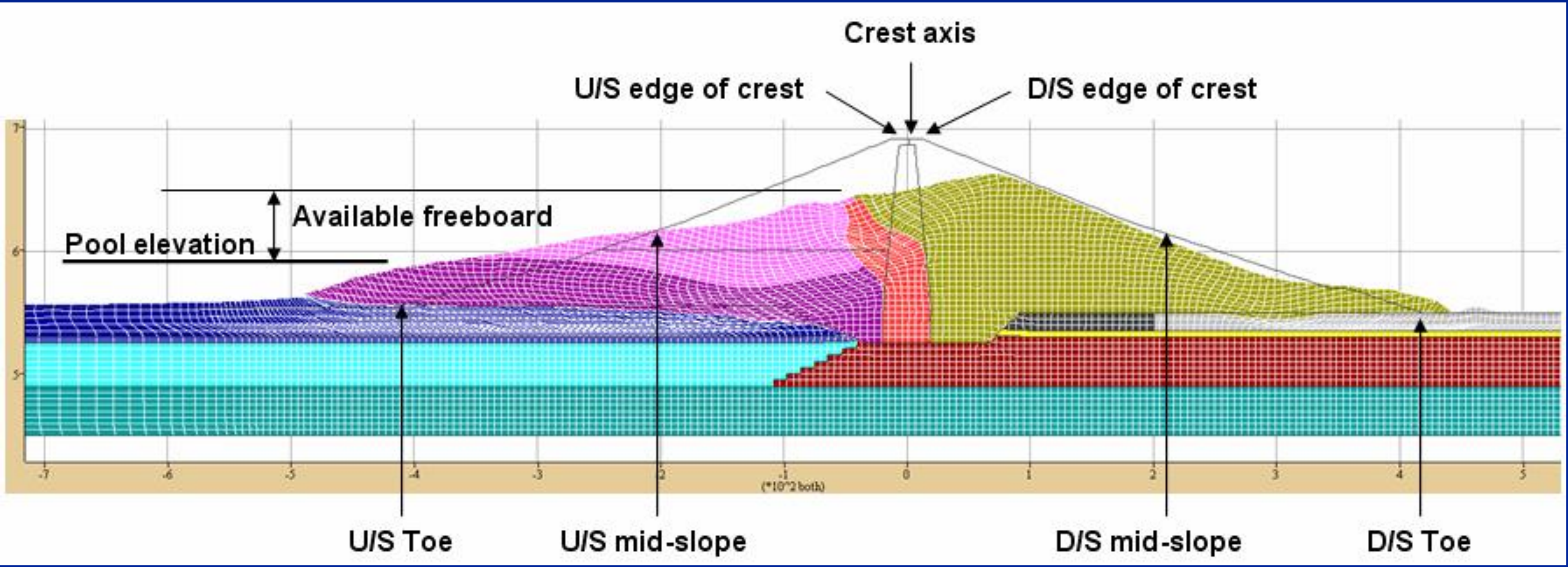
Initial Failure Modes

Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



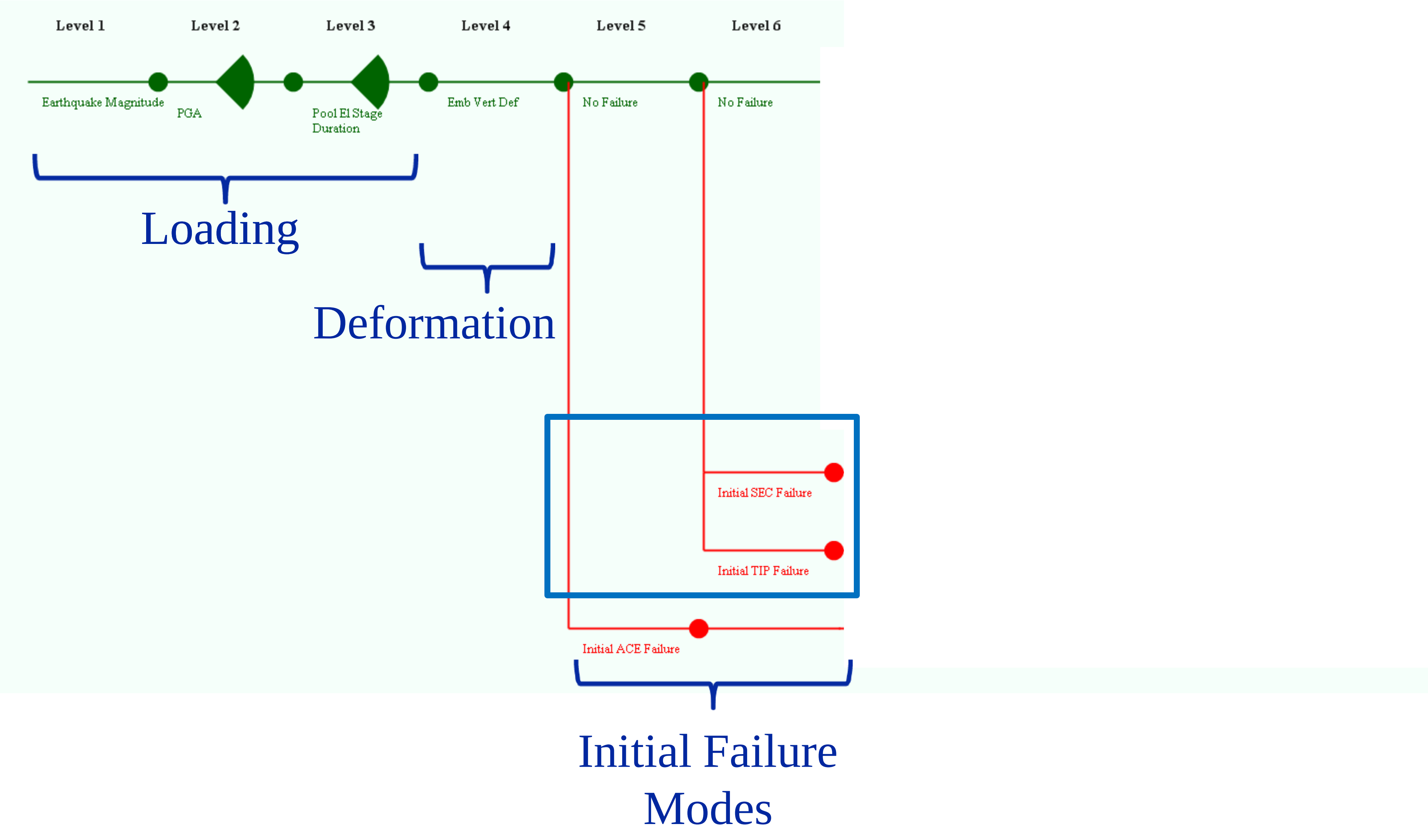
Seepage Erosion through Cracks (SEC) and Tower-induced Piping (TIP) Failure Modes



- Used Event Tree Method Guided by the USACE Piping and Seepage Toolbox
- All estimates made by Engineering Team
- Loss of Outlet control

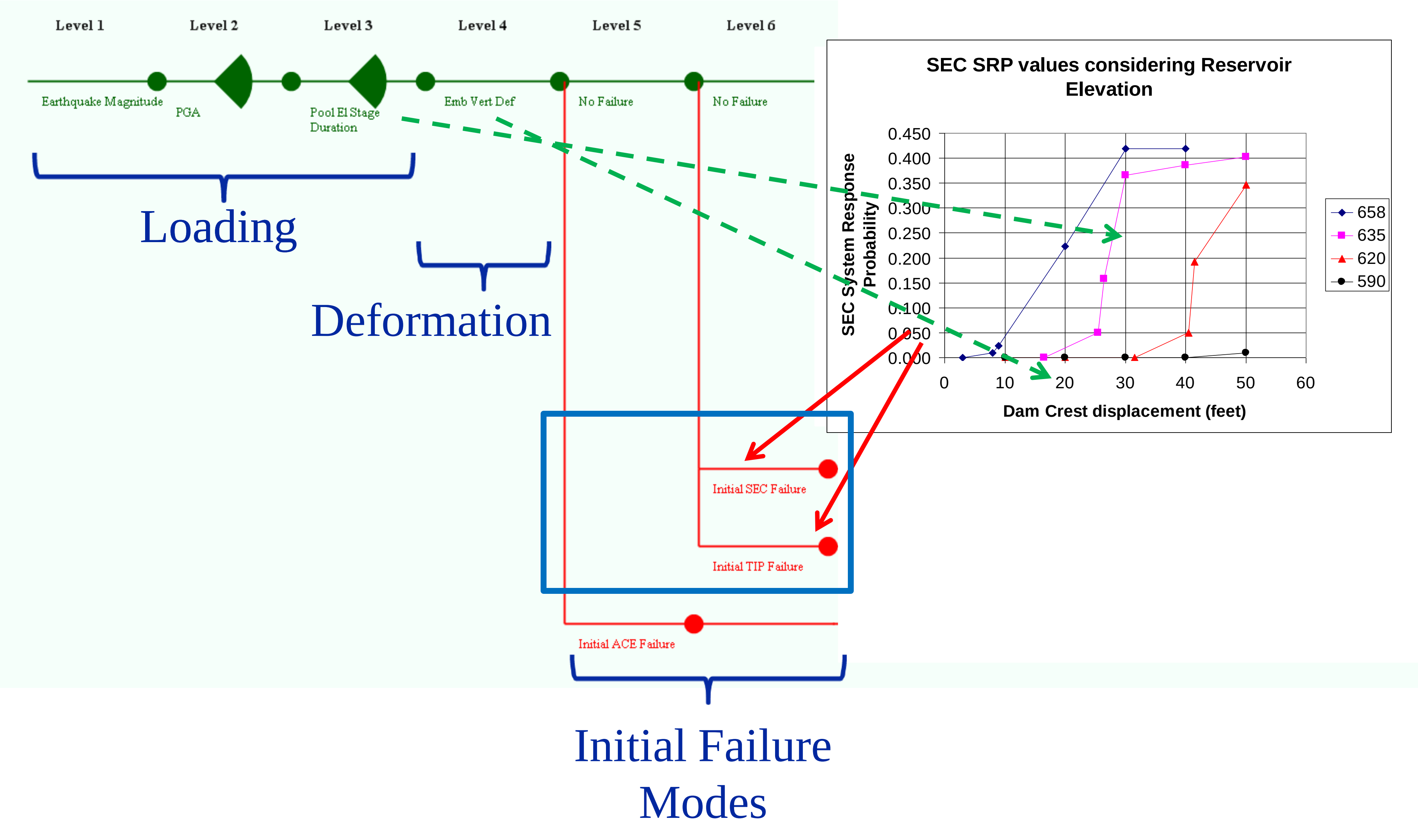
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7

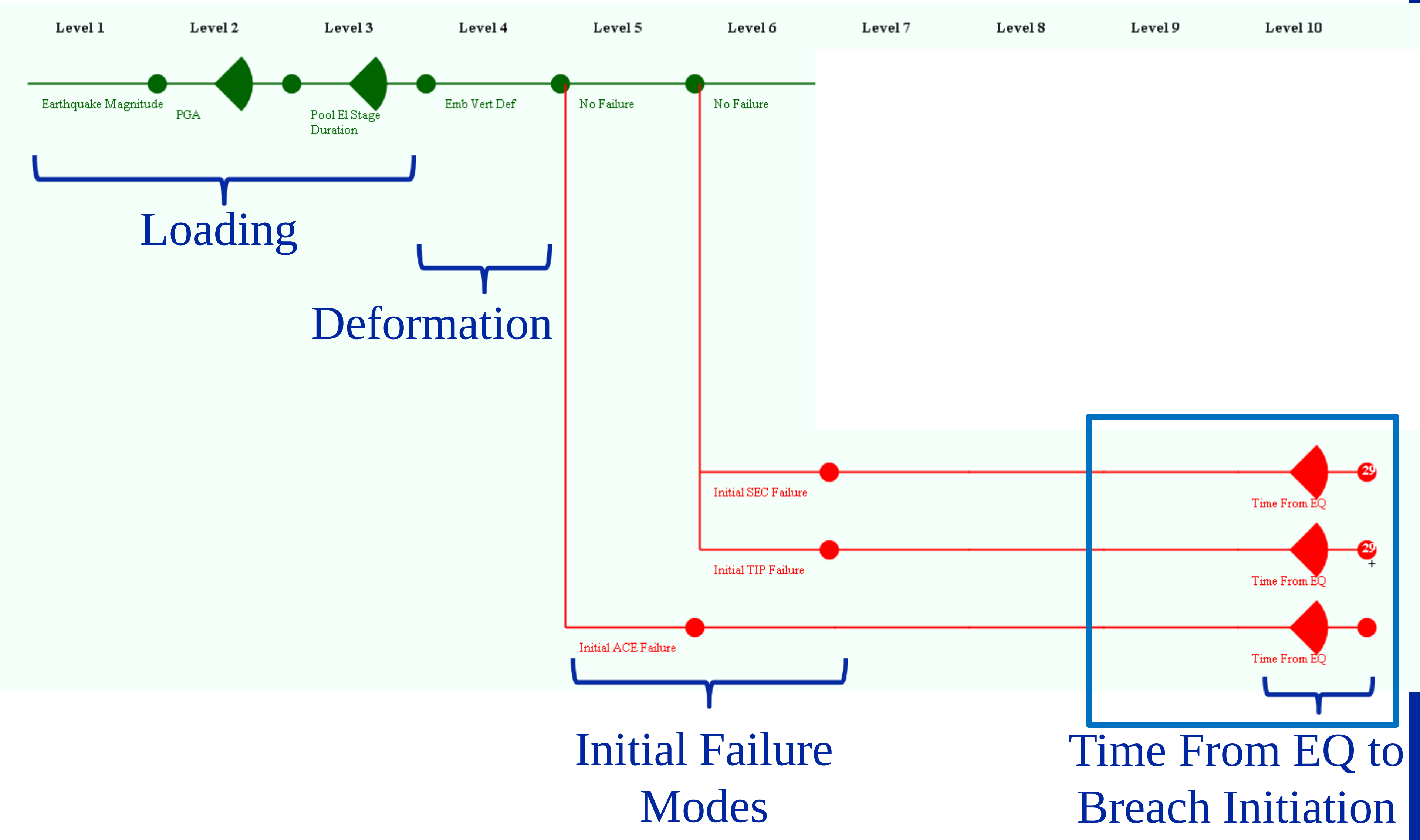


Event Tree for Estimating Individual Conditional Probabilities of a SEC Failure

- Initiation – Flaw exists[1]
  - Initiation – Erosion starts
    - Continuation– Unfiltered exit exists (consider: no erosion/some erosion/excessive erosion/continuing erosion)
      - Progression – Roof forms to support a pipe
        - Progression – Upstream zone fails to fill crack
          - Progression – Upstream zone fails to limit flows
            - Intervention fails
              - Dam breaches (consider all likely breach mechanisms)
                - Consequences occur

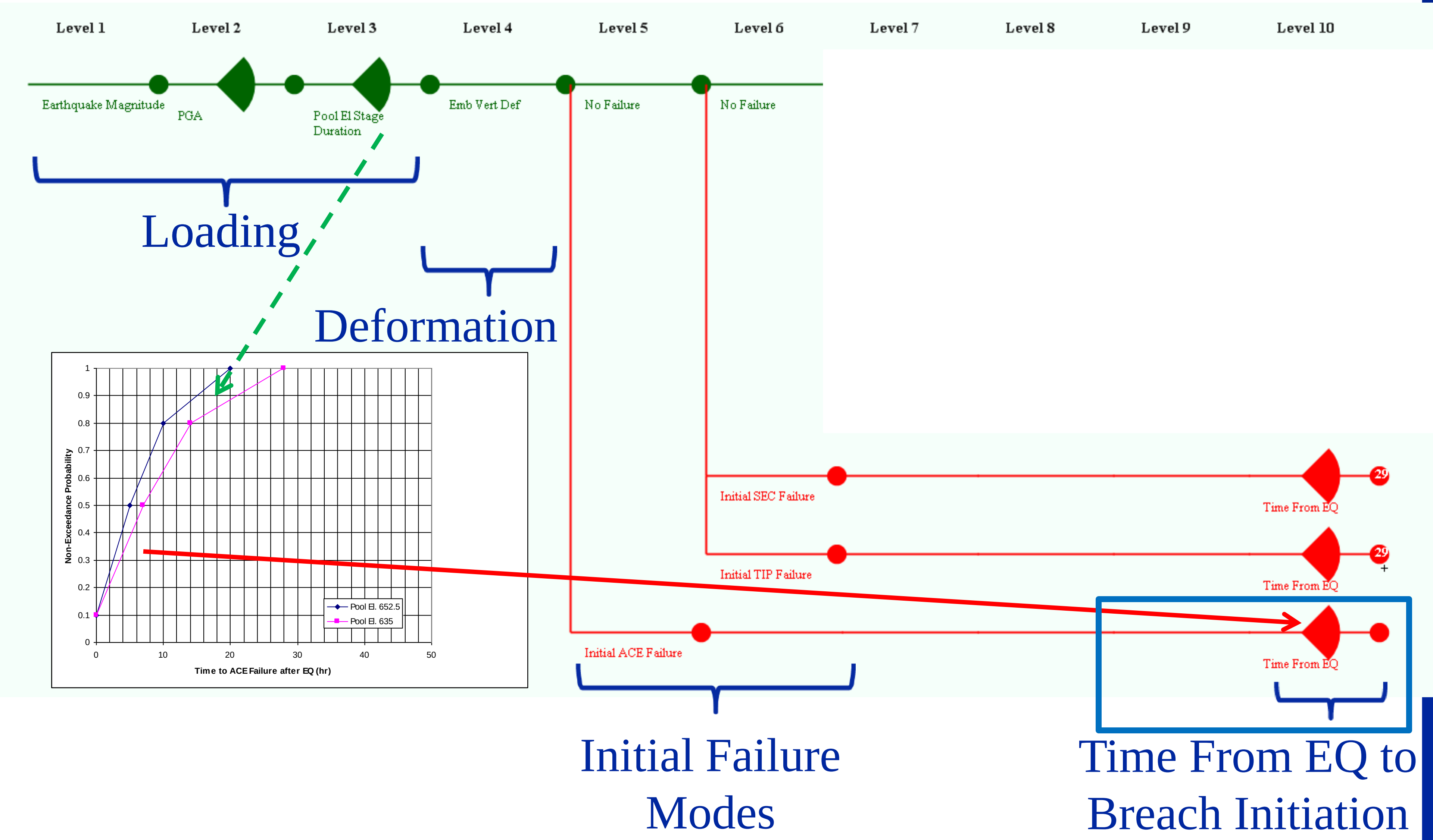
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



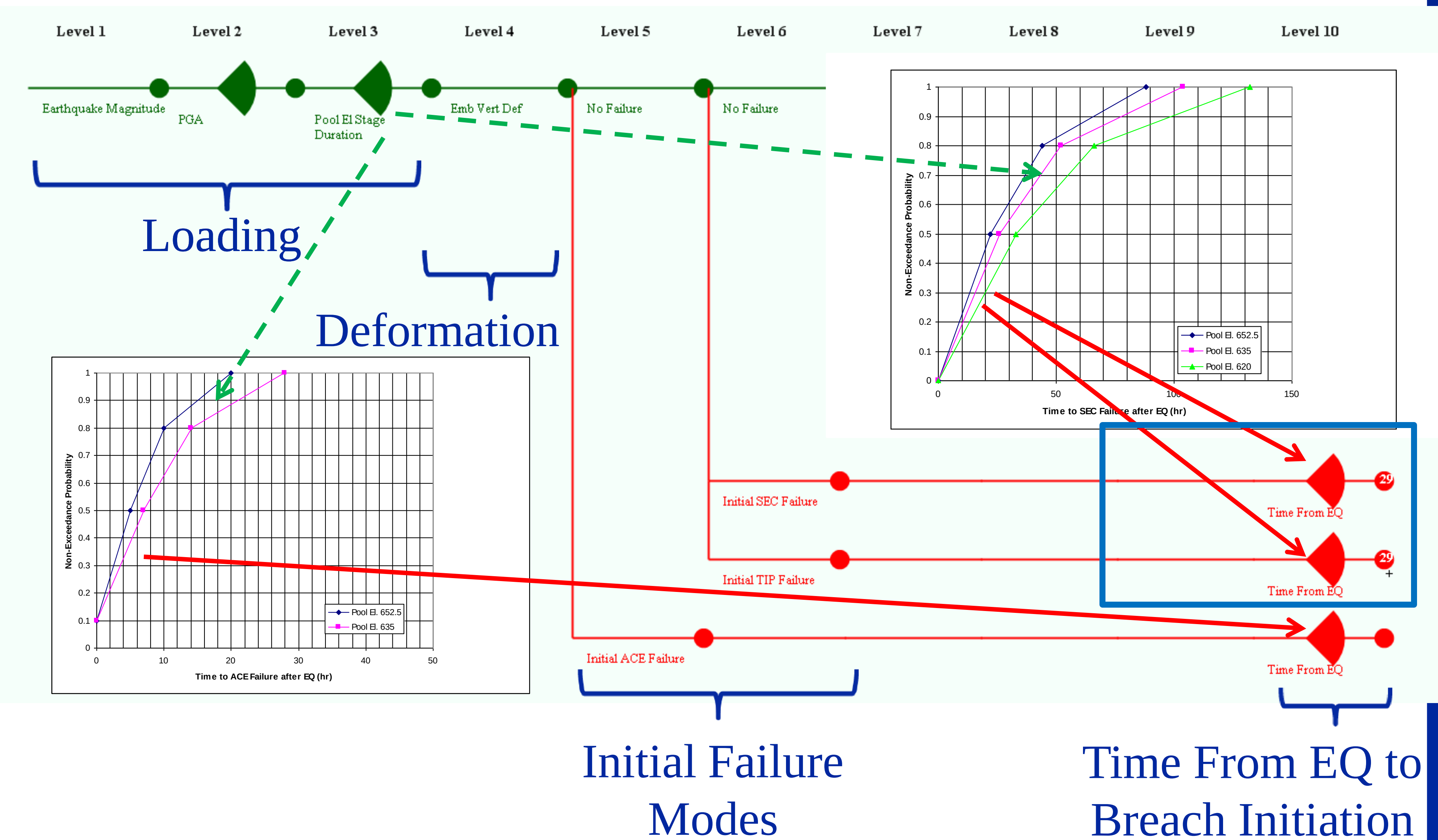
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



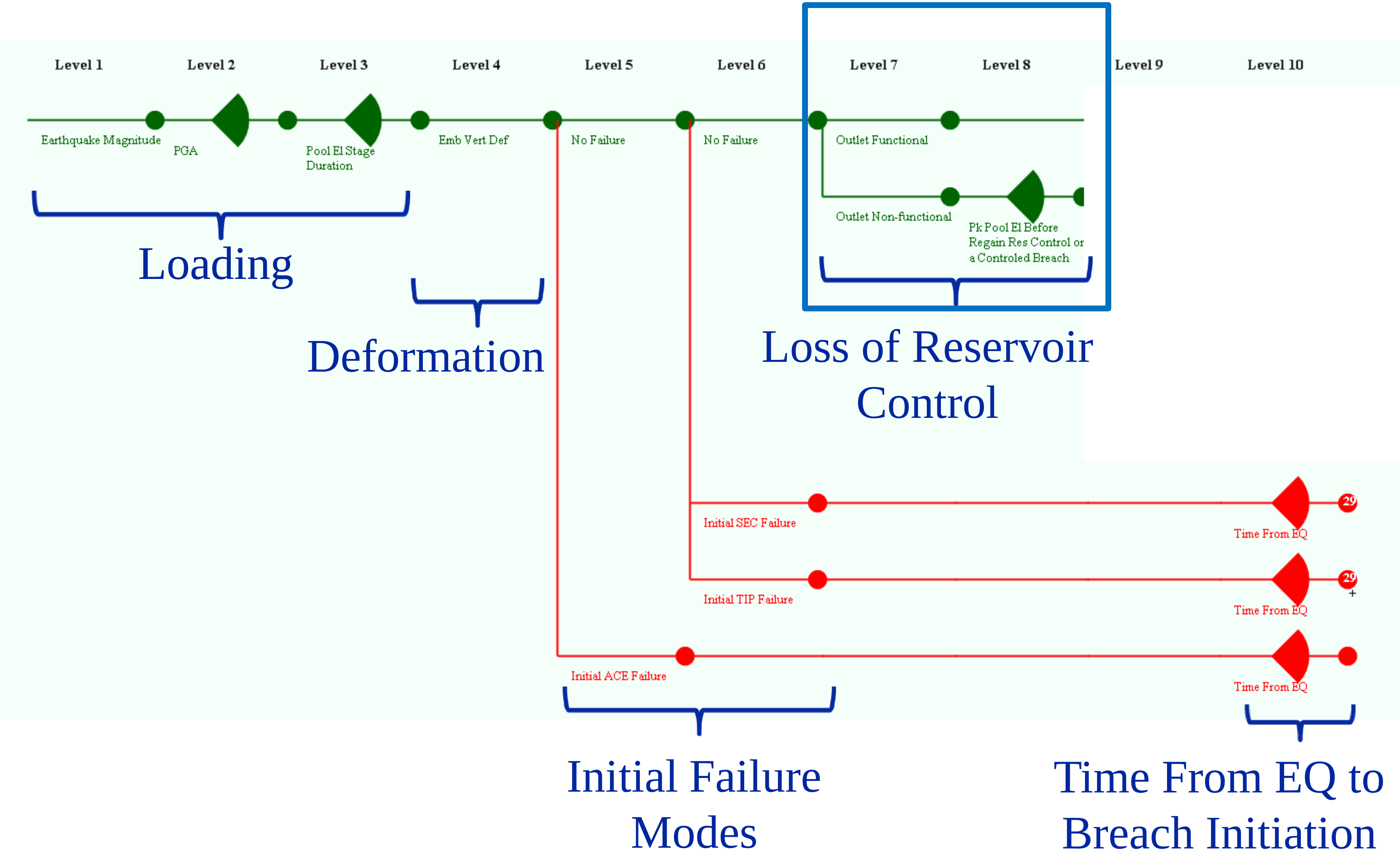
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



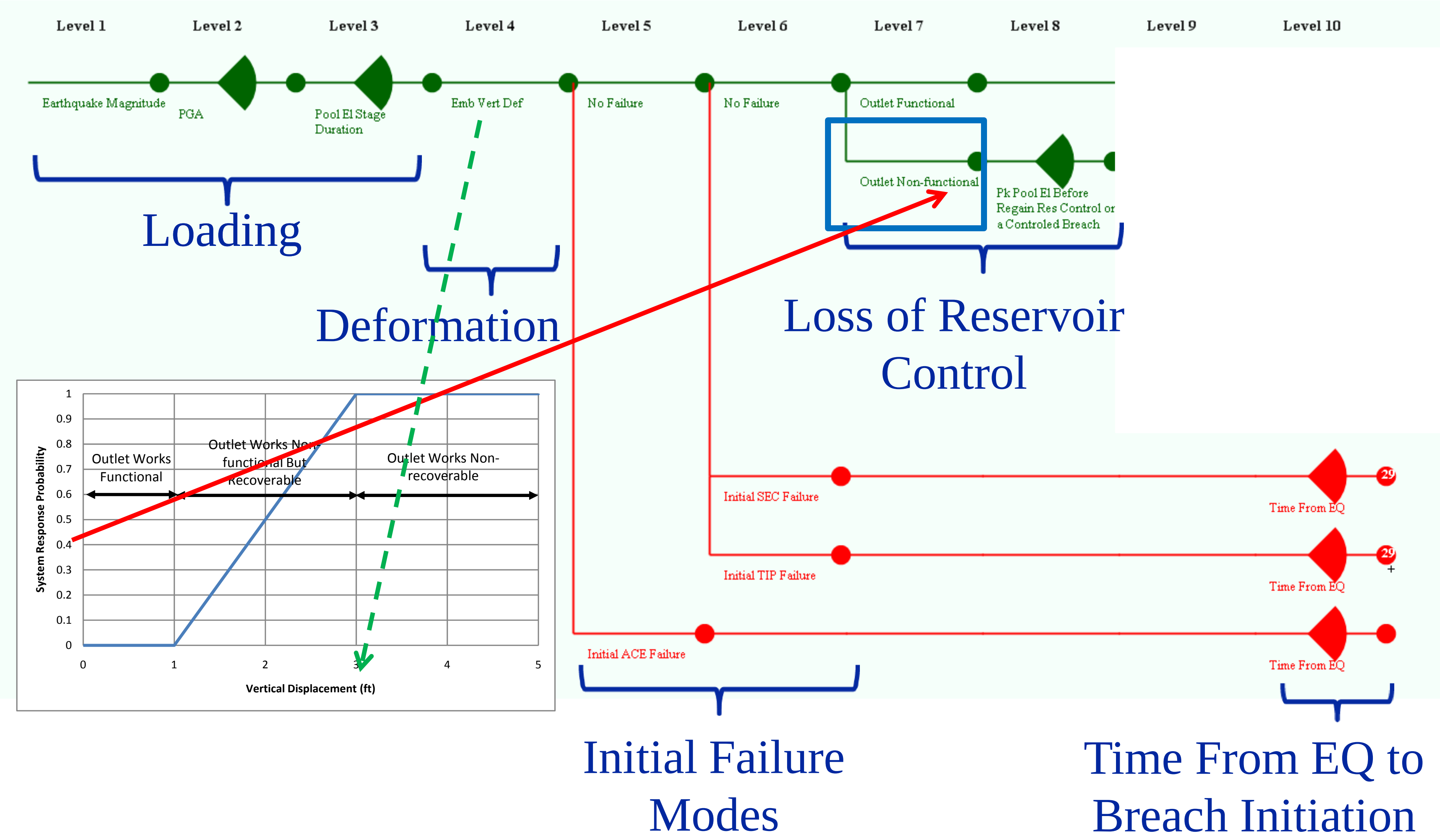
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



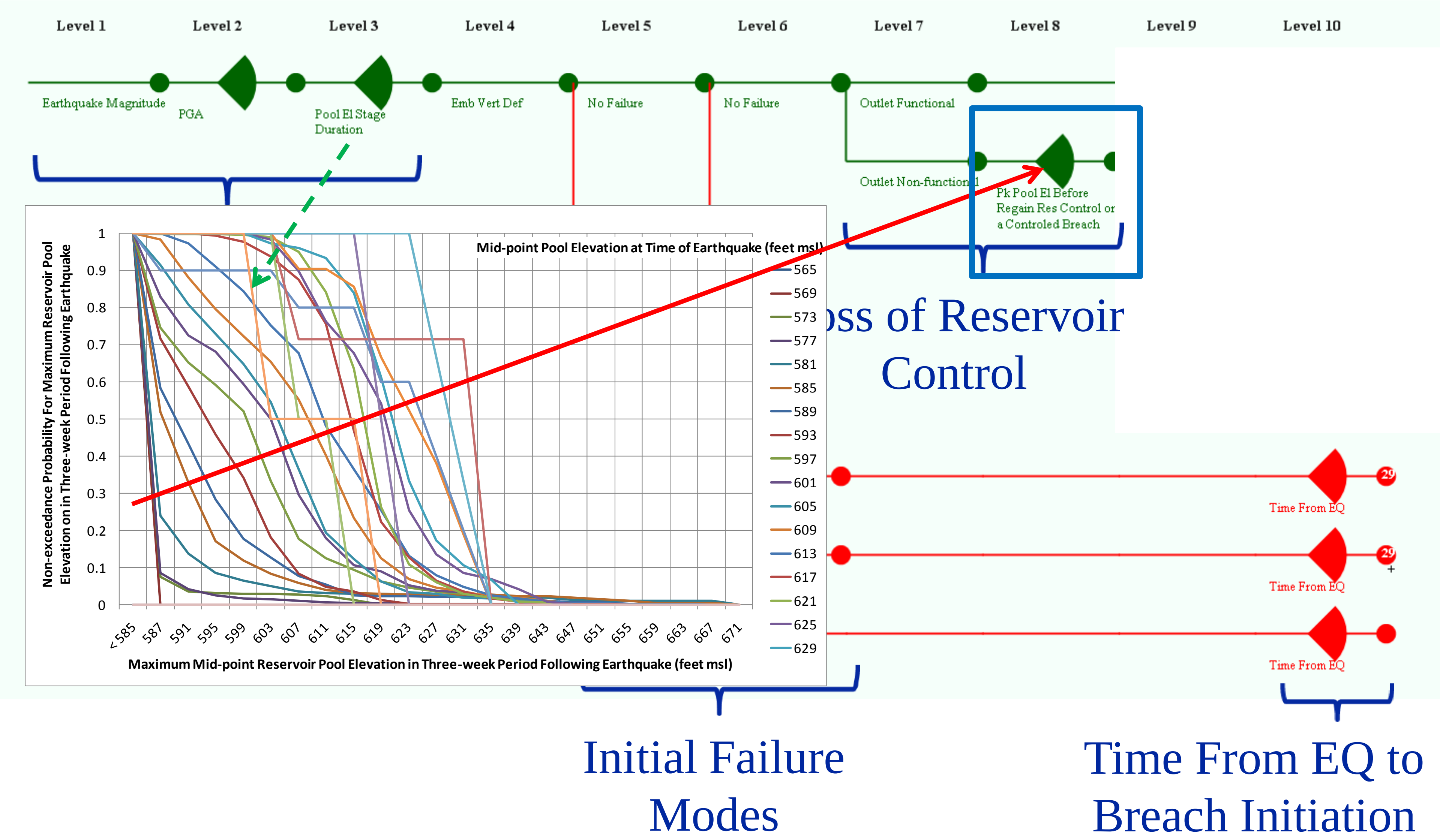
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



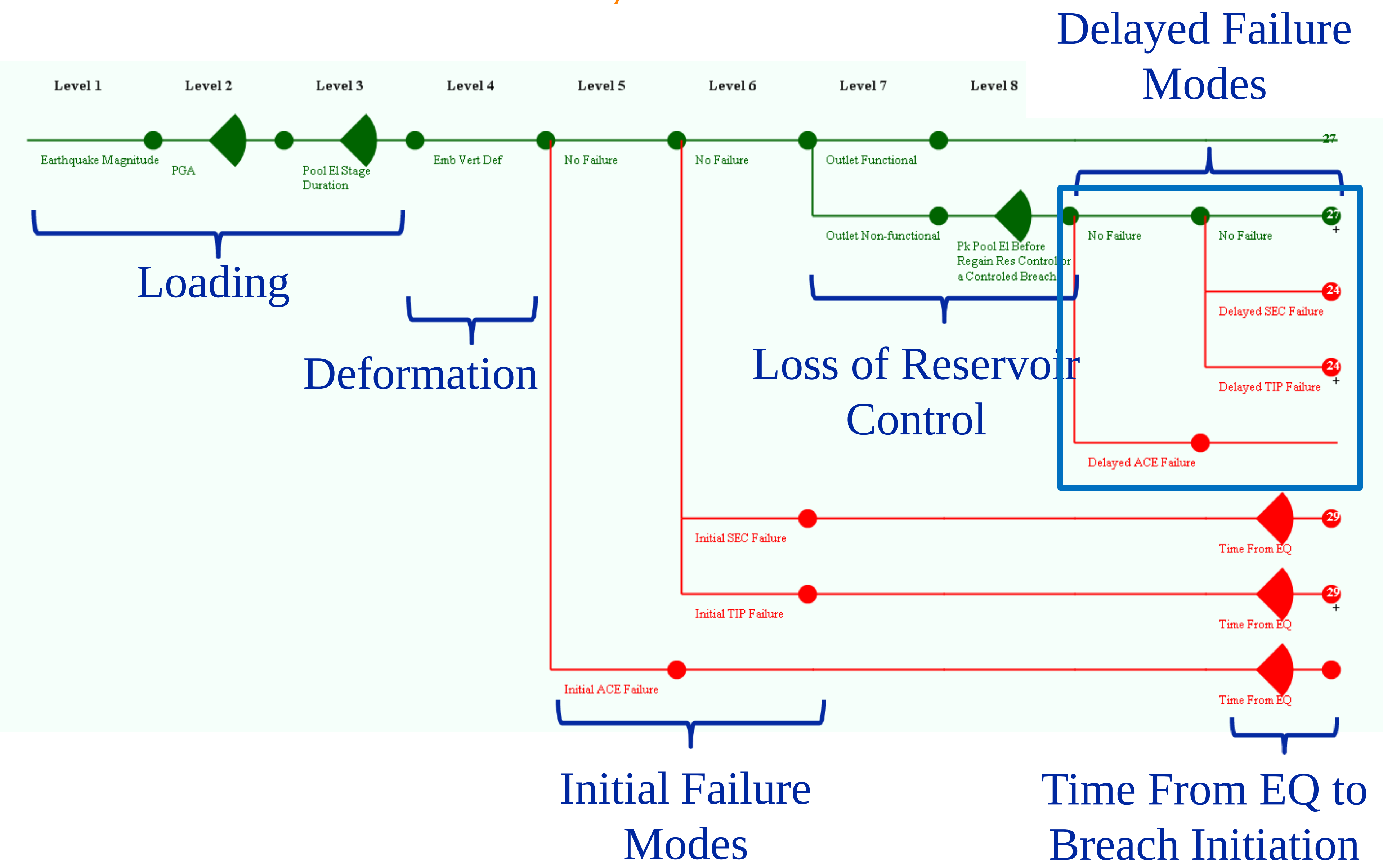
Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



Earthquake Event Tree

For < M6.5, M6.5 – 7 & > M7



Estimated Life Loss

Earthquake Failure Modes

Breach-Inundation Case	Failure Modes	Exposure Case	Warning Time Adjustment (ΔWT) (mins)	Total (1 + 4 + 6)		Average Fatality Rate
				PAR	Life Loss	
E.590	SEC, TIP and ACE	Day	> 200	48,508	9.4	0.0002
		Night	> 200		9.4	0.0002
E.630	SEC, TIP and ACE	Day	> 200	49,485	9.9	0.0002
		Night	> 200		9.9	0.0002
E.FP	SEC, TIP and ACE	Day	-30	61,821	310.4	0.0050
		Night	-60		599.4	0.0097
	SEC, TIP and ACE	Day	90	61,821	195.7	0.0032
		Night	60		203.9	0.0033
	SEC, TIP and ACE	Day	> 200	61,821	18.7	0.0003
		Night	> 200		18.7	0.0003
	ACE	Day	-45	61,821	451.4	0.0073
		Night	-60		599.4	0.0097

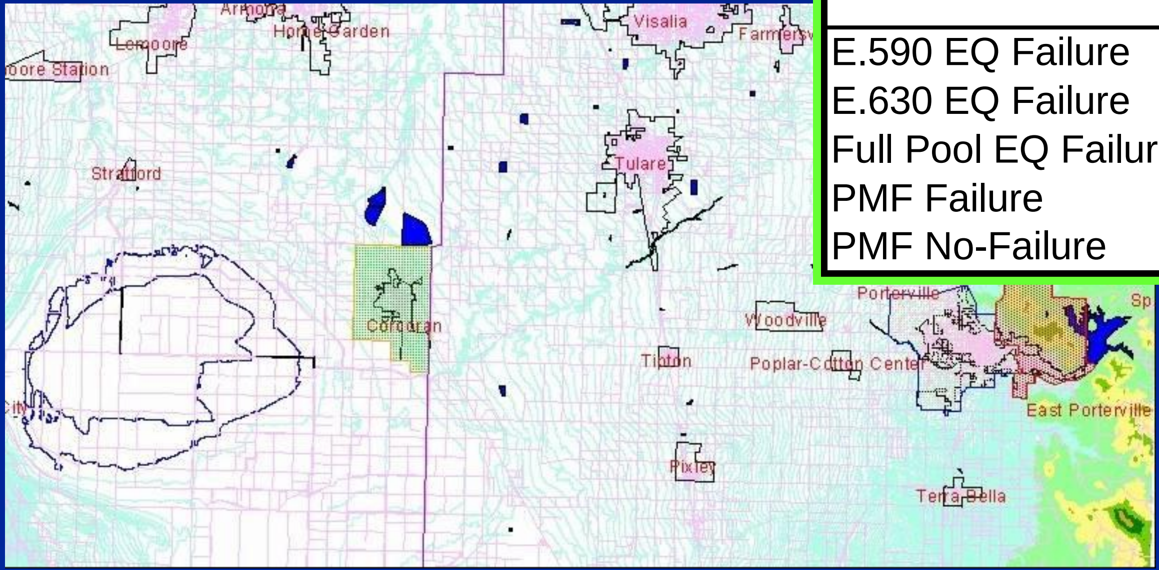
Flood and Flood-internal Failure Modes and Flood No Failure

Breach-Inundation Case	Failure Modes	Exposure Case	Warning Time Adjustment (ΔWT) (mins)	Total		Average Fatality Rate
				PAR	Life Loss	
F.PMF	All Flood & Flood-internal	Day	> 200	115,176	27.5	0.0002
		Night	> 200		27.5	0.0002
F.FP		Day	> 200	61,821	12.4	0.0002
		Night	> 200		12.4	0.0002
F.630		Day	> 200	49,485	9.9	0.0002
		Night	> 200		9.9	0.0002
F.590		Day	> 200	48,508	9.4	0.0002
		Night	> 200		9.4	0.0002
F.PMF NF	No Failure	Day	> 200	56,793	12.8	0.0002
		Night	> 200		12.8	0.0002
F.FP NF		Day	> 200	Not available	0.0	0.0000
		Night	> 200		0.0	0.0000
F.630 NF		Day	> 200	Not available	0.0	0.0000
		Night	> 200		0.0	0.0000
F.590 NF		Day	> 200	Not available	0.0	0.0000
		Night	> 200		0.0	0.0000

Economic Consequences of Dam Failure

Estimated flood damages to agricultural lands in Tulare Lakebed

Breach Case	Breach Run	Flood Damages ($M)
E.590 EQ Failure	E.590	7
E.630 EQ Failure	E.630	14
Full Pool EQ Failure	E.FP	31
PMF Failure	F.PMF	56
PMF No-Failure	F.PMF NF	45



Estimated economic damages ($M) to agriculture and structures

Breach Case	Consequence Center				
	2) Eastern Porterville Area	3) Western Porterville Area	4) Tulare County	5) Corcoran	6) Kings County
E.590	187	59	264	0.6	7.6
E.630	560	91	669	0.7	15
E.FP	625	74	725	1.0	33
F.PMF	895	125	1,051	3.0	3.2
F.PMF NF	421	91	529	0.8	0.9

Other Recent Applications

- Ash Piles at a TVA Power Plant
  - EQ Induced Liquefaction
  - Static Liquefaction
- Mine Closure in the Yukon
  - Tailings Dams
  - Containment Dikes

Important lingering questions

- Importance of establishing a Threshold Earthquake Load
- Mean strength values are used for probabilistic slope stability analysis
- Selection of $(N_1)_{60}$ values for probabilistic liquefaction analysis
- Thickness of the liquefiable layer – Keaton and Anderson