CONVENTIONAL CONCRETE DAMS

Presented by

Dr. Enrique E. Matheu

Field Review Group Meeting
and Program Review

Earthquake Engineering Research Program

OUTLINE

- **Introduction**
- **Time-domain solutions for nonlinear problems of concrete dams (EQTIME2D)**
    - **Foundation flexibility model**
    - **Preprocessor (EQTIMEpre)**
- **Validation of dynamic nonlinear analysis methods for concrete dams**
    - **Evaluation of shake table results**
    - **iDAMS database**
- **Performance evaluation of concrete dams using linear time-history analysis**
- **International collaboration efforts**
- **Summary and conclusions**

SEISMIC RESPONSE OF CONCRETE DAMS

- **The prediction of the seismic performance of concrete dams constitutes a challenging problem.**
- **Different approaches can be used to generate a "solution" to the problem, ranging in complexity and modeling capabilities.**

Static analysis

Eigenvalue / Modal analysis

Linear dynamic analysis

Nonlinear dynamic analysis

RESEARCH OBJECTIVES

- **Development and validation of improved procedures for seismic analysis and design of concrete dams and their appurtenant structures.**
- **Development of guidance documents and training tools.**
- **Development of database of observational evidence.**

OUTLINE

- Objectives
- **Time-domain solutions for nonlinear problems of concrete dams (EQTIME2D)**
    - **Foundation flexibility model**
    - **Preprocessor (EQTIMEpre)**
- Validation of dynamic nonlinear analysis methods for concrete dams
    - Evaluation of shake table results
    - iDAMS database
- Performance evaluation of concrete dams using linear time-history analysis
- International collaboration efforts
- Summary and conclusions

EQTIME2D

- **Product description:**
  - ⇒ **The objective is to develop a computer analysis tool to predict the seismic response of concrete dams.**
  - ⇒ **A direct benefit of this research will be the capability to perform an accurate prediction of the dynamic response of concrete dams.**
  - ⇒ **This capability could translate into savings by allowing the Corps to identify the most economical remediation techniques for each problem.**
  - ⇒ **Effects of cracking of mass concrete are considered, and structure-reservoir and structure-foundation interactions are also incorporated.**

EQTIME2D

- **Multi-purpose modular platform**
  - ⇒ **Eigenvalue, static (incremental) and dynamic analysis options.**
  - ⇒ **Implicit integration with full and modified Newton-Raphson iterations.**
  - ⇒ **Static initialization with gravity and hydrostatic loading.**
  - ⇒ **Proportional damping model (tangent).**
  - ⇒ **Consistent hydrodynamic mass matrix.**
  - ⇒ **Smeared crack model (fixed crack evolution).**
  - ⇒ **Foundation flexibility model**

FOUNDATION FLEXIBILITY MODEL

- **Interaction effects between the dam, the foundation, and the reservoir need to be considered for the analysis of the seismic response of dams.**
- **Foundation and reservoir are usually modeled as regions extending to infinity (radiation damping).**
- **The presence of the foundation modifies the dynamic response of the system by incorporating flexibility effects, and material and radiation damping mechanisms.**
- **These effects have been modeled typically in the frequency domain. But the nonlinear behavior of the concrete demands a time domain formulation.**

FOUNDATION FLEXIBILITY MODEL (cont.)

- **Foundation effects can be efficiently represented by dynamic impedance functions.**
- **This substructure approach is computationally less expensive than the direct modeling of the foundation rock.**
- **A set of impedance functions is used to define the relation between forces and motions (displacements) at the dam-foundation interface.**

$$\mathbf{F} = \begin{Bmatrix} F_b^x \\ F_b^y \\ M_b \end{Bmatrix} e^{i\omega t}, \quad \mathbf{u} = \begin{Bmatrix} u_b^x \\ u_b^y \\ \theta_b \end{Bmatrix} e^{i\omega t}$$

$$\Rightarrow \quad \begin{Bmatrix} F_b^x \\ F_b^y \\ M_b/R \end{Bmatrix} = \begin{bmatrix} \hat{k}_{xx} & 0 & \hat{k}_{x\theta} \\ 0 & \hat{k}_{yy} & 0 \\ \hat{k}_{x\theta} & 0 & \hat{k}_{\theta\theta} \end{bmatrix} \begin{Bmatrix} u_b^x \\ u_b^y \\ R\theta_b \end{Bmatrix}$$

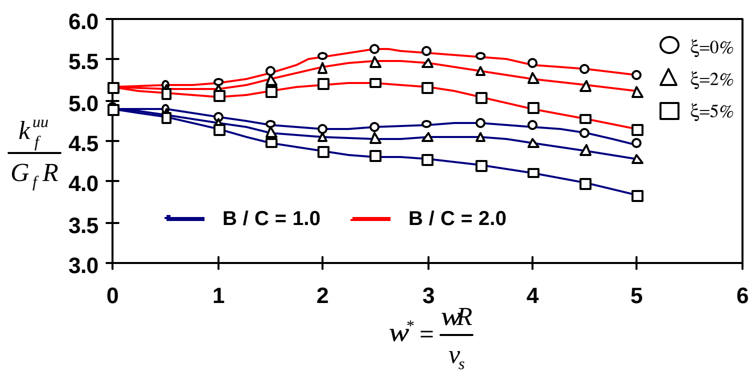
FOUNDATION FLEXIBILITY MODEL (cont.)

- **In this case, the dam-foundation interface is assumed to act as a perfectly rigid massless slab, and therefore it is allowed to undergo only rigid body motions, that is, sliding, rocking, and vertical motion.**
- **It is assumed that this rigid slab rests on top of a uniform isotropic three-dimensional viscoelastic half-space.**
- **The 2-dimensional structure is assumed to have an equivalent length along the longitudinal axis of the dam.**
- **This allows the use of the 3-dimensional solution for a viscoelastic half-space.**

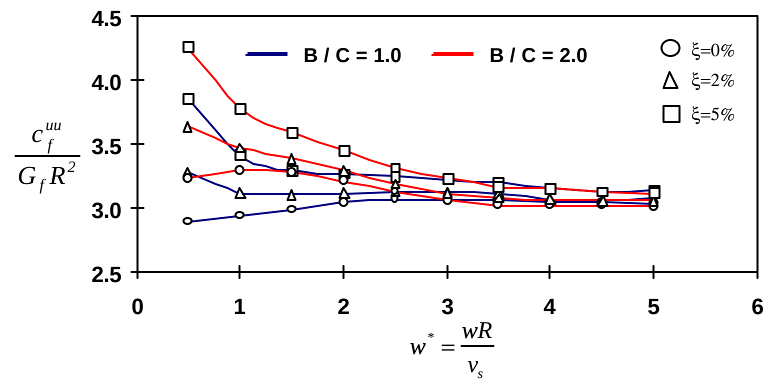
FOUNDATION FLEXIBILITY MODEL (cont.)

- **The frequency-dependent impedance coefficients represent the foundation elastic flexibility and the energy dissipated by damping mechanisms (radiation and material damping)**

Foundation Stiffness Coefficient



Foundation Damping Coefficient



- **The fact that these coefficients depend on the frequency complicates the solution. The problem is simplified by adopting frequency-independent values.**

FOUNDATION FLEXIBILITY MODEL (cont.)

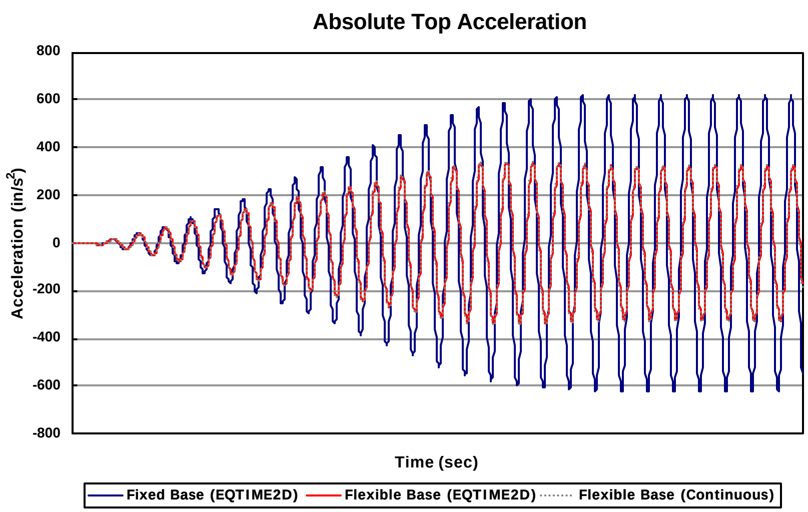
- **Rigid dam-foundation interface constraint:**

  $\Rightarrow$ **To employ this rigid dam-foundation interface model along with the (flexible) finite element discretization associated with the dam model, the base of the dam must be restricted from all possible deformational modes of response and allowed only to undergo rigid body motions.**

  $\Rightarrow$ **This is achieved through a penalty formulation, which produces an additional stiffness matrix that must be assembled into the stiffness matrix in correspondence with the dam-foundation interface degrees of freedom.**

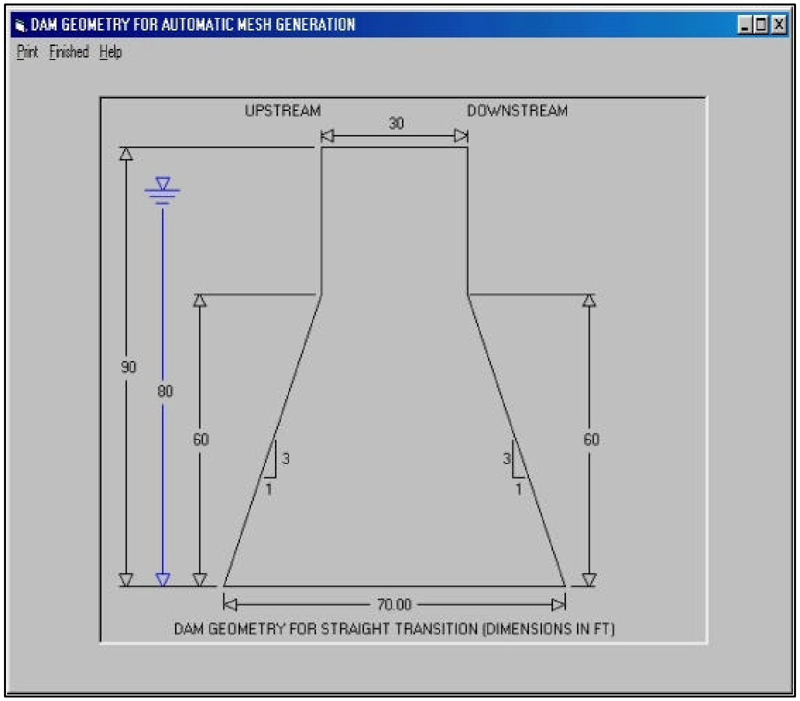
FOUNDATION FLEXIBILITY MODEL (cont.)

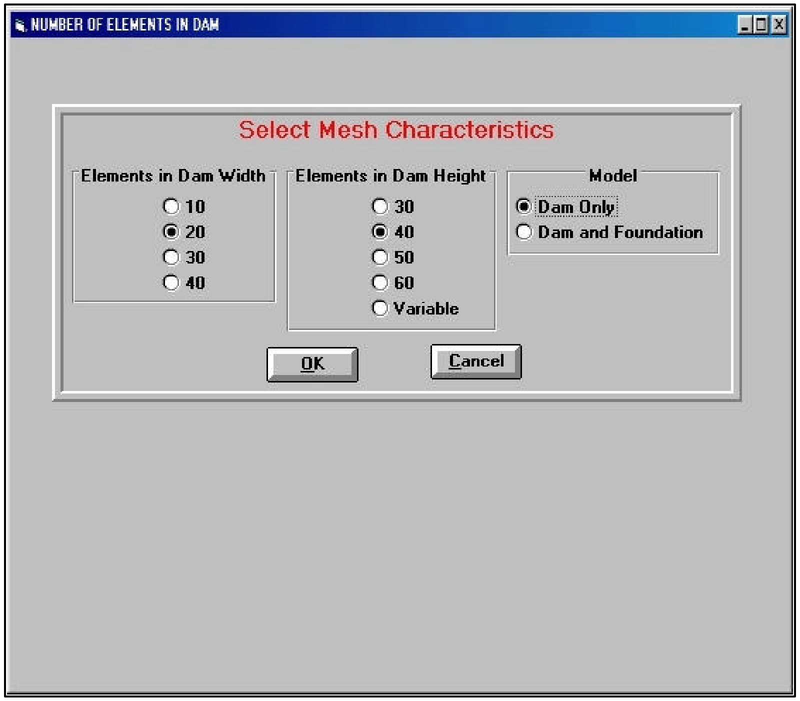
- **Test cases:**
  - ⇒ **Bending vibration of a cantilever beam with an elastic support (analytical and numerical solutions)**
  - ⇒ **Shake table results (calibration)**



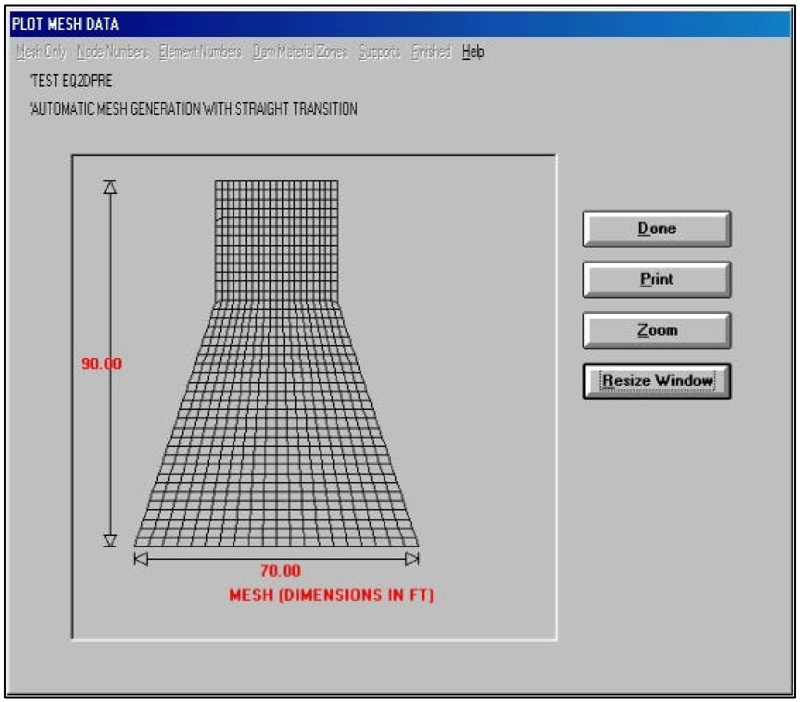
EQTIME2D preprocessor

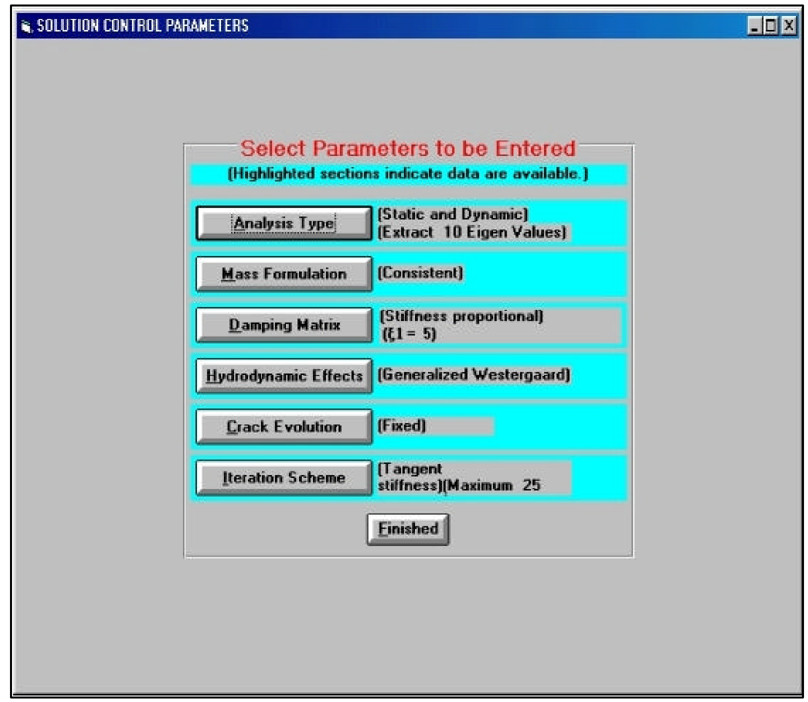
EQTIME2D preprocessor



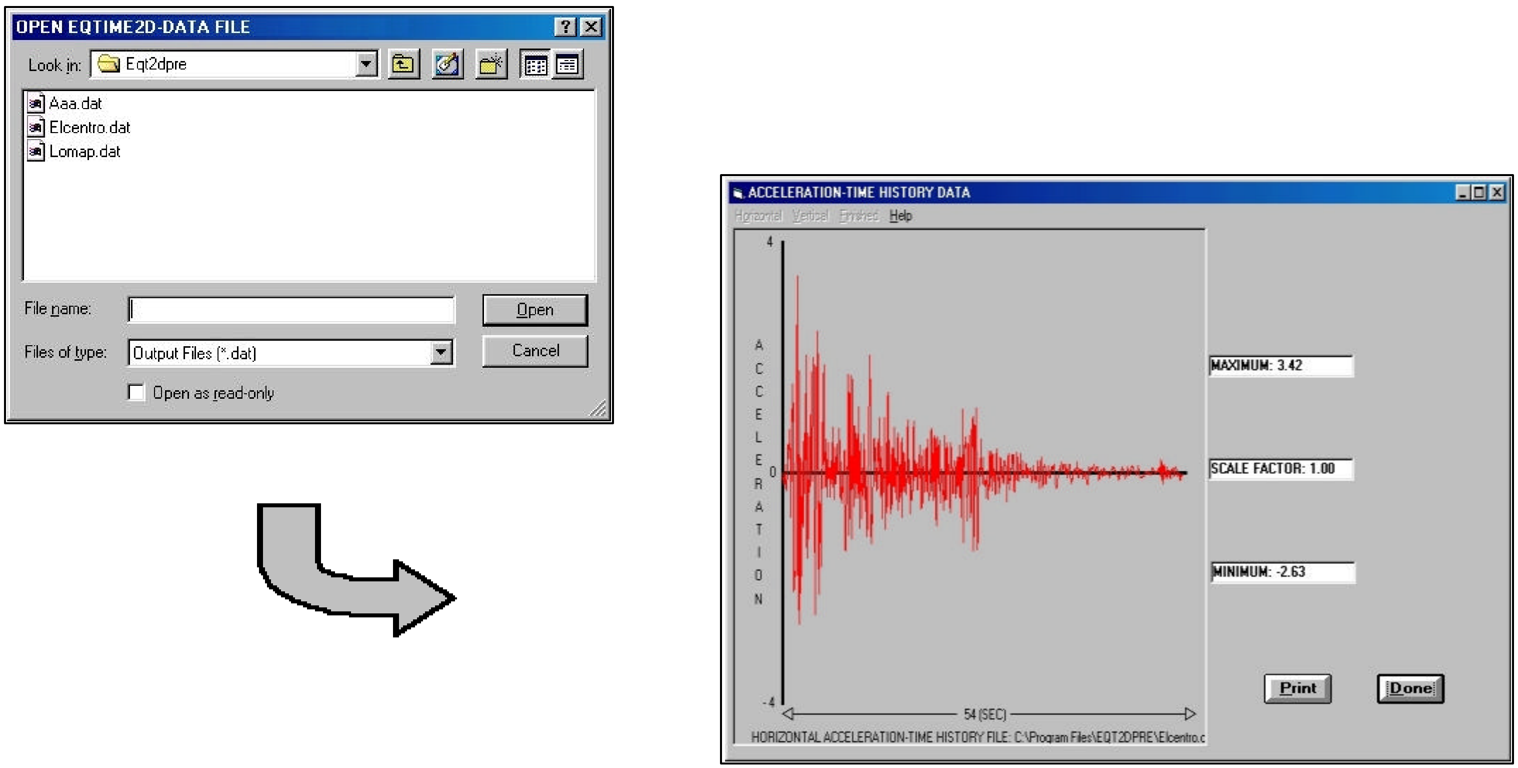


EQTIME2D preprocessor

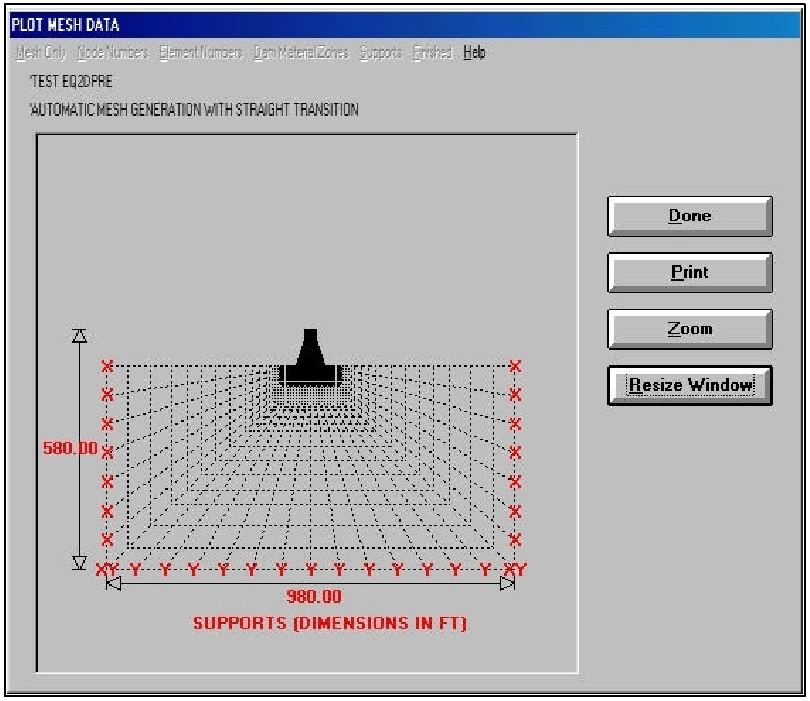


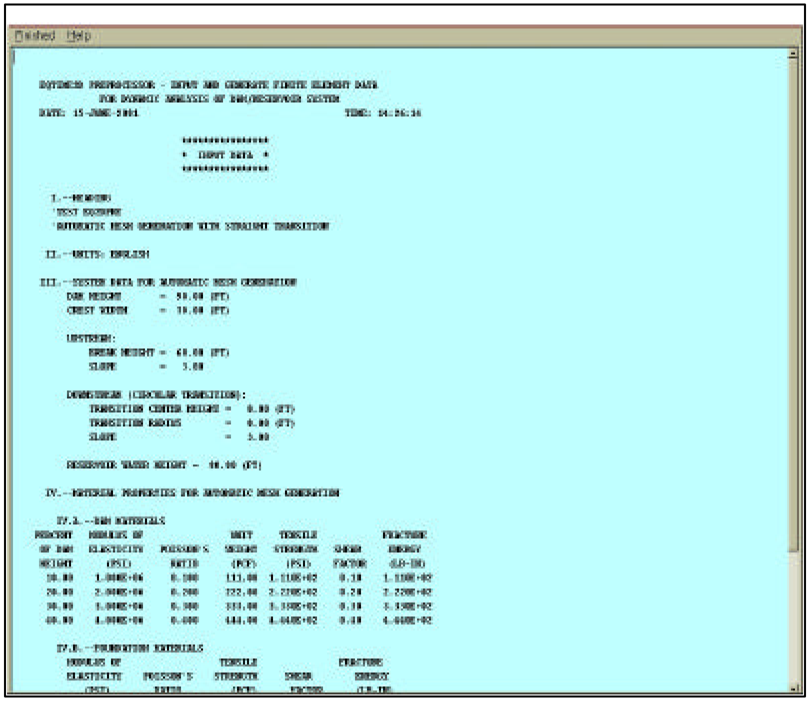


EQTIME2D preprocessor



EQTIME2D preprocessor





OUTLINE

- Objectives
- Time-domain solutions for nonlinear problems of concrete dams (EQTIME2D)
  - Foundation flexibility model
  - Preprocessor (EQTIMEpre)
- **Validation of dynamic nonlinear analysis methods for concrete dams**
  - **Evaluation of shake table results**
  - **iDAMS database**
- Performance evaluation of concrete dams using linear time-history analysis
- International collaboration efforts
- Summary and conclusions

SHAKE TABLE EXPERIMENTS

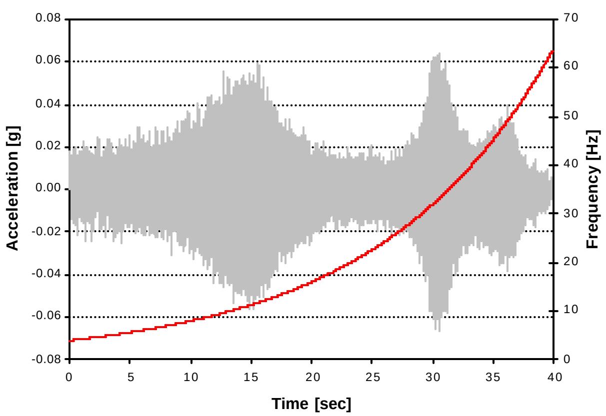
- **Objectives:**
  - ⇒ **To simulate the dynamic behavior of a monolith of Koyna Dam.**
  - ⇒ **To observe and identify response characteristics and failure mechanism.**
  - ⇒ **To provide data for validation and calibration of analytical models.**
- **Koyna Dam:**
  - ⇒ **Gravity dam subjected to significant structural damage due to seismic ground motion (Koyna earthquake, 1967).**
  - ⇒ **Post-earthquake field data and previous laboratory results are available:**
    - **University of California, Berkeley (1980).**
    - **Bureau of Reclamation (1999).**

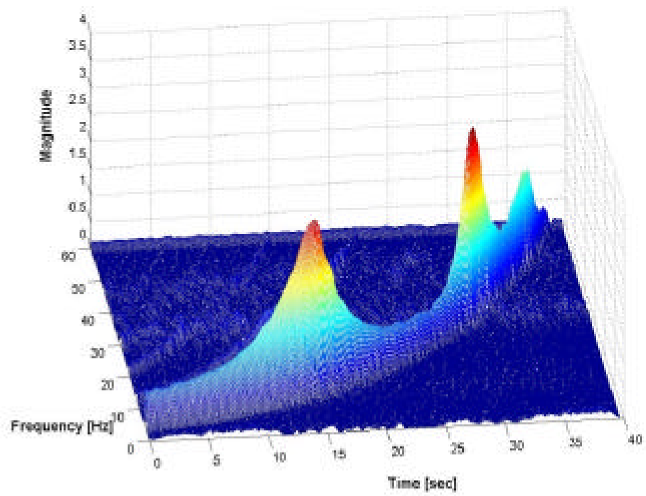
SHAKE TABLE EXPERIMENTS (cont.)

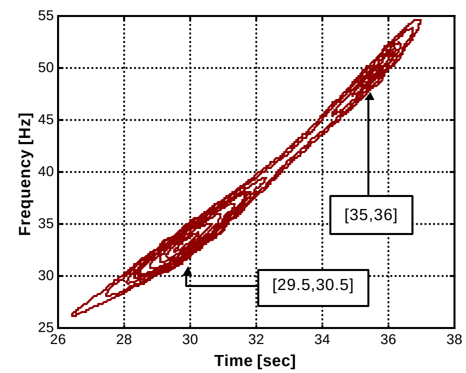
- **Re-evaluation of the results from the shake table tests using the Maximum Entropy Method:**
  - ⇒ **The Maximum Entropy Method (MEM) is an alternate method to the Fast Fourier Transform (FFT) for estimating the power spectrum of a time signal.**
  - ⇒ **The MEM is a polynomial estimate in which all the free parameters are in the denominator. This is good for identification of resonant behavior, where the response will be much larger than nearby frequencies.**
  - ⇒ **Furthermore, the power spectrum estimate is a polynomial in frequency, so the resolution is not limited. This is another advantage over the FFT.**

SHAKE TABLE EXPERIMENTS (cont.)

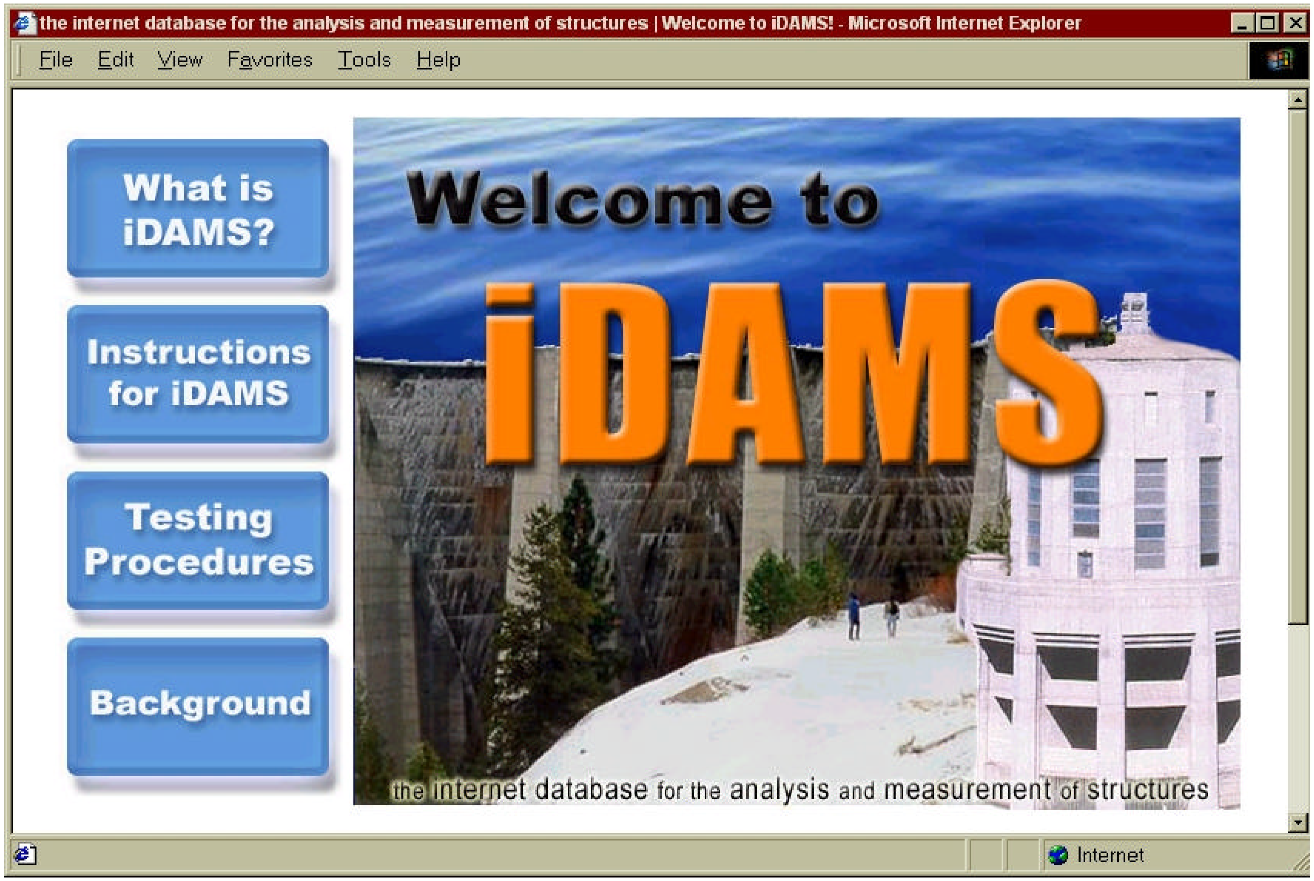
- **Analysis of sine sweep test results**







iDAMS


the internet database for the analysis and measurement of structures | Welcome to iDAMS! - Microsoft Internet Explorer
File Edit View Favorites Tools Help
What is iDAMS?
Instructions for iDAMS
Testing Procedures
Background
Welcome to
iDAMS
the internet database for the analysis and measurement of structures
Internet

iDAMS *(cont.)*

- ***iDAMS*** **is an interactive database for the evaluation of field test procedures and measured responses on dam structures.**
- **The database offers suggested guidelines and procedures for field testing. Available field measurements include acceleration and pressure responses acquired using ambient, forced vibration, and transient testing procedures.**
- **The engineer can utilize *iDAMS* to become familiar with the dynamic response of civil structures and to analyze newly acquired data that can be added to the database**

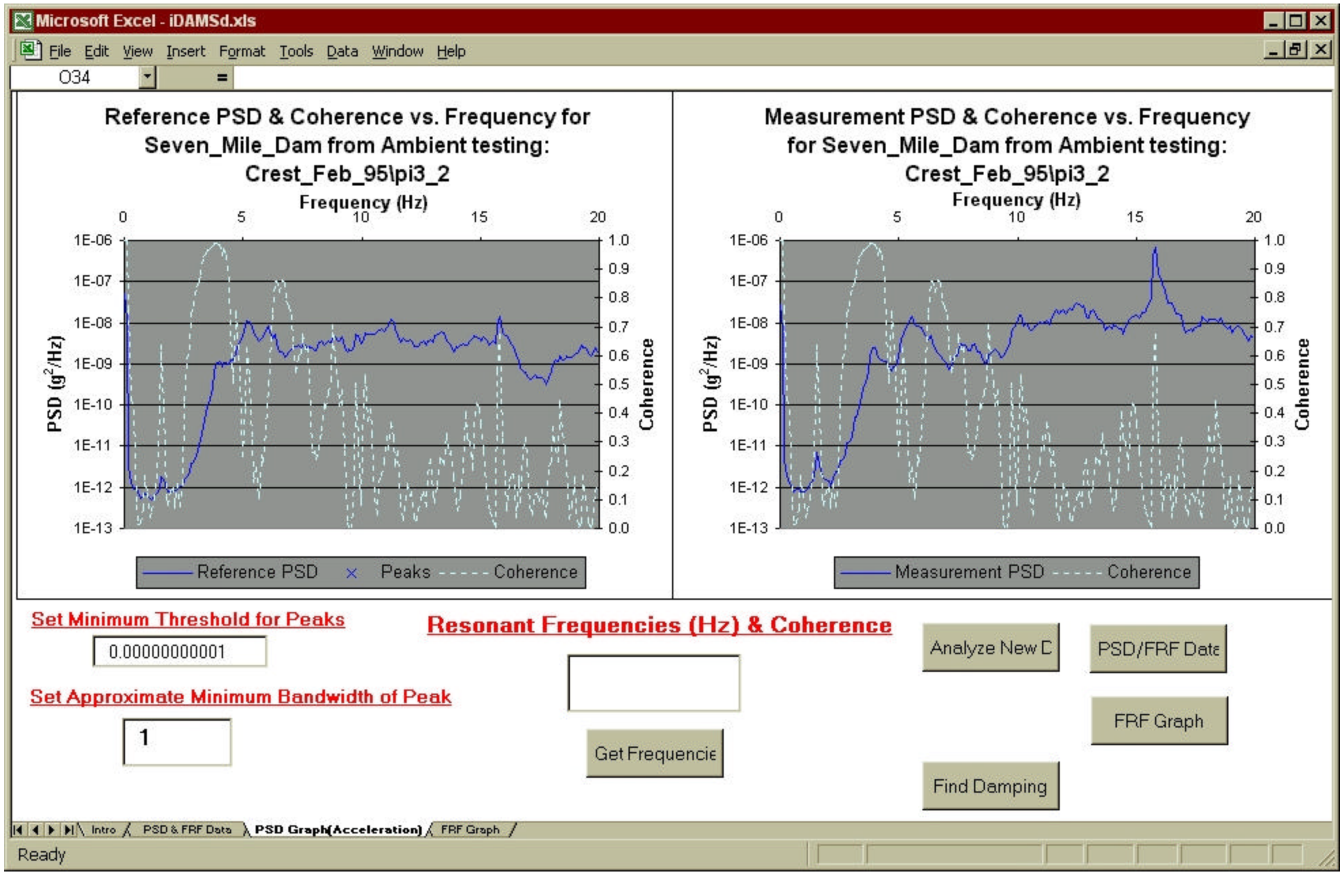
iDAMS *(cont.)*

- ***iDAMS*** **can also form an essential component to periodic health monitoring of a structure.**
- **Analysis capabilities include graphical representation of measured responses, automated resonant peak identification, animation of measured response shapes, and non-traditional spectral analysis techniques, which include the Maximum Entropy Method.**
- **These features combine to make** ***iDAMS*** **a very useful tool for analysis and comparison of structural testing data, and for calibration of structural models.**

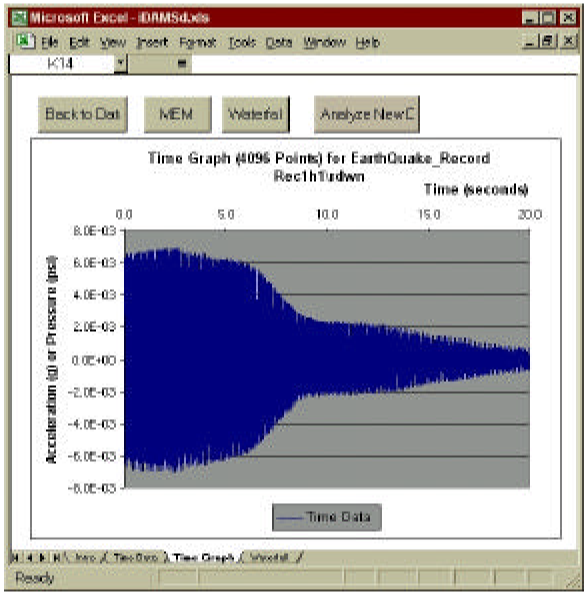
iDAMS (cont.)

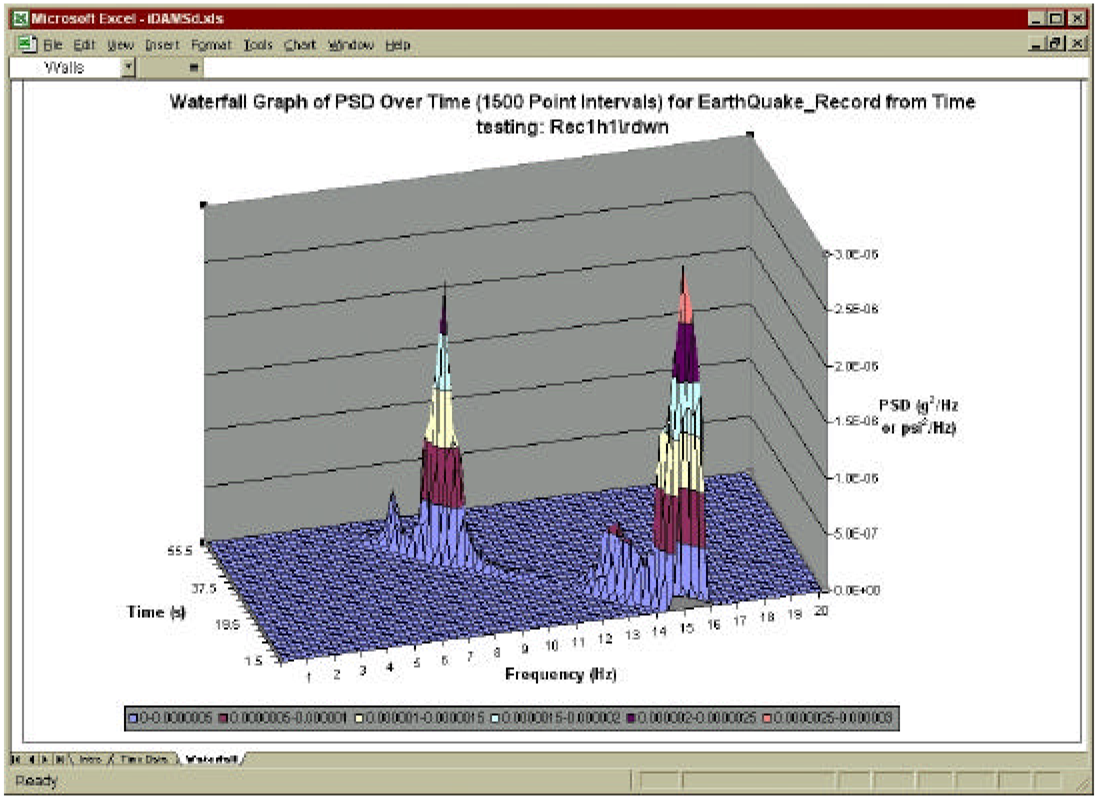
Select:

- Structure type
- Structure
- Data type
- Data set
- Location



iDAMS (cont.)


Microsoft Excel - iDAMSd.xls
Back to Dat
MEM
Waterfall
Analyze New
Time Graph (4096 Points) for EarthQuake_Record
Rec1h1\rdwn
Time (seconds)
Acceleration (g) or Pressure (psi)
Time Data
Ready


Microsoft Excel - iDAMSd.xls
Waterfall Graph of PSD Over Time (1500 Point Intervals) for EarthQuake_Record from Time testing: Rec1h1\rdwn
PSD (g²/Hz or psi²/Hz)
Time (s)
Frequency (Hz)
Ready

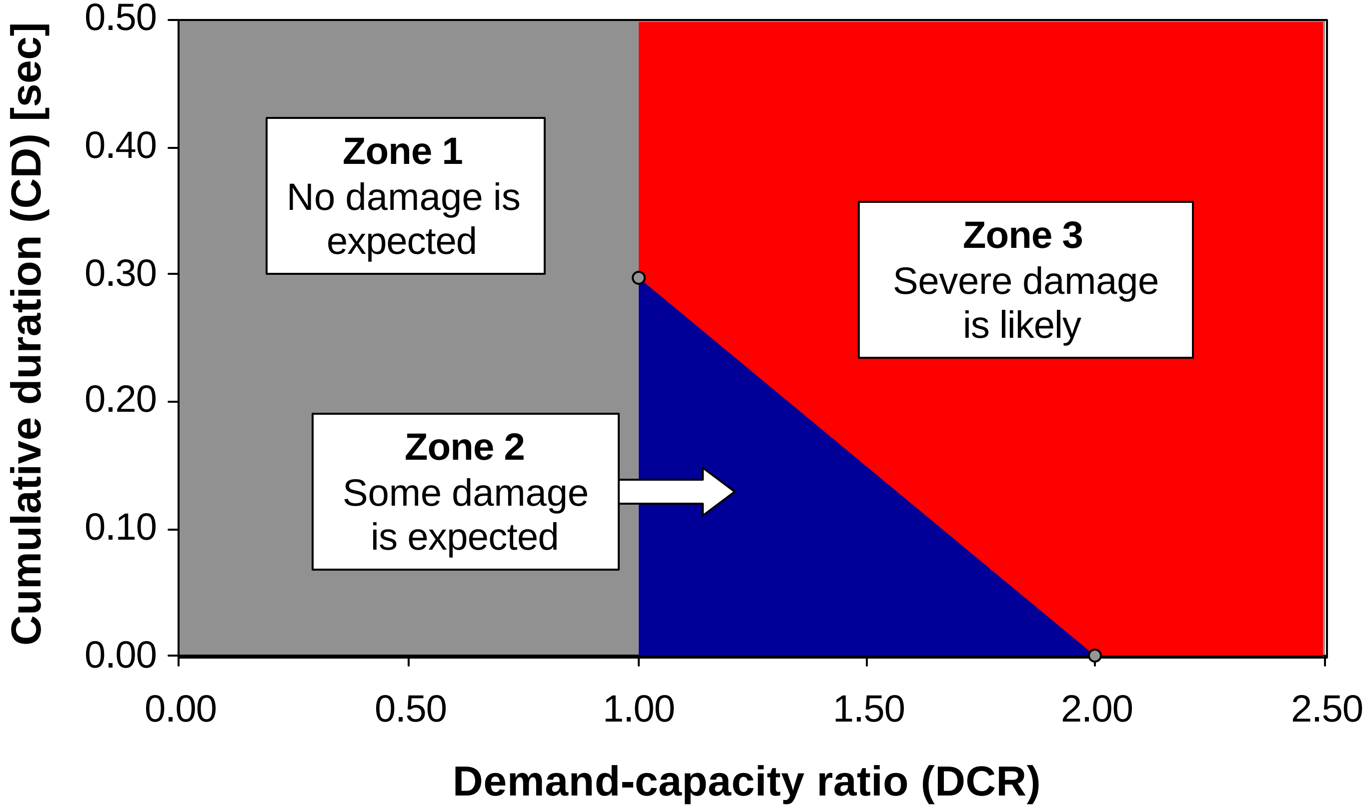
OUTLINE

- Objectives
- Time-domain solutions for nonlinear problems of concrete dams (EQTIME2D)
  - Foundation flexibility model
  - Preprocessor (EQTIMEpre)
- Validation of dynamic nonlinear analysis methods for concrete dams
  - Evaluation of shake table results
  - iDAMS database
- ➢ **Performance evaluation of concrete dams using linear time-history analysis**
- International collaboration efforts
- Summary and conclusions

GUIDELINES FOR LINEAR DYNAMIC ANALYSIS

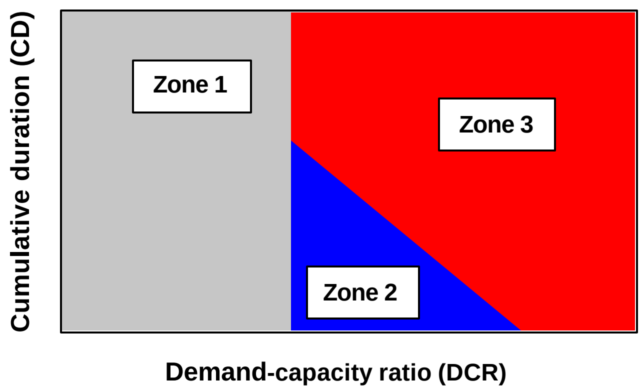
- **The new USACE guidelines (EC 1110-2-6051) present a methodology for qualitative damage estimation using standard results from linear time-history analyses.**
- **They represent a substantial contribution with respect to existing guidance documents.**
- **These guidelines propose a systematic interpretation of the time-history results in terms of local and global performance indices.**
- **Several performance criteria are defined for different types of concrete hydraulic structures. These criteria form the basis for a qualitative estimation of the probable level of damage.**

GUIDELINES FOR LINEAR DYNAMIC ANALYSIS (cont.)

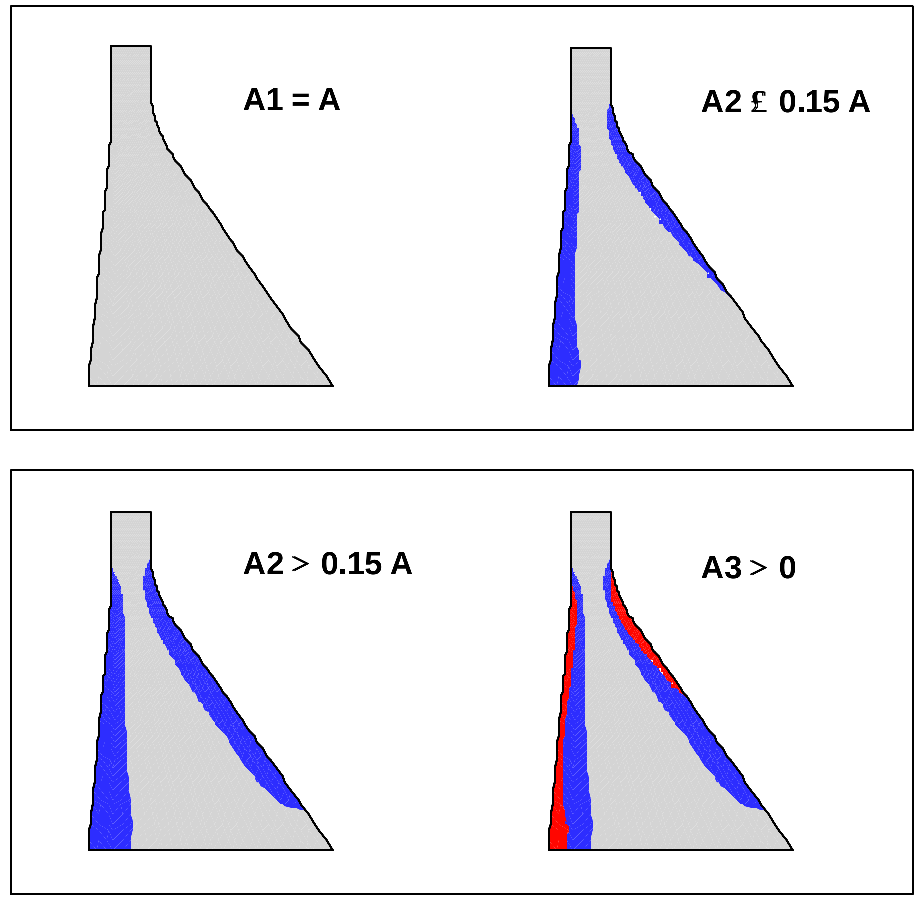


GUIDELINES FOR LINEAR DYNAMIC ANALYSIS (cont.)

Performance is acceptable

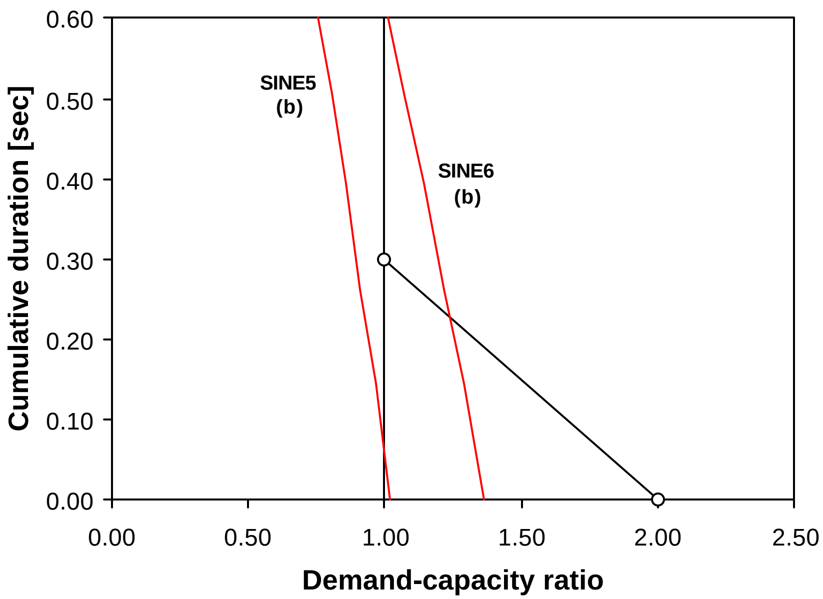


Damage could be severe

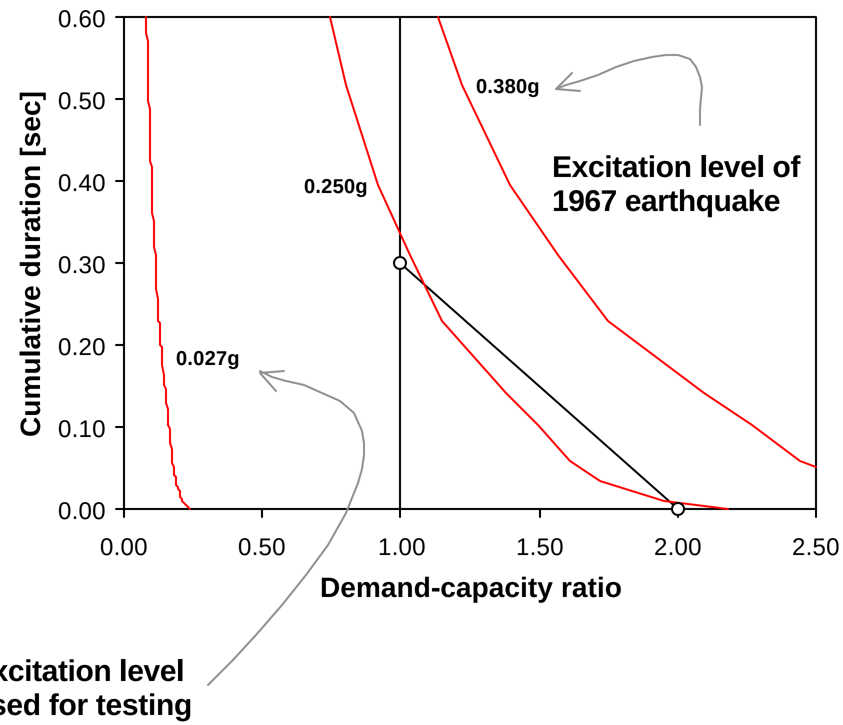


GUIDELINES FOR LINEAR DYNAMIC ANALYSIS (cont.)

SHAKE TABLE TESTS:
Sinusoidal Excitation



SHAKE TABLE TESTS:
Earthquake Excitation



OUTLINE

- Objectives
- Time-domain solutions for nonlinear problems of concrete dams (EQTIME2D)
    - Foundation flexibility model
    - Preprocessor (EQTIMEpre)
- Validation of dynamic nonlinear analysis methods for concrete dams
    - Evaluation of shake table results
    - iDAMS database
- Performance evaluation of concrete dams using linear time-history analysis
- ➢ **International collaboration efforts**
- Summary and conclusions

COLLABORATIVE RESEARCH EFFORTS

- **6-week scientist exchange program in collaboration with the Public Works Research Institute, Ministry of Land, Infrastructure, and Transport, Japan.**
- **Funding from the Japan Science and Technology Agency, Ministry of Education, Culture, Sports, Science and Technology, Japan.**
- **Scope of work**
  - ⇒ **Comparison of U.S. and Japan seismic design guidelines for concrete gravity dams.**

OUTLINE

- Objectives
- Time-domain solutions for nonlinear problems of concrete dams (EQTIME2D)
    - Foundation flexibility model
    - Preprocessor (EQTIMEpre)
- Validation of dynamic nonlinear analysis methods for concrete dams
    - Evaluation of shake table results
    - iDAMS database
- Performance evaluation of concrete dams using linear time-history analysis
- International collaboration efforts

➢ **Summary and conclusions**

SUMMARY AND CONCLUSIONS

- **EQTIME2D:**
  - ⇒ **In the last two years, the fundamental structure of this program has been completed.**
  - ⇒ **Some issues related to the numerical behavior of the nonlinear model adopted to model crack propagation need to be improved.**
  - ⇒ **The corresponding solutions have been identified and the required modifications could be completed within the next 12 months.**
  - ⇒ **Distribution: July 2002.**

SUMMARY AND CONCLUSIONS (cont.)

- **EQTIME2D User's Manual:**
  - ⇒ **Second draft completed (March 2001).**
  - ⇒ **Final version will be distributed with the code (July 2002).**
- **EQTIMEpre:**
  - ⇒ **Initial version completed (November 2000).**
  - ⇒ **Final version: September 2002.**
- **iDAMS:**
  - ⇒ **Web-based version completed (http://idams.eng.hmc.edu)**
  - ⇒ **Development depends on strong collaboration with other agencies.**

SUMMARY AND CONCLUSIONS (cont.)

- **Shake table tests (Koyna Dam 1/20 model):**
  - ⇒ **Draft report completed.**
  - ⇒ **Final preparation for publication (July 2001).**
- **Sub-bottom absorption:**
  - ⇒ **Report with guidelines will be completed this FY.**