Dynamic Testing and Numerical Correlation Studies for Folsom Dam

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Introduction

- **Full-Scale Dynamic Testing**
  - Dynamic testing can be effectively used to identify the main dynamic response characteristics of concrete dams.
  - These tests can provide information regarding the relative importance of interaction mechanisms involving the dam, the impounded reservoir, and the underlying foundation region.
  - Test results can be used to assess the limitations of different numerical models employed to predict the response of the system under severe seismic excitations.
  - However…

    Field testing of concrete dams has not been widely embraced in the US as an essential component in the process of evaluating the seismic performance of these structures.

Introduction

- **Folsom Dam Description**

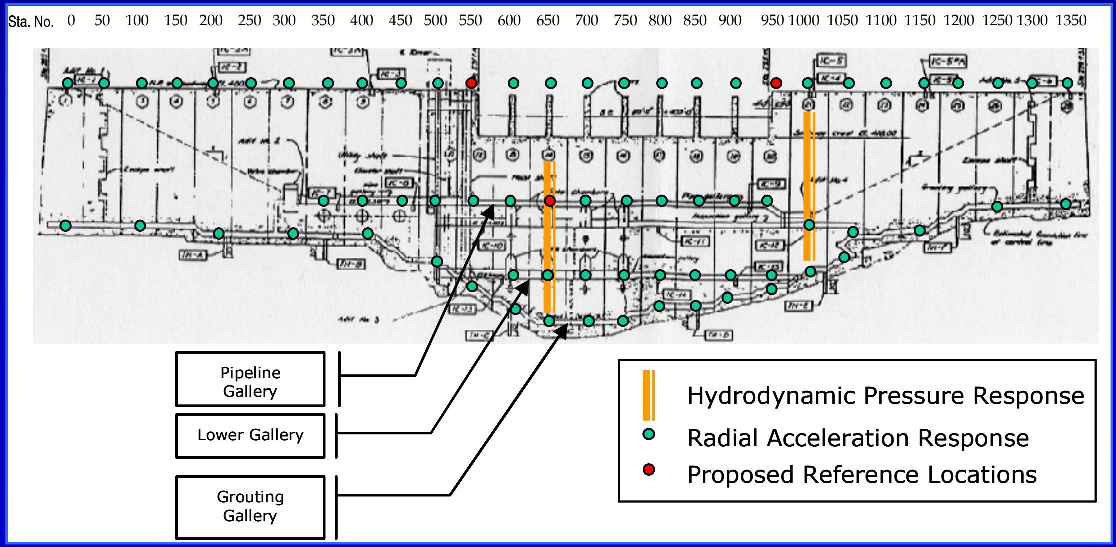
  – Design/construction by USACE (1948-1956), transferred to USBR (1956)
  – Maximum height of gravity section is 340 ft with a crest length of about 1,400 ft.
  – 28 monoliths, 50 ft wide each.
  – Main spillway: 5 ogee monoliths, two tiers of 4 outlets. Emergency spillway: 3 flip bucket monoliths.
 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

Introduction

- **Folsom Dam Dynamic Testing Program**
  - Research study conducted by the U.S. Army Engineer Research and Development Center (ERDC) consisting of a series of field tests and numerical analyses performed on Folsom Dam, California.
  - Ambient surveys and forced vibration tests were conducted to determine the main dynamic characteristics of the dam-foundation-reservoir system.
  - Numerical studies of the observed response behavior were performed using 2D and 3D models of the system.

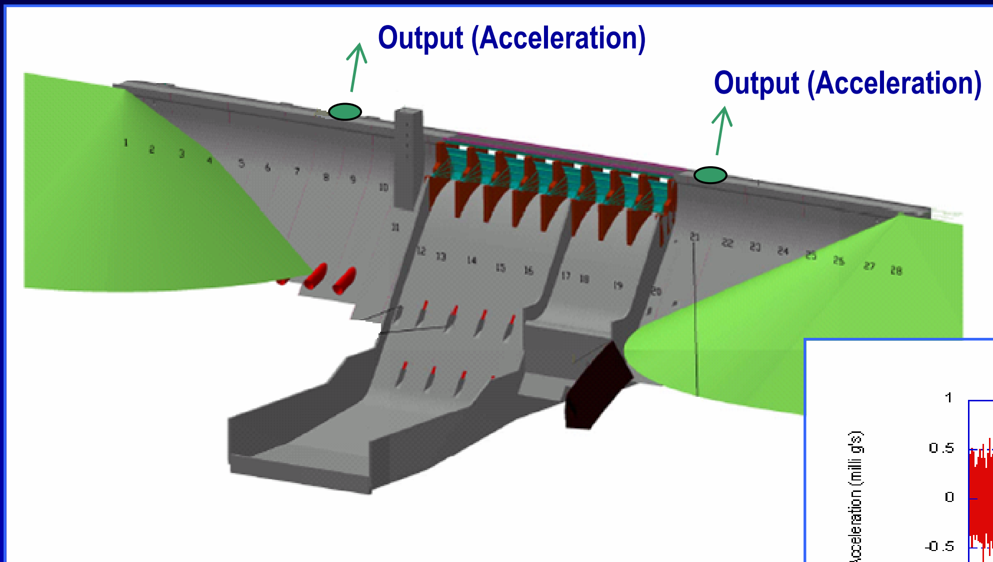
Ambient Survey

- **Survey Description**
  - Ambient survey conducted in March 2004.
  - At each monitored location, ambient acceleration responses excited by environmental conditions were monitored over a 7-minute interval.
  - Ambient hydrodynamic pressure responses were also acquired behind monoliths 14 and 21.



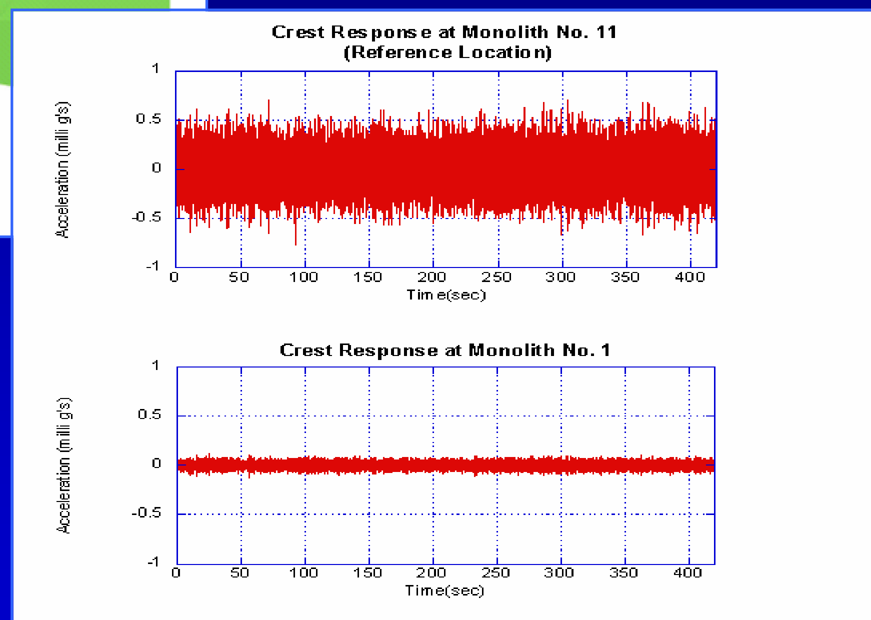
Ambient Survey

- **Sample Signals**



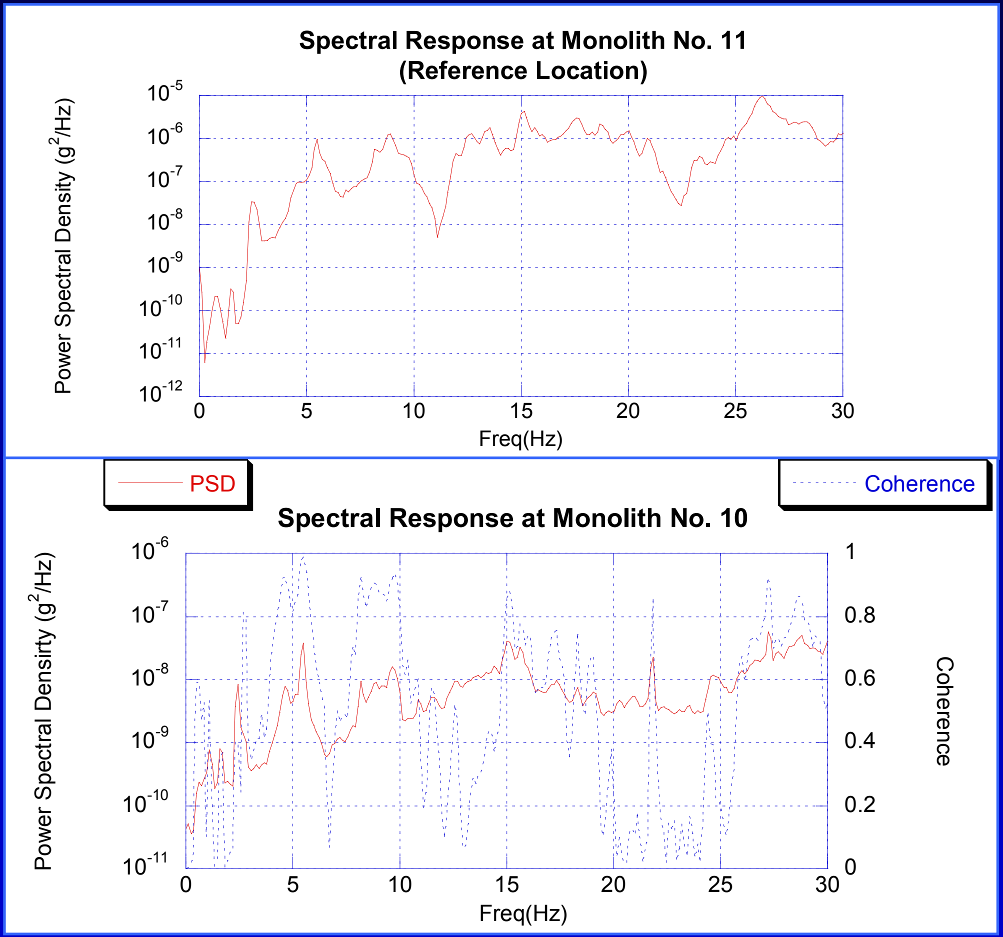
Typical peak acceleration levels range from 0.5 milli-g's at the crest of Monolith 11 to 0.1 milli-g's at the crest of Monolith 1

Noise threshold: 1 micro-g for Honeywell Q-Flex accelerometers QA-700, QA-750, and QA-900.



Ambient Survey

- Results
  - Spectral analysis conducted using the specially developed software *iDAMS*.
  - Both power spectral density and coherence must be examined.
  - Spectral response of Monolith 10 associated with relatively wide regions of coherence approaching unity between 4-6 Hz and between 8-10 Hz.



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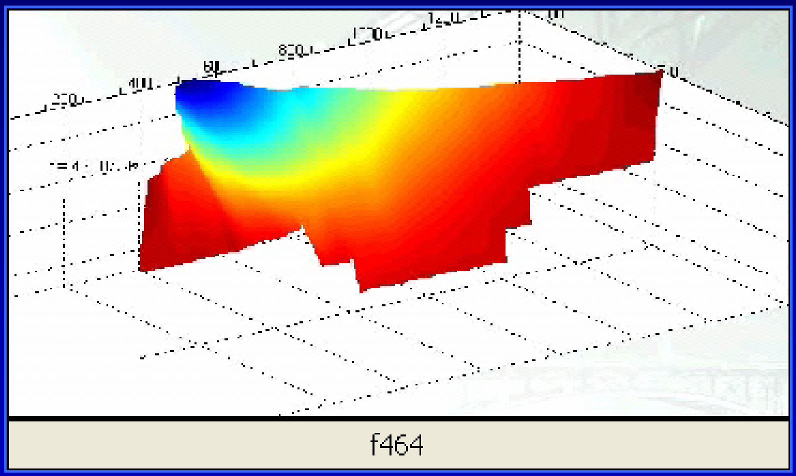
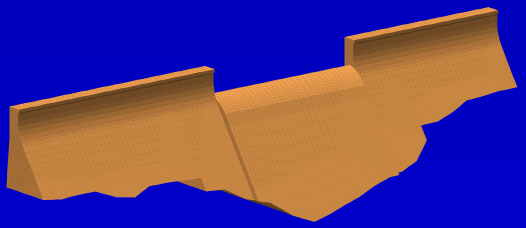
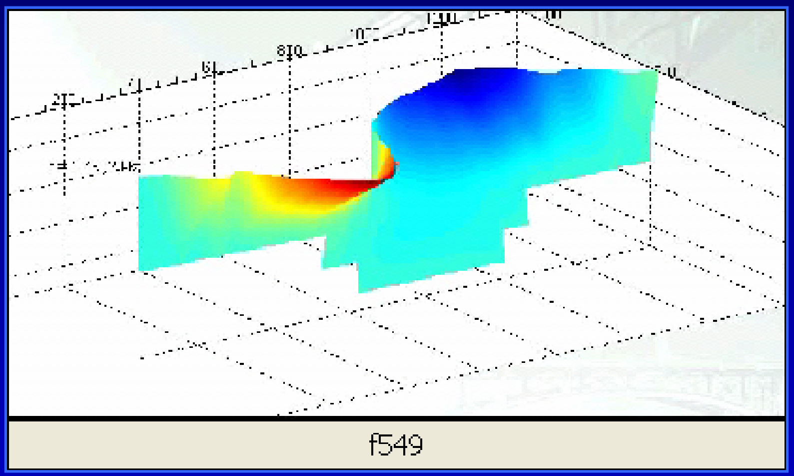
Ambient Survey

- Results
  - Analyses of global measured responses indicated near-monolithic behavior in the dam below 10 Hz.

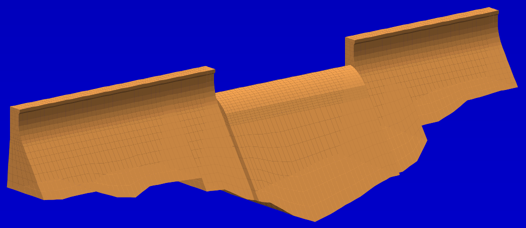


4.64 Hz





5.49 Hz



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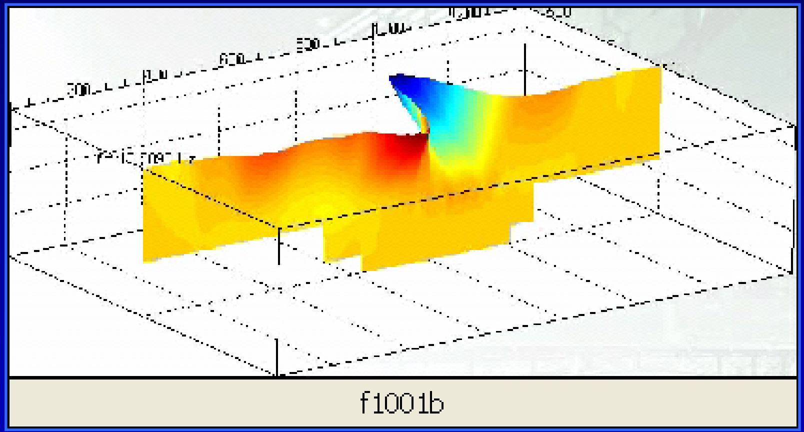
Ambient Survey

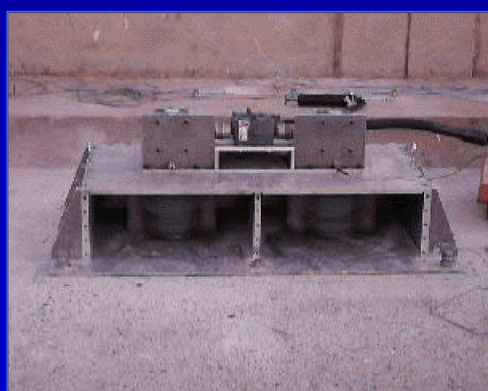
- Results
  - The portion of the roadway that spans the spillway section appears to respond with amplified motions in the vicinity of 10-12 Hz.
  - The response of the bridge deck above 10 Hz may require further investigation in order to determine whether it would remain operational during a seismic event.

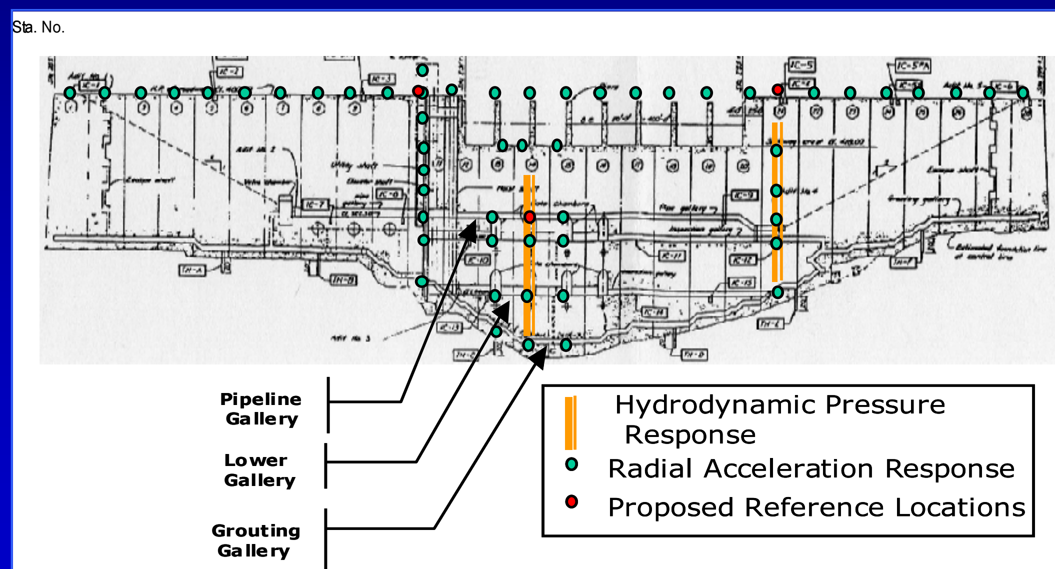


10.01 Hz

Forced Vibration Tests

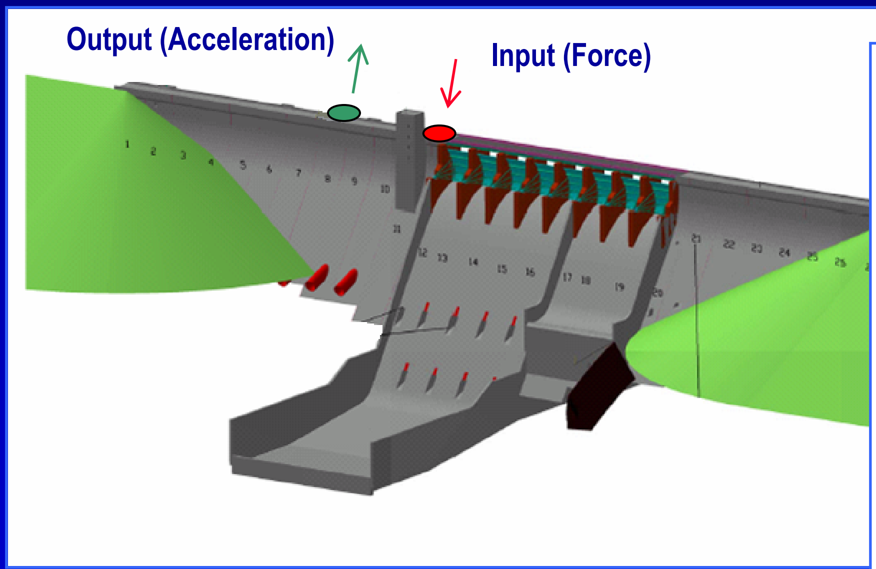
- **Test Description**
  - Results from the ambient survey provided confidence that a single eccentric mass vibrator (shaker) would excite steady-state responses in the dam, reservoir and adjacent foundation.
  - Forced vibration tests conducted at Folsom Dam in June 2004.
  - Shaker locations:
    - Monoliths 11, 14, 21

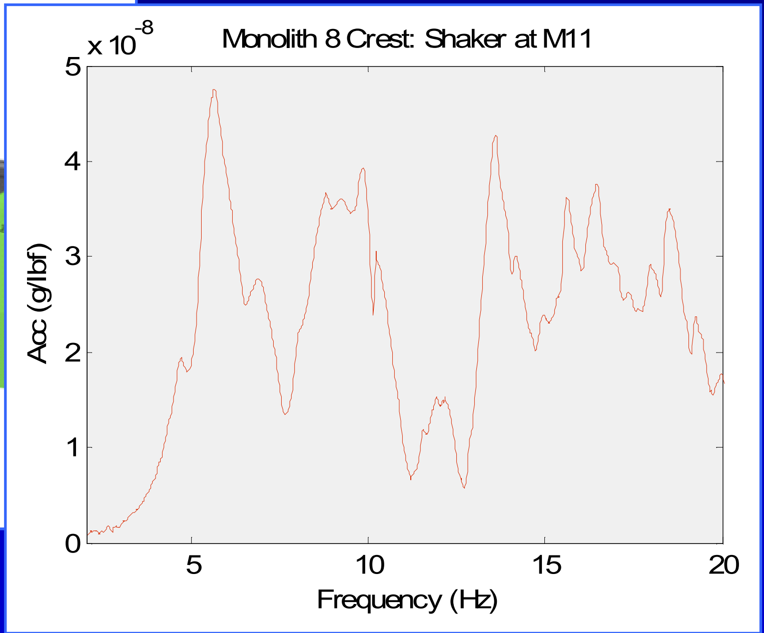




Forced Vibration Tests

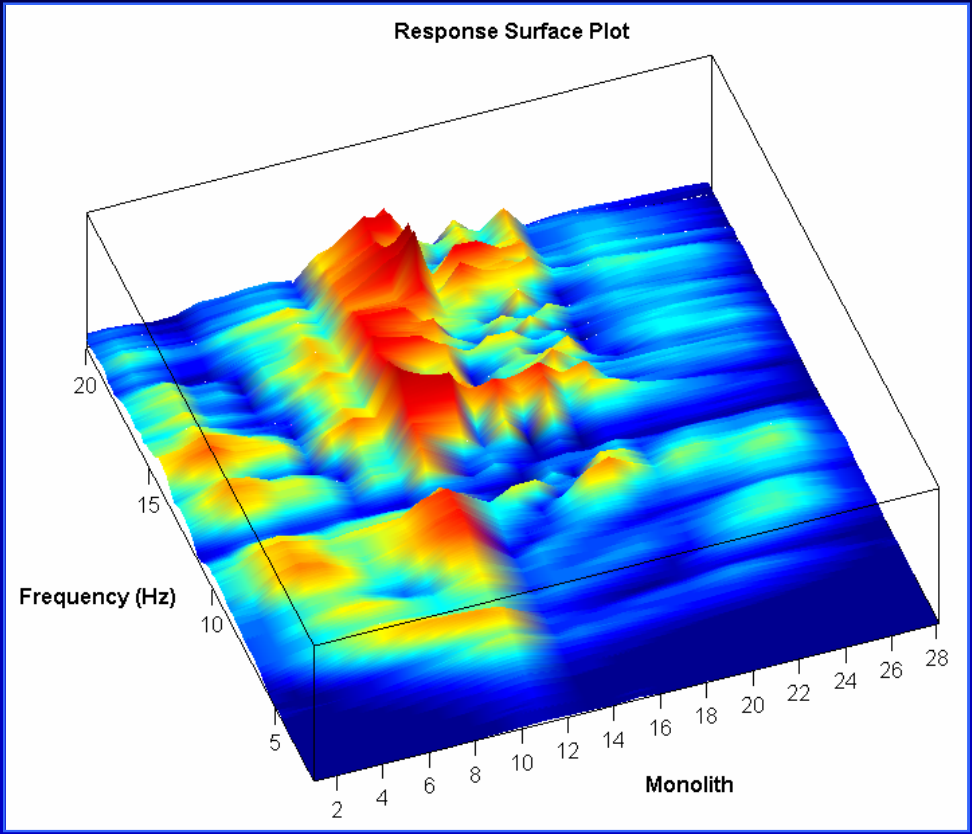
- Acceleration Frequency Responses
  - Peak below 5 Hz corresponds to the fundamental symmetric resonance at 4.65 Hz.
  - Large peak below 6 Hz corresponds to the second fundamental resonance at 5.46 Hz.





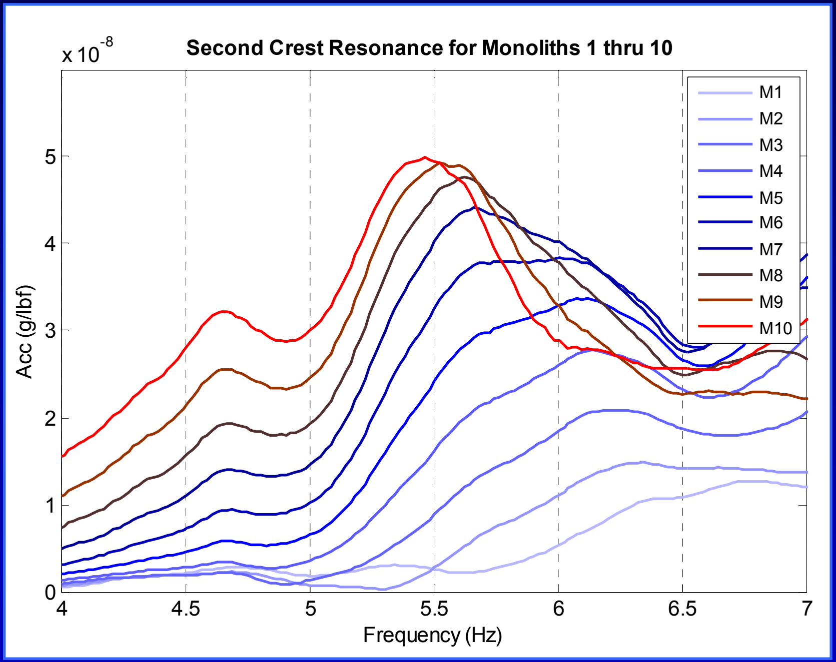
Forced Vibration Tests

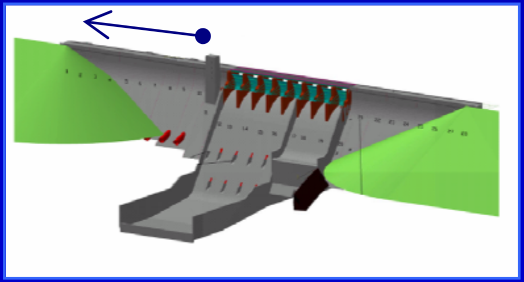
- **Dominant Responses**
  - Global comparison of acceleration response functions measured with shaker mounted on Monolith 11 (crest).
  - Below 10 Hz, second resonance dominates (Monoliths 4-12).
  - Above 12 Hz, response clearly dominated by spillway behavior.



Forced Vibration Tests

- **Crest Responses for Monoliths 1-10**
  - Stationary fundamental resonance at 4.65 Hz.
  - Sliding character of second system resonance beginning at 5.46 Hz.
  - Largest and narrowest resonance peak at Monolith 10.
  - Smaller and wider peaks for monoliths closer to the abutment.





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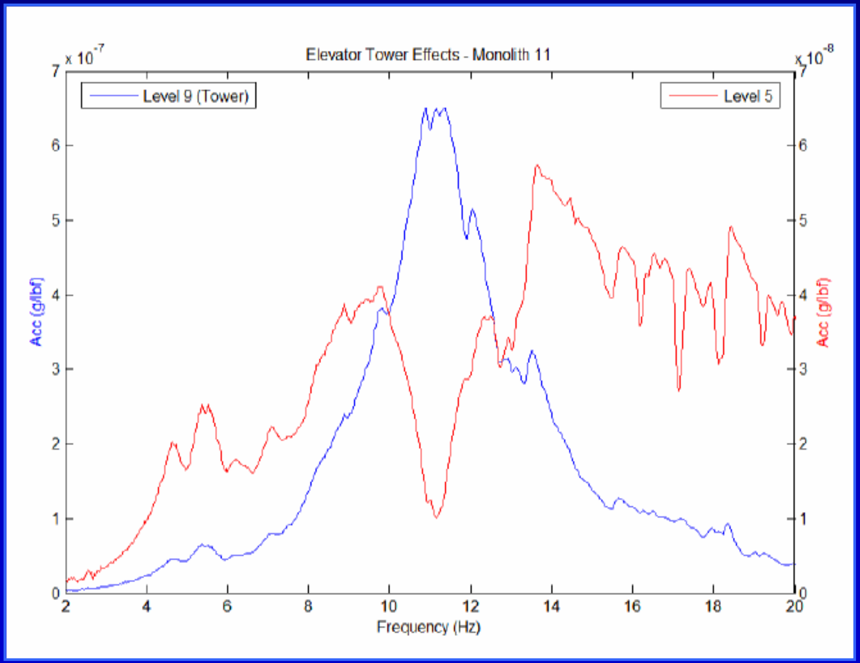
Forced Vibration Tests

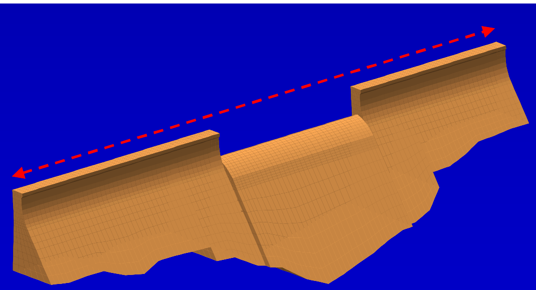
- **Influence of Elevator Tower**
  - Tower exhibits fundamental resonance near 11.6 Hz (blue curve) that coincides with an anti-resonance in the dam (red curve) indicated by the acceleration response acquired 60 ft below the crest in Monolith 11.

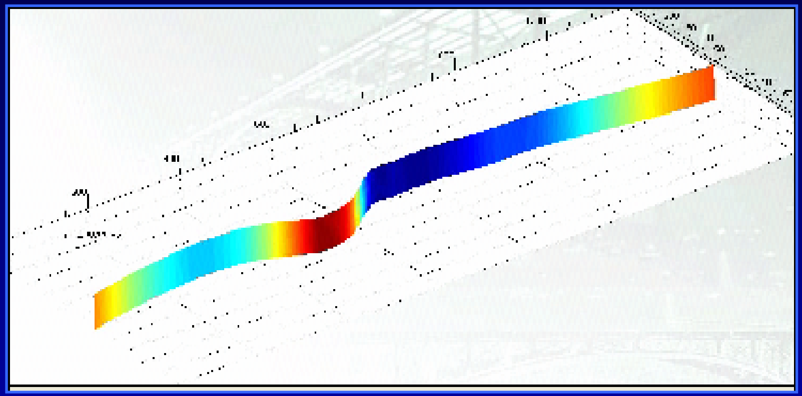


Forced Vibration Tests

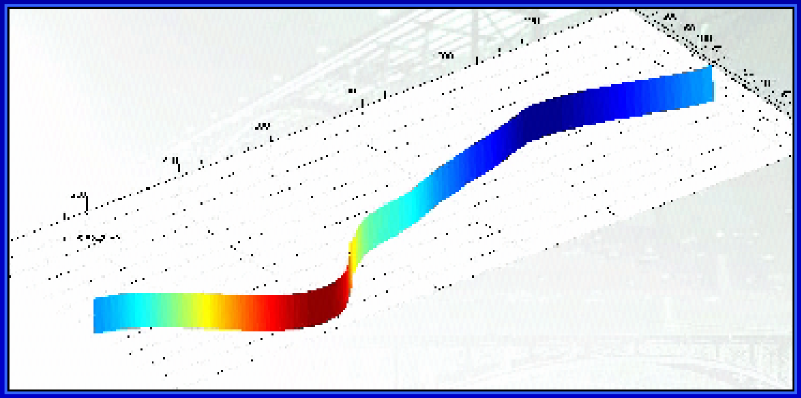
- System Characteristics

Resonant Frequency (Hz)	Half-Power Method	Pole Fitting
4.65	-	4.0-6.5 %
5.46	5.6-8.4 %	4.8-7.0 %
6.24	-	4.0-8.0%
7.16	6.3-8.0%	4.0-7.8%
8.00	-	-
8.87	-	-





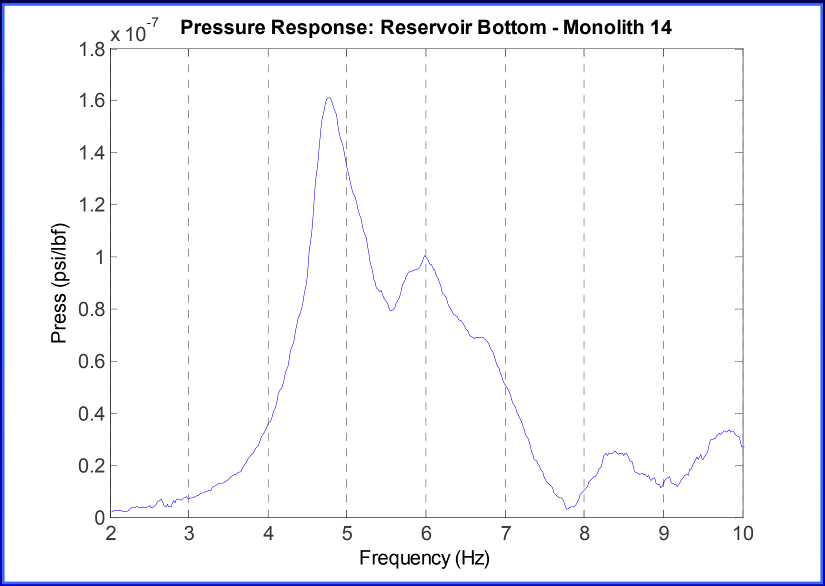
4.65 Hz

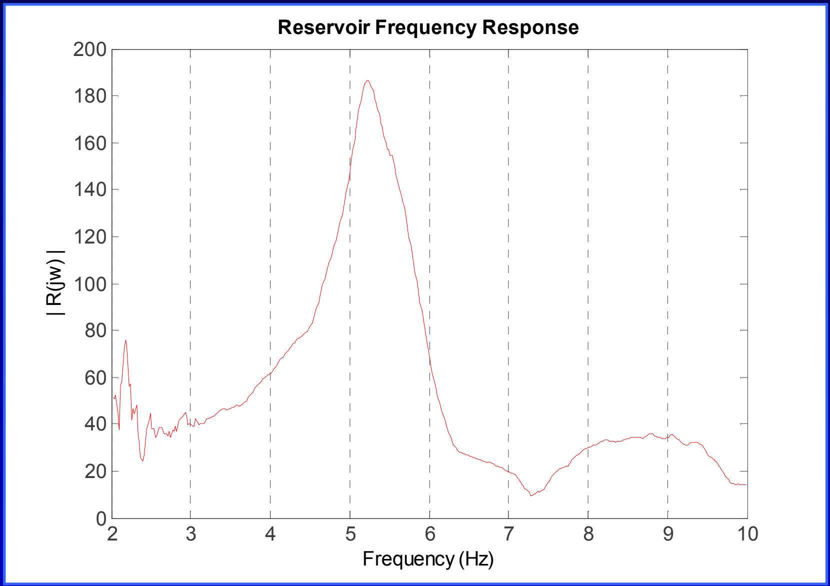


5.46 Hz

Forced Vibration Tests

- Reservoir Response Characteristics





$$H_{eff} = \frac{C_w}{4\,f_{reservoir}} = \frac{4720\,\text{ft/sec}}{4 \cdot 5.23\,\text{Hz}} \cong 226\,\text{ft}$$

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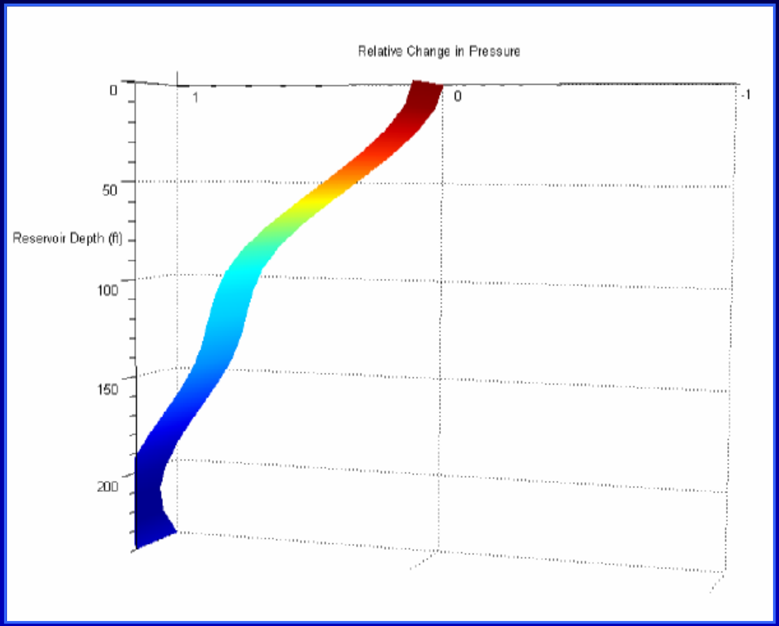
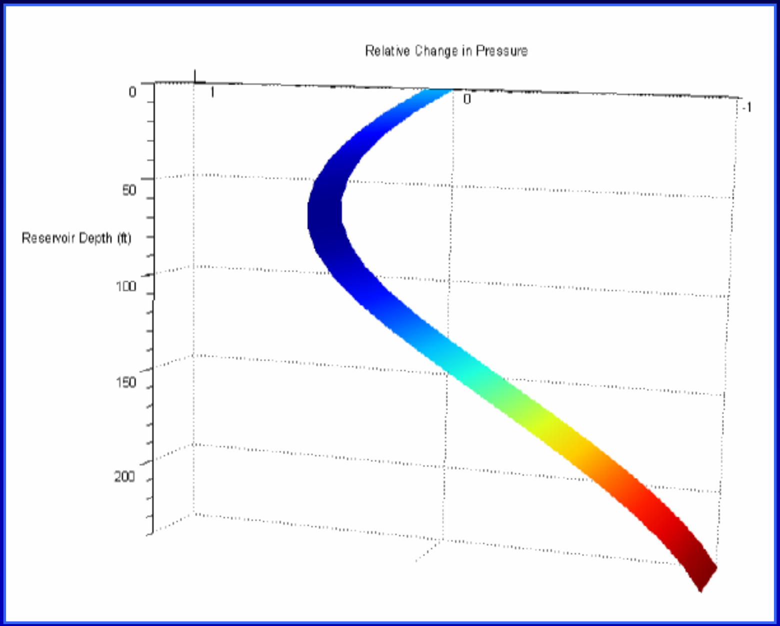
Forced Vibration Tests

- Reservoir Response Characteristics



Fundamental resonance for hydrodynamic pressure profile



Second resonance for hydrodynamic pressure profile

Numerical Correlation Studies

- **Preliminary Study Objectives**
  - To develop numerical models that represent the dam, reservoir, and foundation to capture observed response behavior acquired during forced vibration tests at Folsom Dam (“baseline model”).
  - Key issues:
    - Dam-foundation interaction

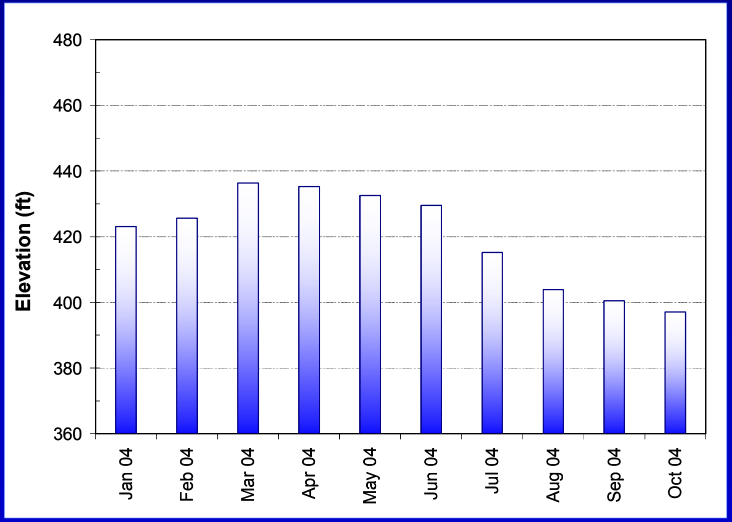
      Consideration of foundation flexibility effects
    - Dam-reservoir interaction

      Incorporation of hydrodynamic effects
    - Tower influence on dam response

      Consideration of vibration reduction by dynamic tuning

Numerical Correlation Studies

- **Baseline Model Assumptions**
  - Linear elastic behavior assumed throughout system.
  - 3D dam model (8,103 solid brick elements).
  - Includes tower, roadway, and varying spillway monolith geometries.
  - Foundation region idealized as massless (stiffness only contribution).
  - Reservoir modeled using Westergaard's simplified model to define added masses along upstream face.
  - Reservoir elevation 430'.



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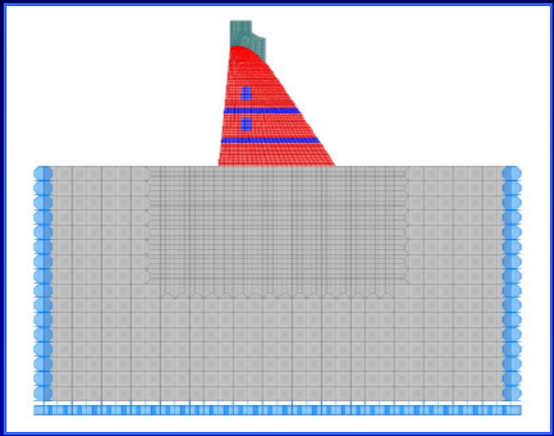
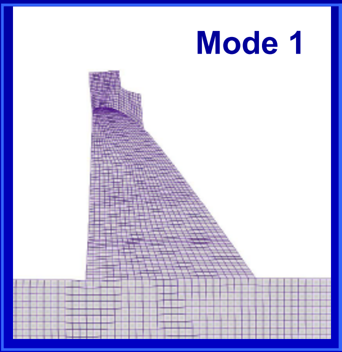
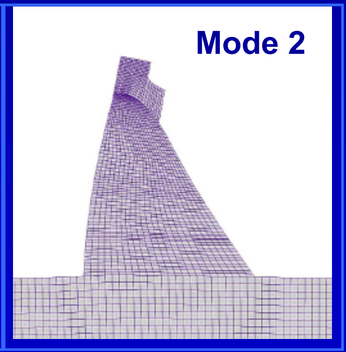
Numerical Correlation Studies

- 2D Models (SAP2000)



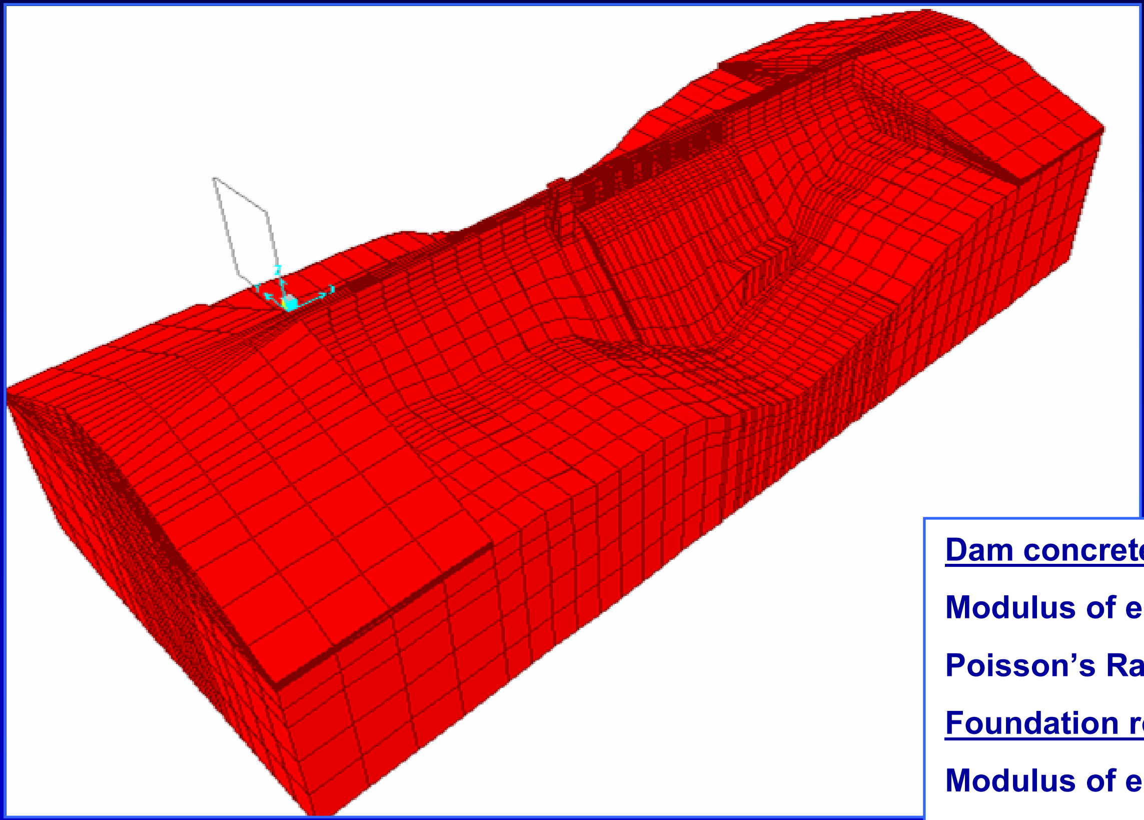




Mode	Natural Frequencies [Hz]			
	Monolith 14		Monolith 21	
	Rigid	E_c/E_f = 0.25	Rigid	E_c/E_f = 0.25
1	5.23	4.68	5.00	4.67
2	12.31	10.80	10.50	9.52
3	14.63	12.43	16.80	14.37
4	19.96	18.31	18.98	16.95
5	25.73	24.40	28.53	26.09

Numerical Correlation Studies

- 3D Model (SAP2000)



Dam concrete:

Modulus of elasticity (E_c) = 849,000 Kips/ft^2

Poisson's Ratio = 0.19

Foundation rock:

Modulus of elasticity (E_f) = 1,584,000 Kips/ft^2

Poisson's Ratio = 0.30

E_c / E_f = 0.54

Numerical Correlation Studies

- **Measured Resonances vs Computed Natural Frequencies**

Ambient Vibration Survey Resonant Frequency (Hz)	Forced Vibration Survey Resonant Frequency (Hz)	Natural Frequency (Hz) (SAP2000)
4.64	4.65	4.67
5.49	5.46	5.35
Not Observed	Not Observed	5.91
6.47	6.24	6.56
7.32	7.16	7.47
8.18	8.00	8.40
8.91	8.87	8.82

Numerical Correlation Studies

- **SAP2000 and EACD-3D (Empty Reservoir Condition)**

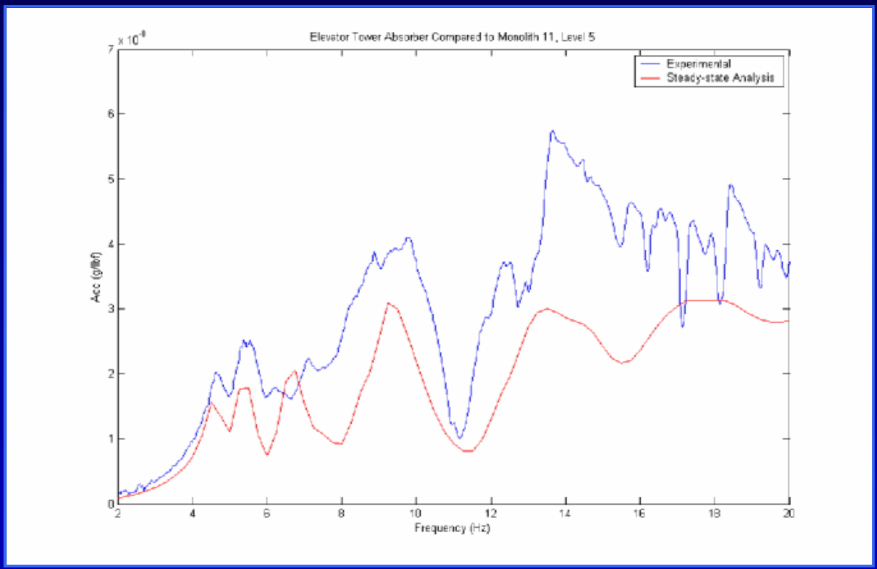
Natural Frequency (Hz)		
SAP2000	EACD-3D	EACD-3D (Adjusted)
5.71	6.06	5.71
6.29	6.67	6.28
6.84	7.30	6.87
7.45	8.01	7.54
8.61	9.41	8.86

– **EACD-3D will be used to quantify water compressibility effects including energy absorption due to sediments at the bottom of the reservoir.**

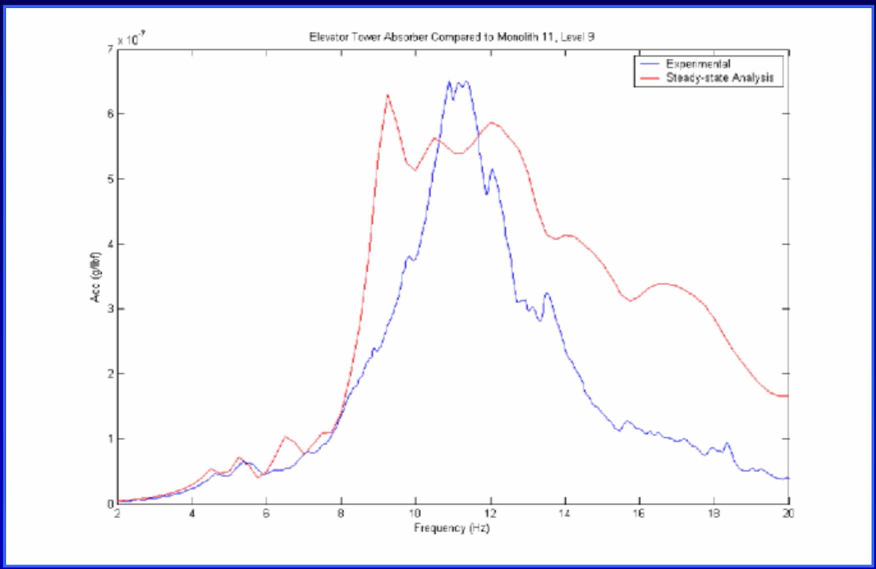
– **The flexibility of the foundation rock can be included but associated inertia and damping effects are ignored.**

Numerical Correlation Studies

- **Influence of Elevator Tower**



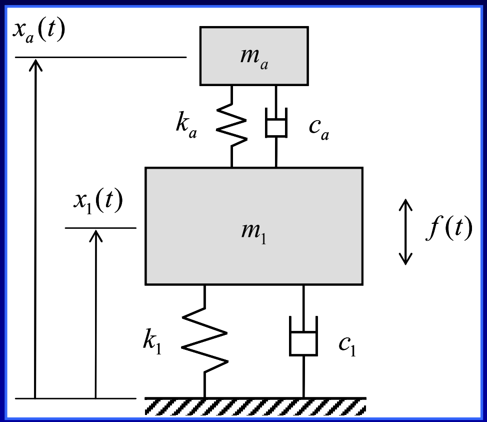
Comparison of measured and predicted response Level 5 (dam)



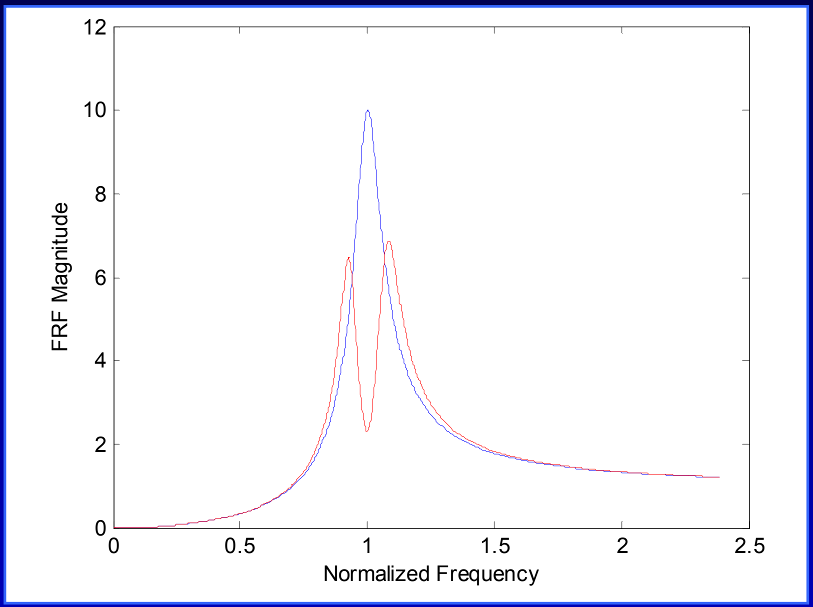
Comparison of measured and predicted response Level 9 (tower)

Numerical Correlation Studies

- Elevator Tower as Tuned Vibration Absorber



Tuned vibration absorber model

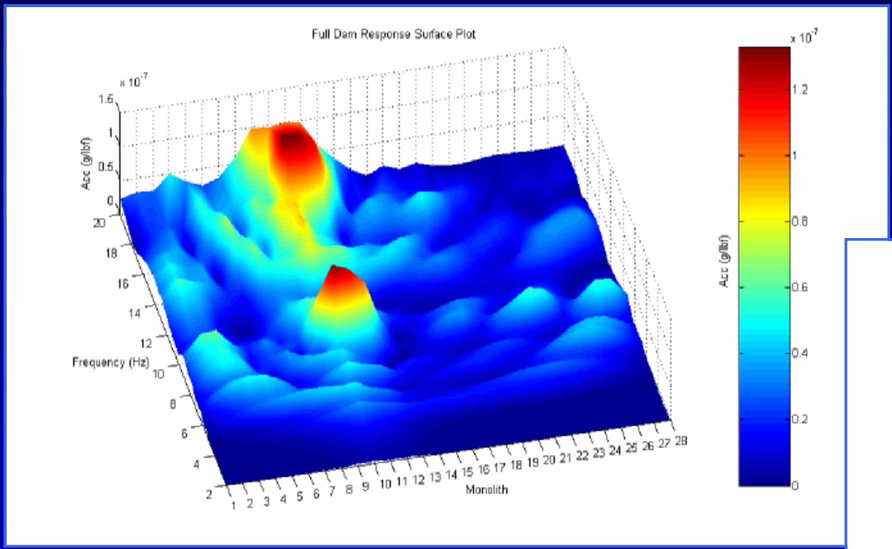


The blue line represents the response of the main system without the vibration absorber. The red line represents the response of the main system including the presence of the absorber.

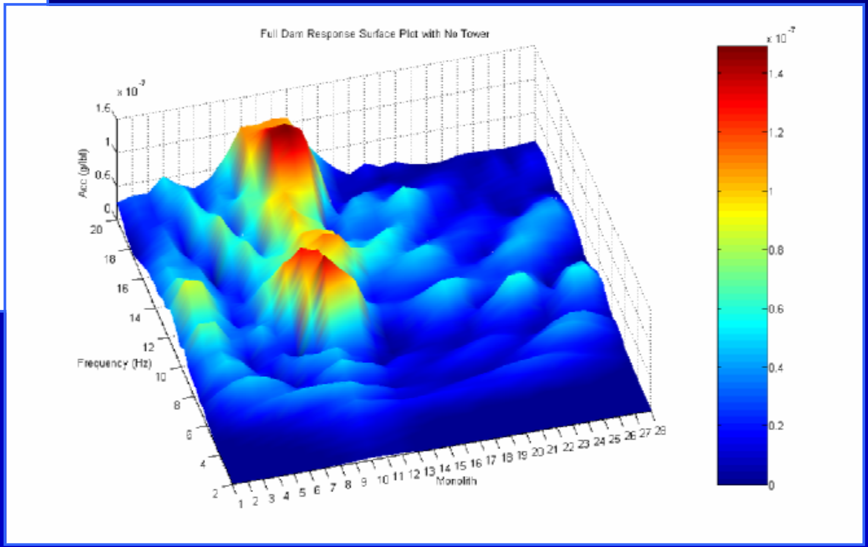
The response indicates two "split" resonances that straddle the original fundamental frequency.

Numerical Correlation Studies

- Surface Plot Comparison of Crest Acceleration Responses



Tower included



Tower removed

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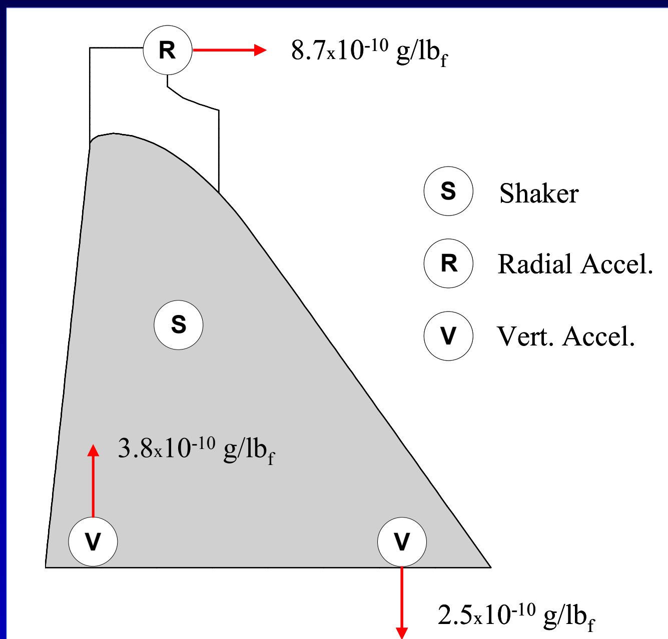
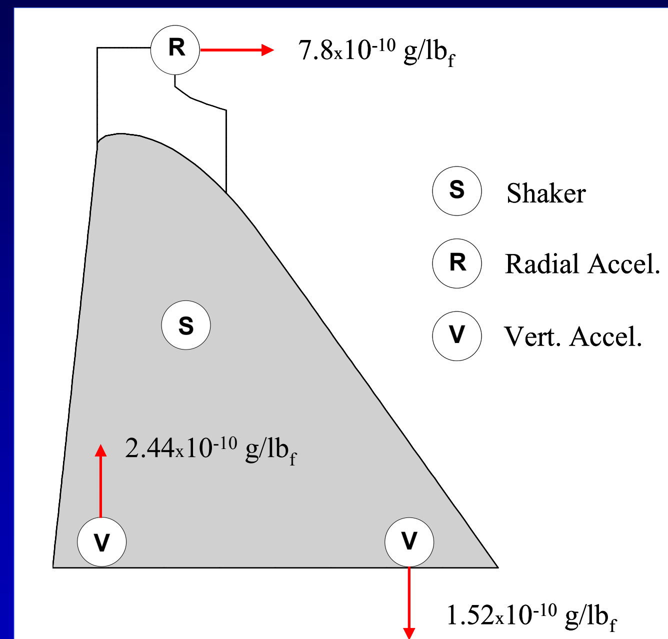
Numerical Correlation Studies

- **Foundation Flexibility Effects at Monolith 14**



Measured response



Numerical model

Summary

- A series of dynamic tests have been completed at Folsom Dam to gain detailed understanding of its dynamic response characteristics, including dam-foundation and dam-reservoir interaction.
  - Dam response behavior observed along the crest indicated monolithic dam response below 10 Hz.
  - The elevator tower acts as a vibration absorber tuned near 11 Hz and affects dam response across all monoliths.
  - Evidence of foundation flexibility was observed at the base of Monolith 14.
  - Fundamental reservoir resonance at 5.23 Hz influences the fundamental system resonance at 4.65 Hz.
- A preliminary numerical correlation study indicated that the 3D model is capable of capturing several major response characteristics at Folsom Dam.
  - Above 6 Hz, a variety of influencing factors will require further investigation including water compressibility effects and appropriate damping values for resonances at higher frequencies.

Acknowledgments

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