Seismic Stress Analysis of Folsom Dam

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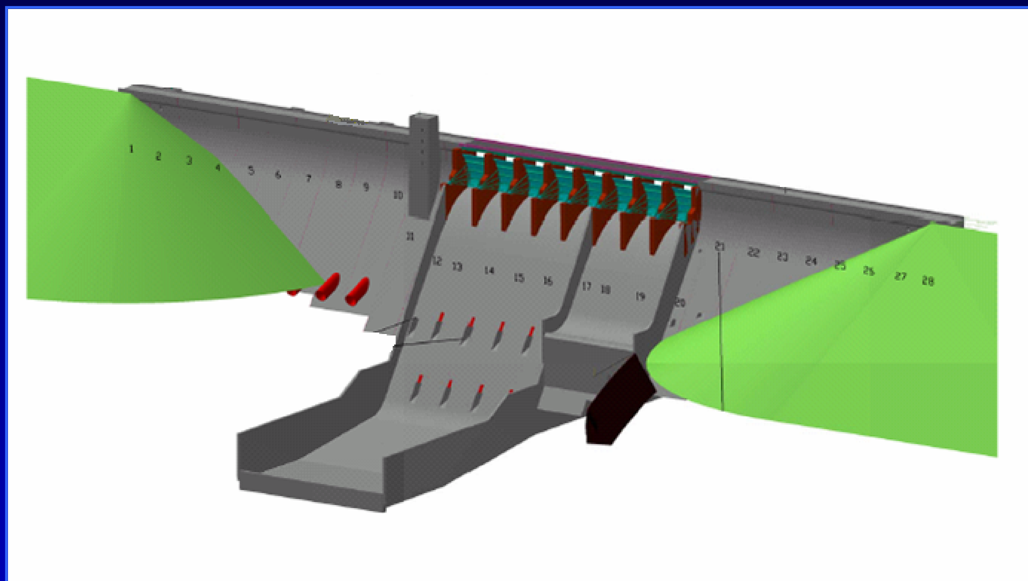
Introduction

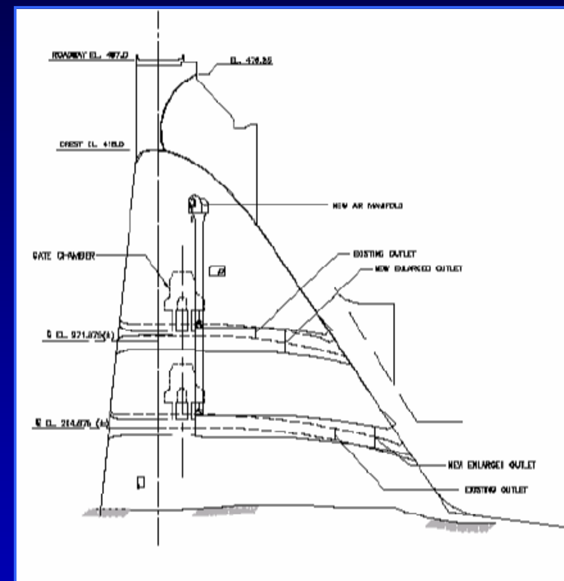
- **Folsom Dam Description**

  - Design/construction by USACE (1948-1956), transferred to USBR (1956)
  - Maximum height of gravity section is 340 ft with a crest length of about 1,400 ft.
  - 28 monoliths, 50 ft wide each.
  - Main spillway: 5 ogee monoliths, two tiers of 4 outlets. Emergency spillway: 3 flip bucket monoliths.
  - Embankment wrap fill and wing dams

Introduction

- **Outlet Works Modification Project**

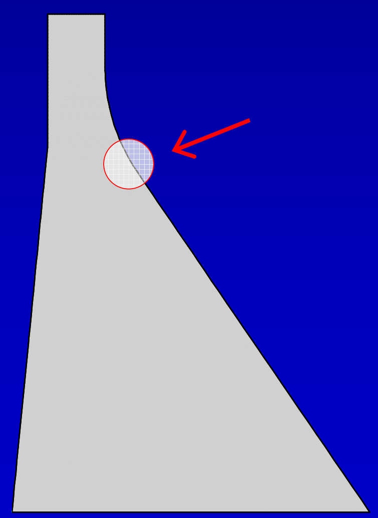




- **Project will increase the river outlet release capacity from 26,000 cubic feet per second to 115,000 cubic feet per second.**
- **Spillway section modifications basically consist of enlarging the four existing upper tier river outlets (9.33 ft by 14 ft), constructing two new upper tier river outlets of the same size, and enlarging the four existing lower tier river outlets (9.33 ft by 12 ft).**

Previous Stress Analyses

- DSAP Evaluation
  - DSAP seismic evaluation completed in 1989.
  - Peak ground acceleration (PGA) for the horizontal direction defined as 0.35g.
  - Analyses performed using the computer program EAGD-84, considering the tallest non-overflow monolith as critical section.
  - Different values of foundation modulus (5.8, 7.9, and 11.0 10^6 psi) and wave reflection coefficient (0.75, 0.79, and 0.82) were considered.
  - Maximum principal stresses reached about 870 psi on the downstream face, near the lower end of the circular transition.



Previous Stress Analyses

- DSAP Evaluation

Concrete Material Properties

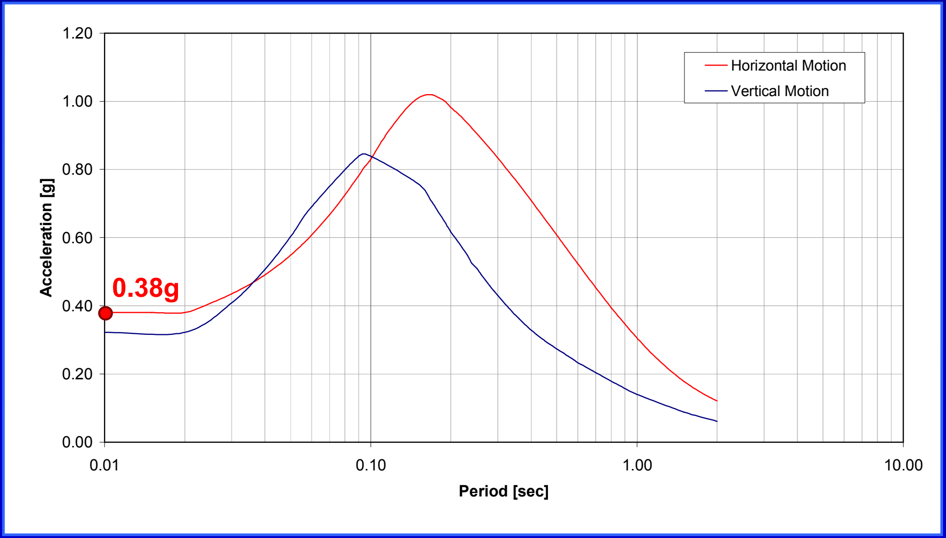
Modulus of Elasticity Dynamic (10^6 psi)	Poisson's Ratio	Unit Weight (pcf)
5.9	0.19	158

Foundation Rock Properties

Modulus of Elasticity Dynamic (10^6 psi)	Poisson's Ratio	Unit Weight (pcf)
5.8	0.30	167
7.9	0.25	171
11.0	0.20	174

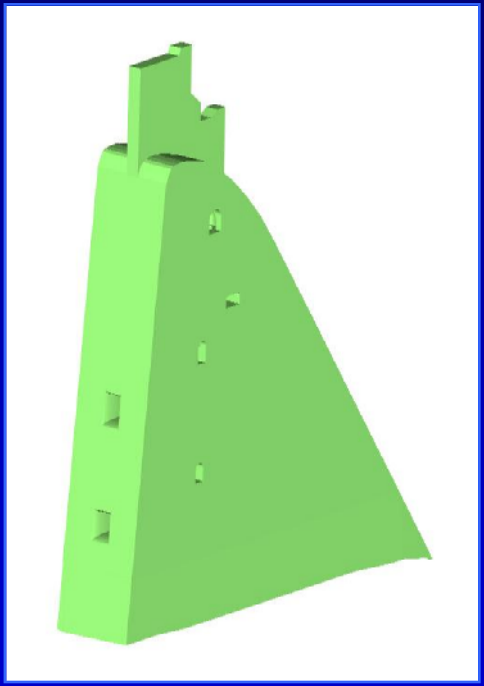
Ground Motions

- **Maximum Credible Earthquake**
  - Event of magnitude 6.5 at a source-to-site distance of 14 km, on the eastern branch of the Bear Mountains fault zone.
  - Horizontal PGA values corresponding to the 50th and 84th percentile were determined as 0.24g and 0.38g, respectively.
  - Vertical response spectrum defined using a period-dependent scaling factor.



Response-Spectrum Based Analyses

- Approach
  - 3D GTSTRUDL FE mesh of 50-ft wide dam monoliths.
  - Chopra's simplified procedure used to develop sets of lateral forces .
  - Horizontal and vertical components of input motion.
  - Peak dynamic responses obtained by combination using SRSS rule.
  - Dynamic responses combined with static results (monolith weight, hydrostatic pressures, and uplift).
  - Results used for design of reinforced concrete liners.

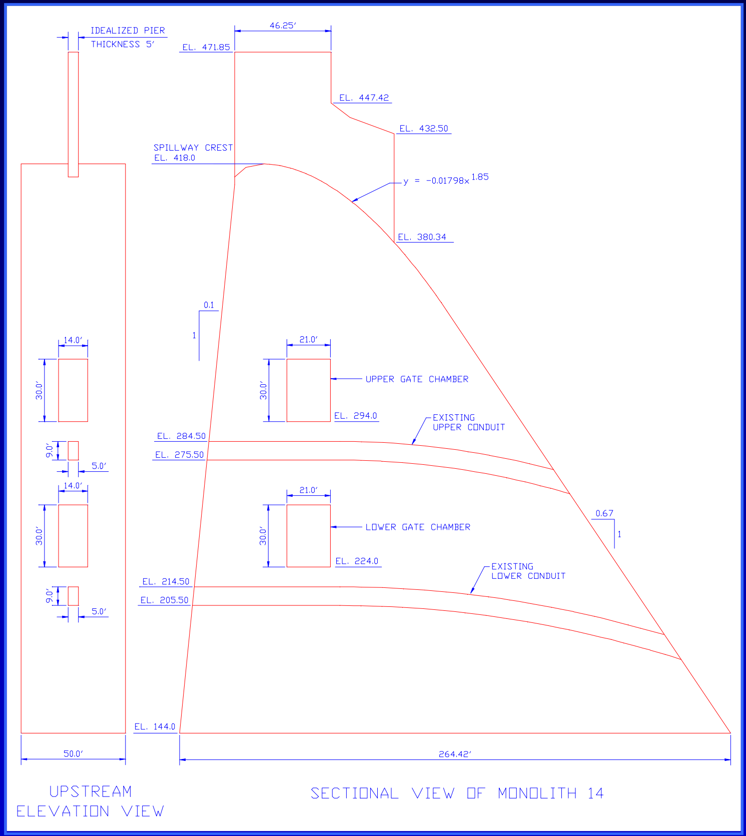


Response-Spectrum Based Analyses

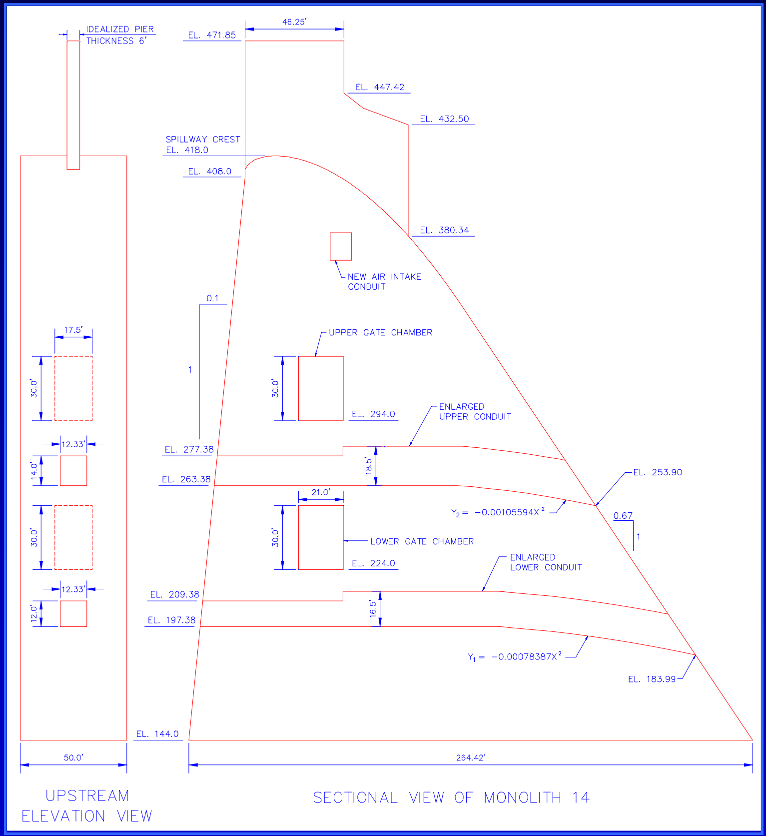
- **Chopra's Simplified Procedure**
  - Dynamic response can be described by the fundamental mode of vibration of the dam on rigid foundation rock.
  - Mode shape does not take into account foundation flexibility.
  - Analysis of fundamental-mode response still a complex problem because of frequency-dependent interaction phenomena (dam/reservoir, dam/foundation).
  - By defining frequency-independent parameters, an equivalent SDOF system is used to approximate the dynamic response.
  - FE analysis conducted using sets of lateral forces representing inertial and hydrodynamic actions associated with fundamental-mode including higher-mode correction.

Response-Spectrum Based Analyses

- Evaluation of Different Conditions



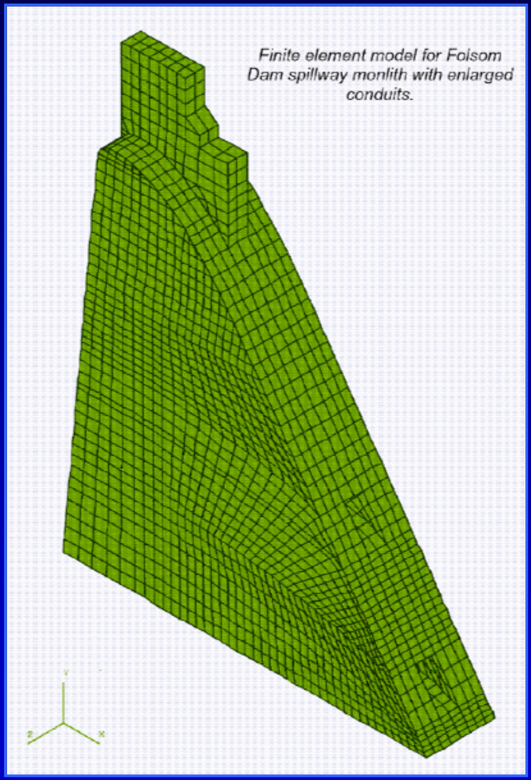
Monolith 14
Existing condition



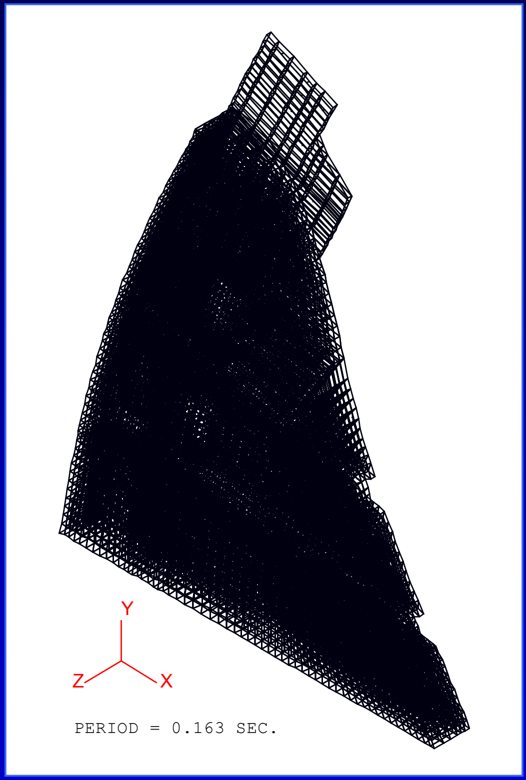
Monolith 14
Modified condition

Response-Spectrum Based Analyses

- Finite Element Model



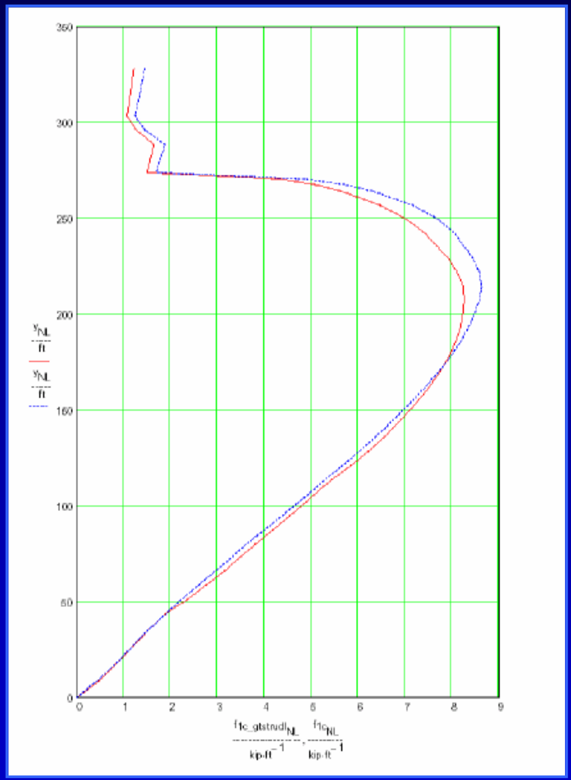
3D model



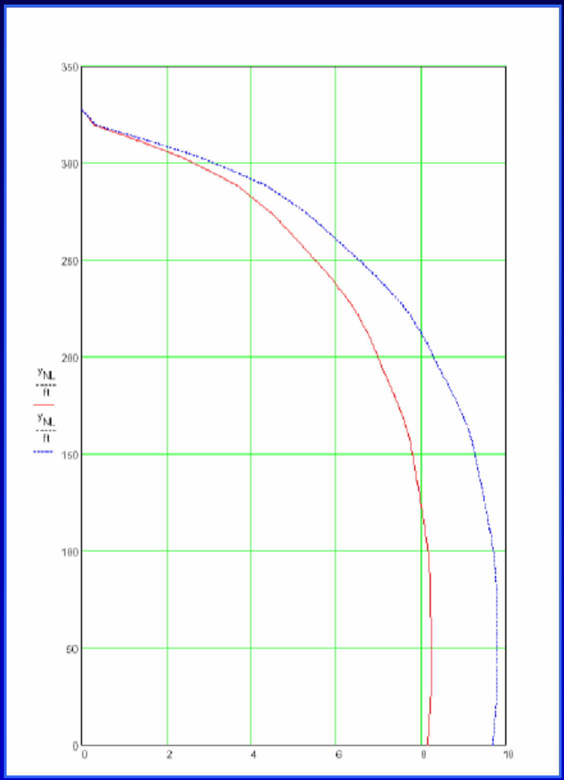
Fundamental mode shape
T_1 = 0.163 sec (f_1 = 6.14 Hz)

Response-Spectrum Based Analyses

- **Equivalent Forces – Fundamental Mode**



Inertia forces associated with fundamental mode response



Hydrodynamic forces associated with fundamental mode response

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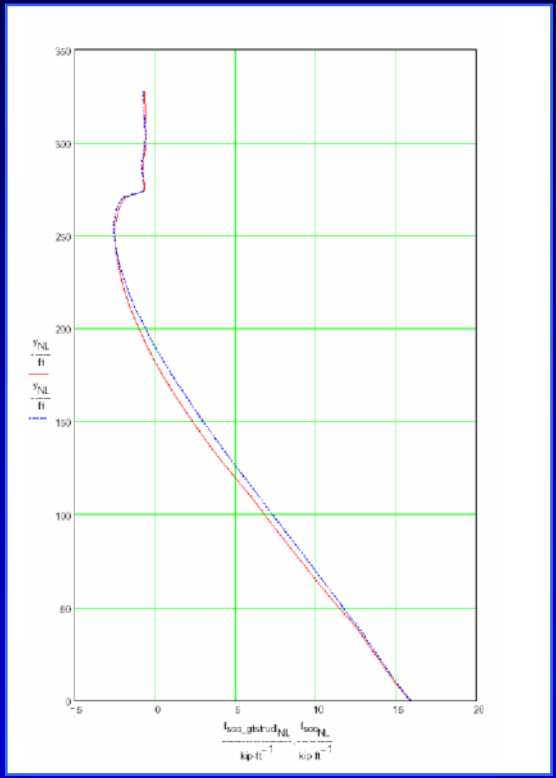
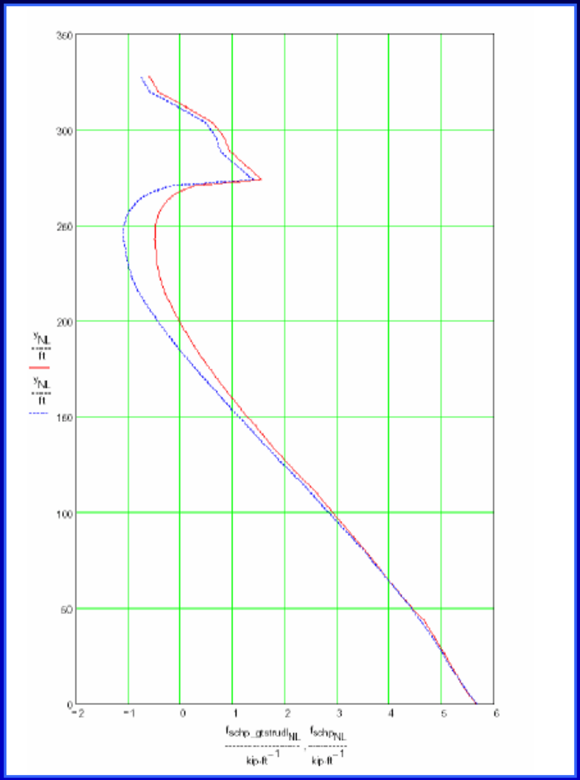
Response-Spectrum Based Analyses

- Equivalent Forces – Higher-Mode Correction



Inertia forces associated with higher-mode contributions



Hydrodynamic forces associated with higher-mode contributions

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Response-Spectrum Based Analyses

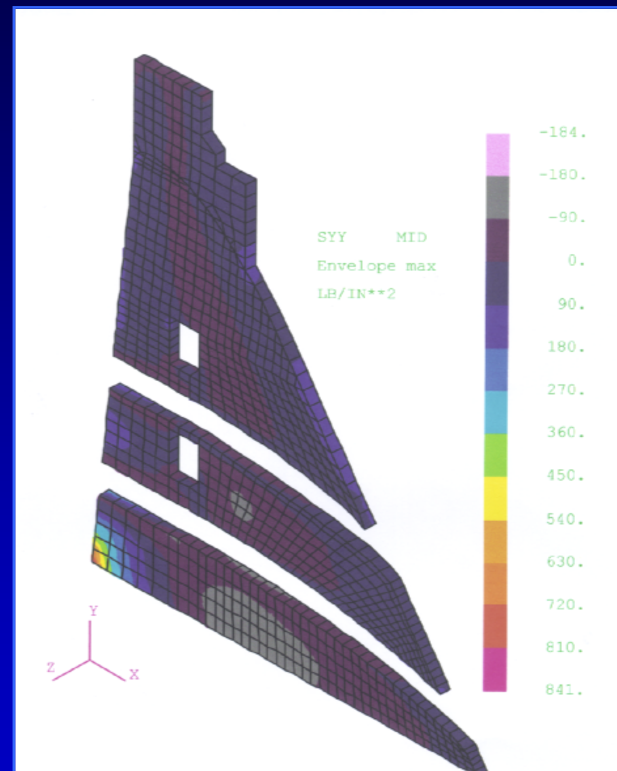
- Cases Analyzed

TABLE 4 SUMMARY OF CASES ANALYZED

Case No.	Monolith	Condition	Modulus of Elasticity of Concrete E_s (psi)	Modulus of Elasticity of Foundation Rock E_f (psi)	Earthquake
1	14	Existing	3.6×10^6	Rigid	-
2	14	Modified	3.6×10^6	Rigid	-
3	14	Existing	5.9×10^6	7.9×10^6	MCE
4	14	Modified	5.9×10^6	7.9×10^6	MCE
5	13	Existing	3.6×10^6	Rigid	-
6	13	Modified	3.6×10^6	Rigid	-
7	13	Existing	5.9×10^6	7.9×10^6	MCE
8	13	Modified	5.9×10^6	7.9×10^6	MCE

Response-Spectrum Based Analyses

- Evaluation of Peak Stresses
  - Results for Monolith 14 showed peak vertical tensile stresses mostly within the apparent dynamic tensile strength (700 psi)
  - Stress concentration (1,140 psi) at the upstream heel but stress values drop sharply within 10 ft.
  - The results for Monolith 21 also indicated stress concentration at the upstream heel (890 psi).



Envelope of maximum normal stresses Syy (psi) at z = 25 ft

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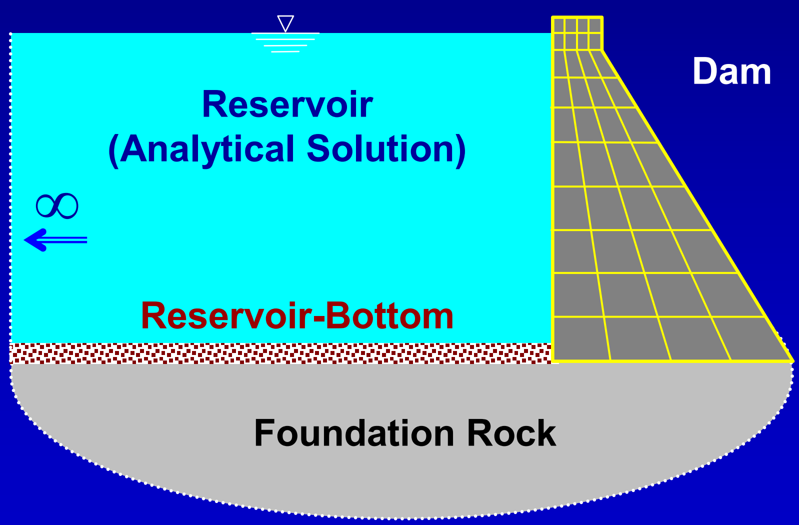
Time History Analyses

- Approach
  - Seismic stress analyses were conducted on 2D FE models of monoliths 14 and 21, subject to ground motion time histories representative of the MCE.
  - Analyses performed with the computer program EAGD-84.
  - Program developed at the University of California at Berkeley (Fenves and Chopra, 1984) to evaluate the seismic response of two-dimensional sections of concrete gravity dams taking into account
    - Dam-water interaction
    - Dam-foundation rock interaction
    - Energy absorption at the bottom of the reservoir

Time History Analyses

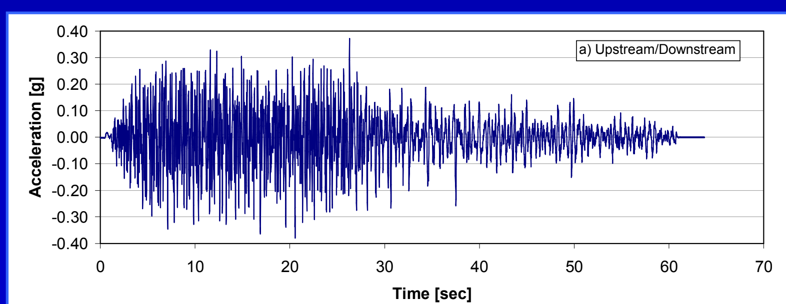
- **Program EAGD-84**
  - Equations of motion solved in the frequency domain assuming linear behavior for the dam-water-foundation system.
  - The foundation region idealized as a homogeneous, isotropic, viscoelastic half-plane.
  - Reservoir modeled as fluid domain of constant depth and infinite length along the upstream direction.
  - Energy absorption associated with reservoir bottom materials quantified by wave reflection coefficient (α).

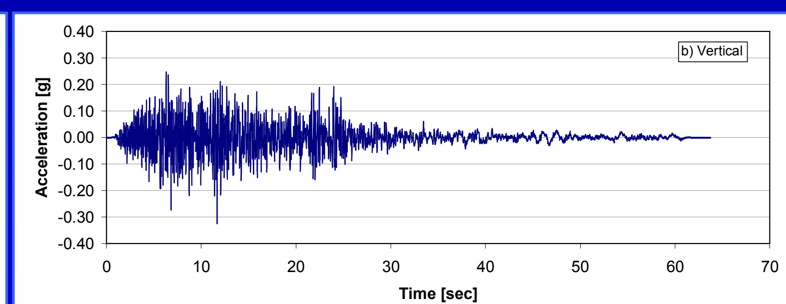


Ground Motion Time Histories

- ## Maximum Credible Earthquake

Earthquake	Mw	Recorded ground motions				Modified time histories		
		Station	Dist. (km)	Comp.	PGA (g)	PGA (g)	PGV (cm/sec)	Direction
1971 San Fernando	6.6	Pasadena – Old Seism. Lab.	19	180	0.09	0.38	27.0	Cross Ch.
				270	0.20	0.38	34.8	Us/Ds
				Vertical	0.09	0.30	13.5	Vertical
1979 Imperial Valley	6.5	Cerro Prieto	26	147	0.17	0.38	23.8	Us/Ds
				237	0.16	0.38	23.1	Cross Ch.
				Vertical	0.21	0.33	11.5	Vertical
1986 Chalfant Valley	6.2	Bishop – Paradise Lodge	23	70	0.16	0.38	28.8	Cross Ch.
				160	0.16	0.38	29.4	Us/Ds
				Vertical	0.13	0.31	11.7	Vertical

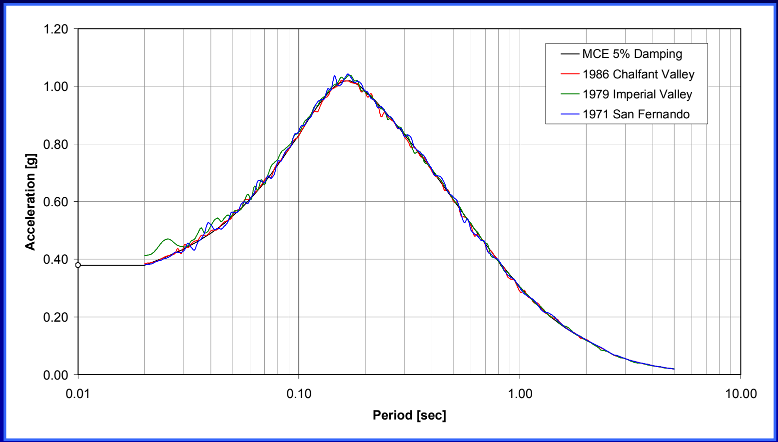




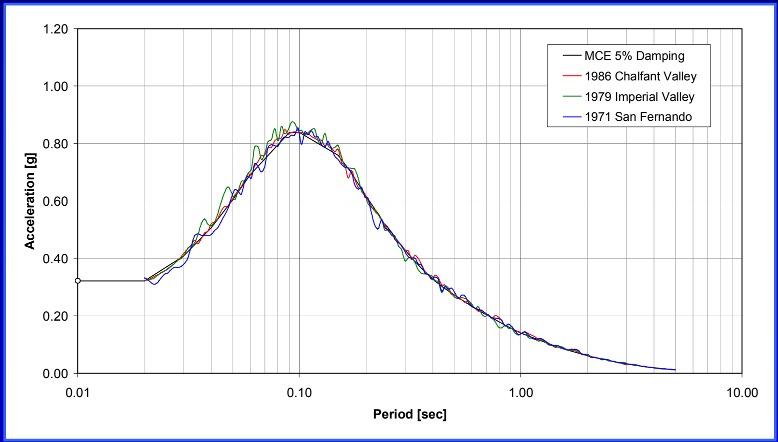
Imperial Valley Earthquake

Ground Motion Time Histories

- Spectral Matching



Comparison of 5%-damped horizontal response spectra for truncated (30 sec) time histories



Comparison of 5%-damped vertical response spectra for truncated (30 sec) time histories

Ground Motion Time Histories

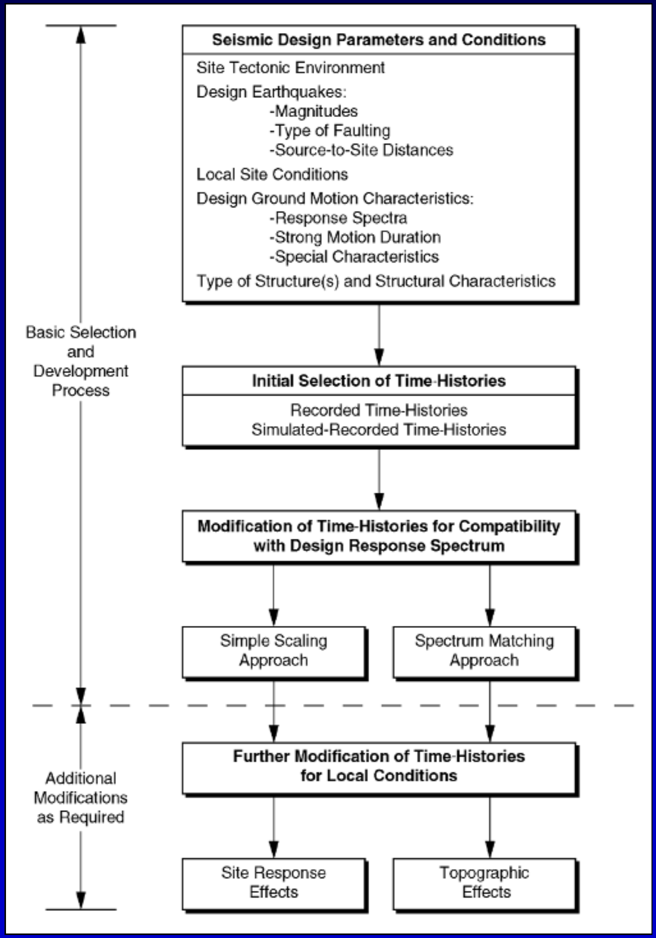
- **Response Spectrum Compatibility**

  – **Simple scaling approach:**

    At least three time-histories for each component of motion should be considered.

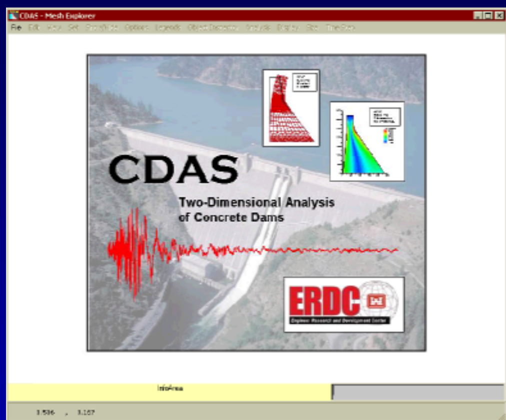
  – **Spectrum-matching approach:**

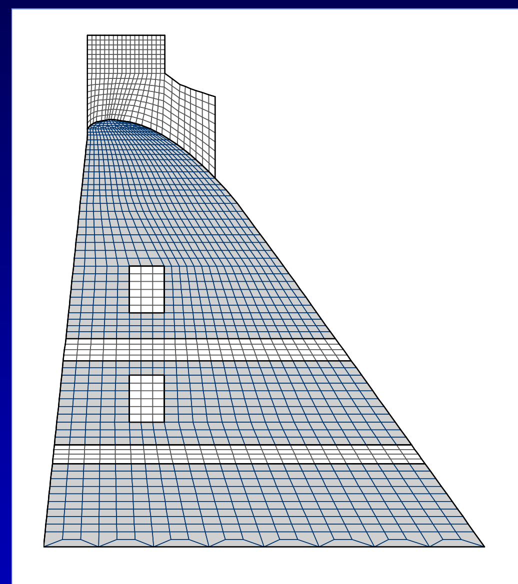
    Linear response is mainly determined by the spectral content of the time-history. If a very close fit to the target spectrum can be obtained, *a single time-history for each component may be sufficient.*



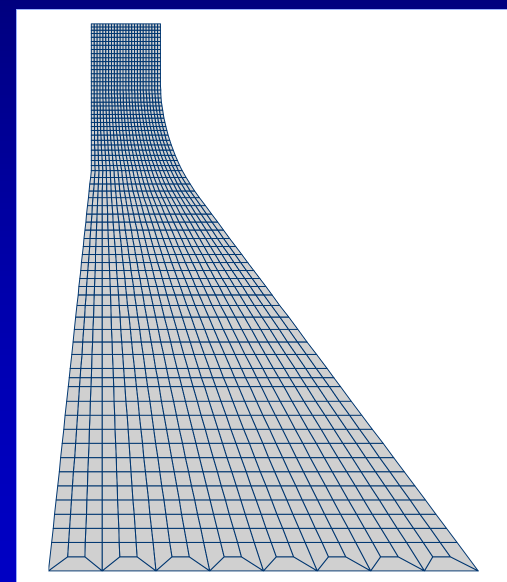
Time History Analyses

- **2D FE Models (EAGD-84)**





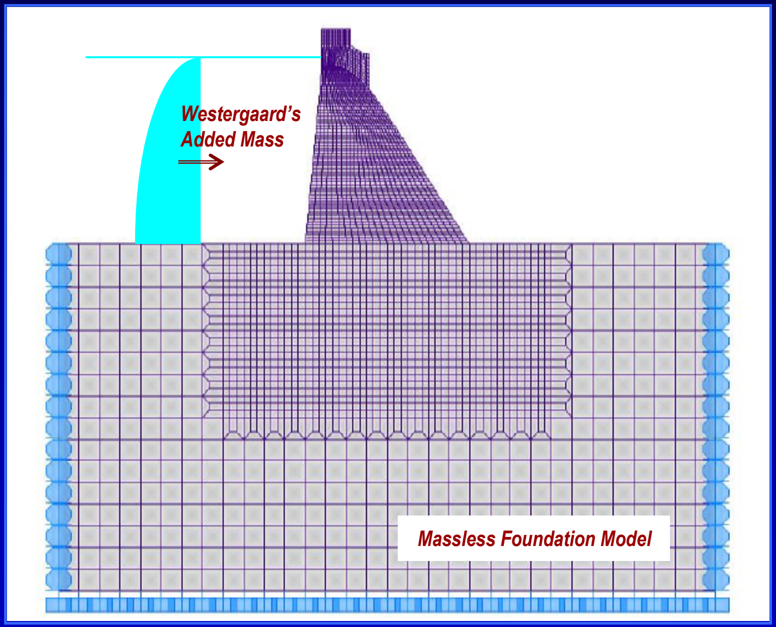
Finite-element mesh for spillway Monolith 14



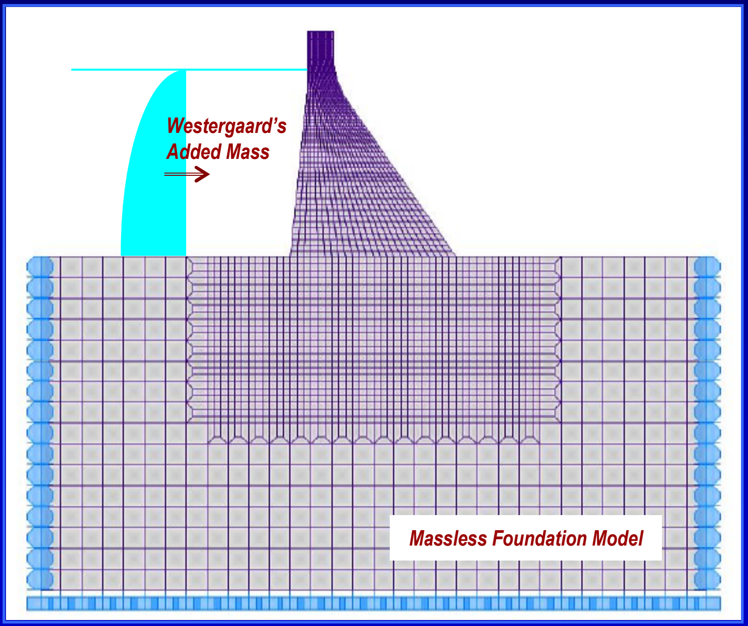
Finite-element mesh for non-overflow Monolith 21

Time History Analyses

- 2D FE Models (SAP2000)



Finite-element mesh for spillway Monolith 14



Finite-element mesh for non-overflow Monolith 21

Time History Analyses

- **Comparison of Natural Periods (2D Models)**

MODE	EAGD84 PERIOD [sec] Rigid	EAGD84 PERIOD [sec] Flexible	SAP2000 PERIOD [sec] Rigid	SAP2000 PERIOD [sec] Flexible
1	0.160	0.222	0.157	0.214
2	0.071	0.139	0.070	0.107
3	0.066	0.098	0.065	0.092
4	0.044	0.054	0.043	0.052
5	0.032	0.041	0.031	0.039

Monolith 14
(Empty reservoir)

3D Model: T_1 = 0.163 sec

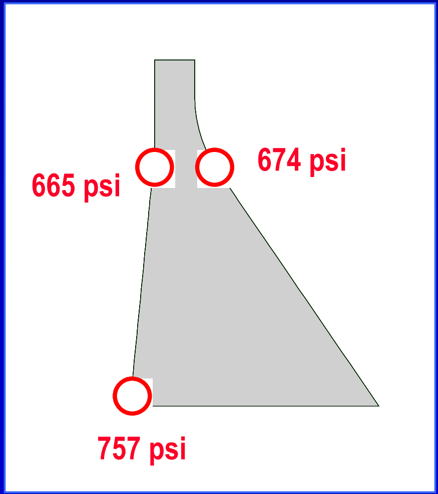
Monolith 21
(Empty reservoir)

MODE	EAGD84 PERIOD [sec] Rigid	EAGD84 PERIOD [sec] Flexible	SAP2000 PERIOD [sec] Rigid	SAP2000 PERIOD [sec] Flexible
1	0.184	0.221	0.184	0.215
2	0.083	0.101	0.083	0.106
3	0.059	0.088	0.059	0.088
4	0.044	0.056	0.044	0.058
5	0.029	0.037	0.029	0.036

Time History Analyses

- **Peak Values of Maximum Principal Stress**

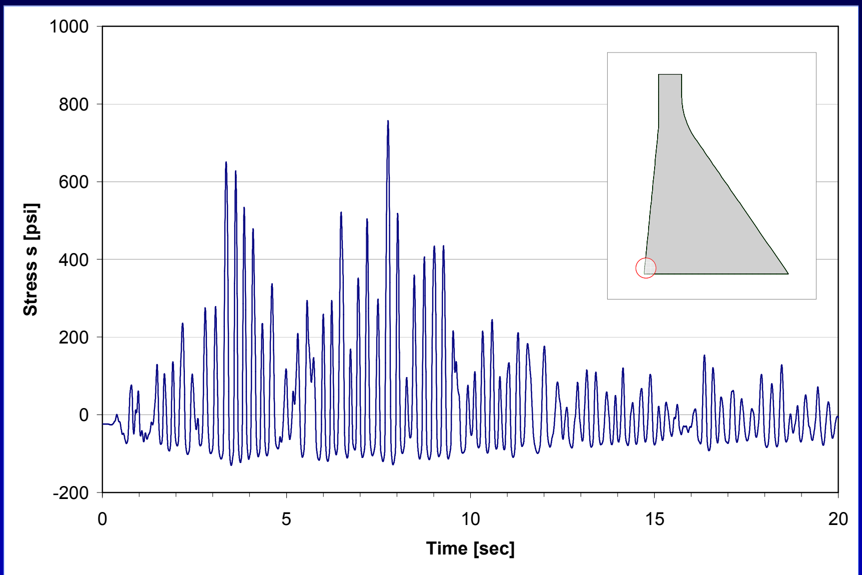
Monolith 21
San Fernando Earthquake
Reservoir pool elevation 466 ft



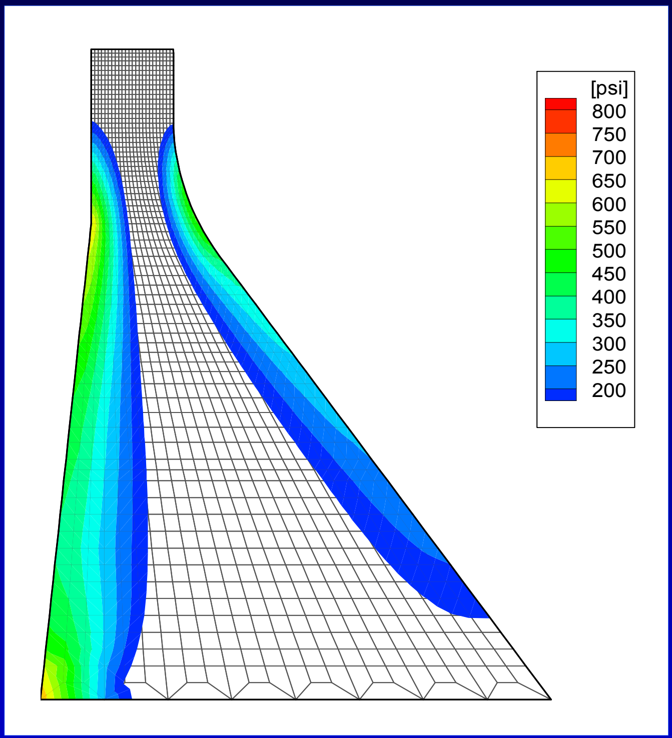
Case	Location	X [ft]	Y [ft]	Time [sec]	σ_{max} [psi]
+H	Base (Heel)	4.85	8.75	7.8	603
+H	Upstream	20.53	196.31	3.4	581
+H	Downstream	61.87	196.31	7.9	604
-H	Base (Heel)	4.85	8.75	3.5	606
-H	Upstream	20.53	196.31	7.9	597
-H	Downstream	63.64	192.92	3.4	593
+H+V	Base (Heel)	4.85	8.75	8.5	571
+H+V	Upstream	20.53	196.31	3.4	613
+H+V	Downstream	61.87	196.31	5.4	598
+H-V	Base (Heel)	4.85	8.75	7.8	757
+H-V	Upstream	20.53	196.31	3.9	665
+H-V	Downstream	63.64	192.92	7.9	641
-H+V	Base (Heel)	4.85	8.75	3.5	717
-H+V	Upstream	20.53	196.31	7.9	623
-H+V	Downstream	61.87	196.31	3.9	674
-H-V	Base (Heel)	4.85	8.75	5.4	618
-H-V	Upstream	20.53	196.31	7.9	579
-H-V	Downstream	60.45	199.25	5.5	616

Time History Analyses

- Stress Time Histories and Stress Contours



Maximum Principal Stress S_1



Normal Vertical Stress S_{yy}
(S_{yy} > 200 psi)

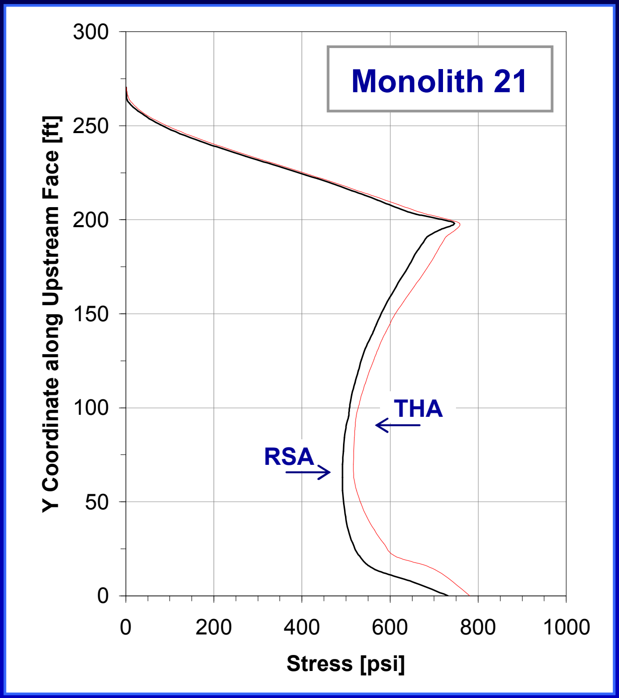
Monolith 21

San Fernando Earthquake +H/-V

Reservoir pool elevation 466 ft

Time History Analyses

- **Comparison with Response Spectrum Approach**



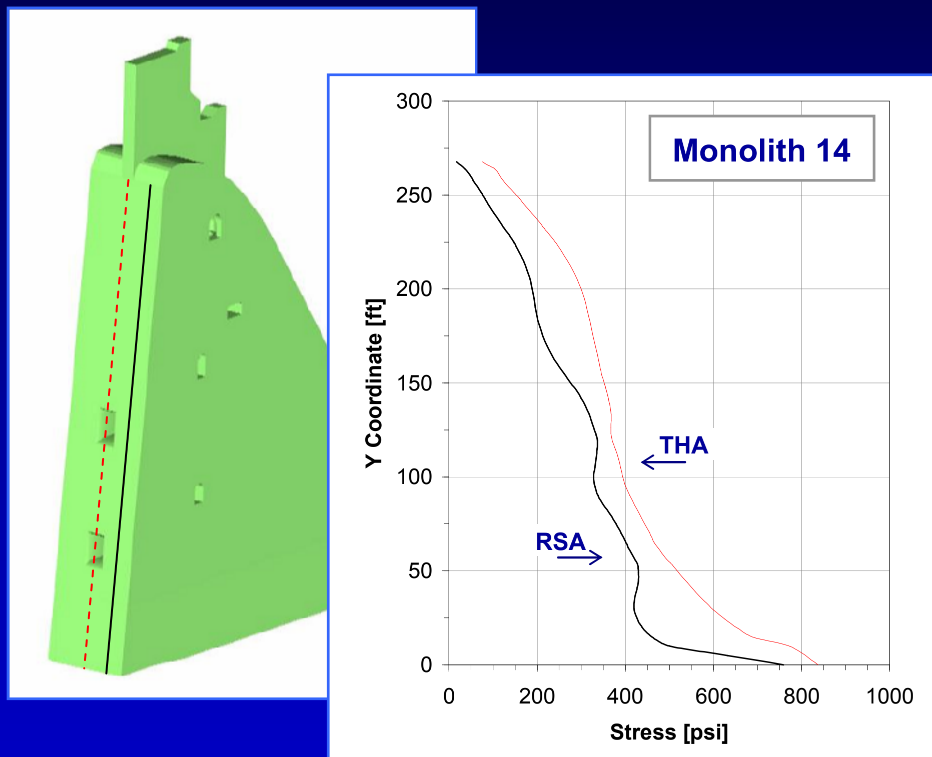
RSA → Maximum stress estimate obtained with the response spectrum approach considering horizontal and vertical input ground motion.

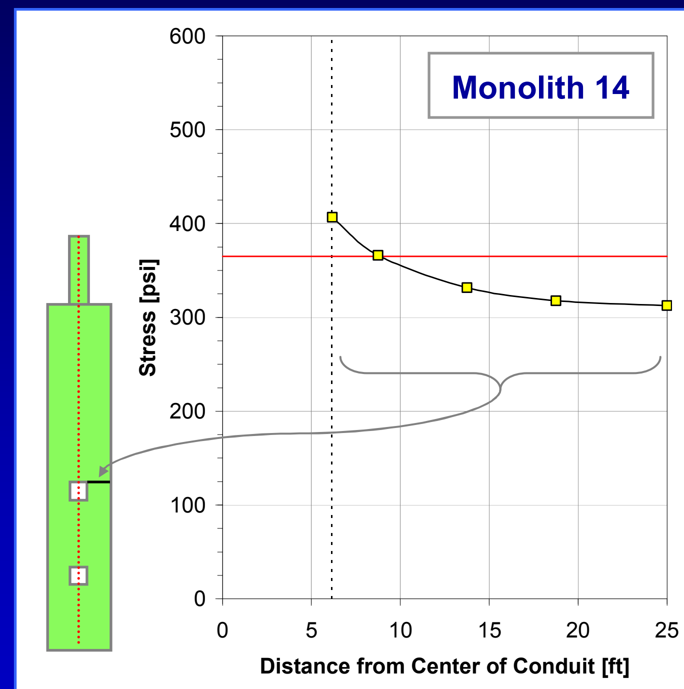
THA → Peak value of dynamic stress time history considering both components of the Imperial Valley Earthquake (combination –H/-V).

Distribution of maximum values of dynamic normal vertical stress along upstream face

Time History Analyses

- **Comparison with Response Spectrum Approach**





Distribution of maximum values of dynamic normal vertical stresses along upstream face

Summary

– Dynamic stress analyses of concrete gravity sections of Folsom Dam conducted using different approaches and considering horizontal and vertical ground motion components.

– Modified (expanded) version of Chopra's single-mode response-spectrum based procedure implemented for 3D FE analyses.

– 2D FE time history validation using EAGD-84, whose analytical formulation is consistent with the previous procedure (hydrodynamic effects, reservoir-bottom absorption, dam-foundation interaction).

– Some regions with tensile excursions above the assumed strength threshold (700 psi) were identified in Monoliths 14 and 21 but they were confined to areas with significant stress gradients and limited to the region immediately near the heel.

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