EARTHQUAKE ENGINEERING

Nonlinear Dynamic Response and Failure Mechanisms of Intake Towers

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Introduction

Problem:

Existing Corps intake towers are lightly reinforced structures with unknown ductility and undetermined failure mechanisms.

Objective:

Develop experimentally validated analysis procedures accounting for available ductility.

Gathright Tower

Final Product:

Design and retrofit guidance incorporating analysis procedures, with potential for substantial savings in avoided retrofit costs.

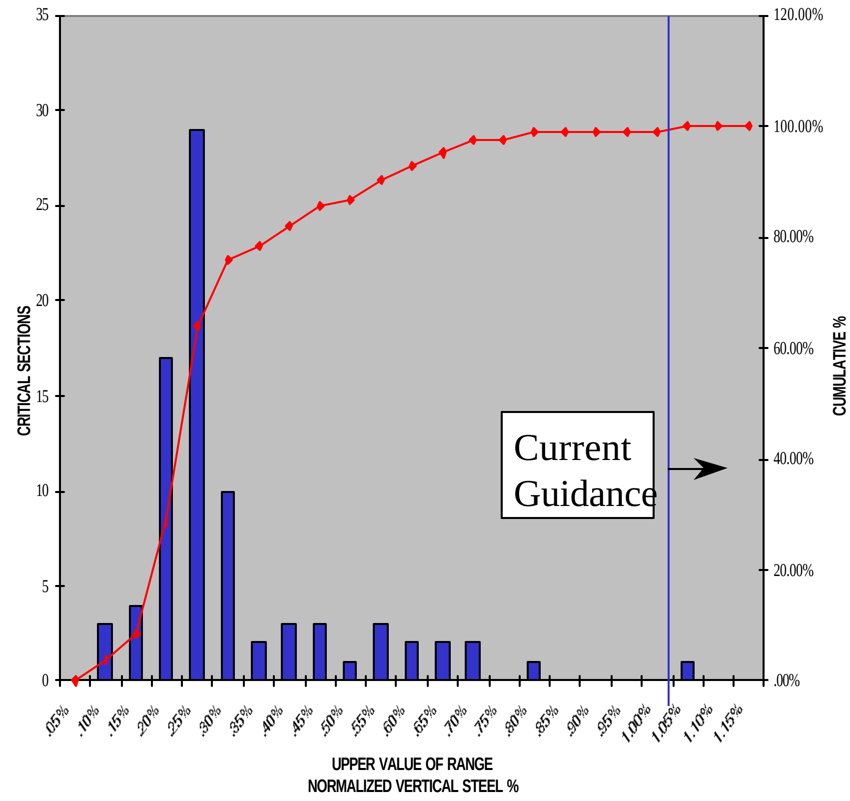
Background

Potential Savings:

- 72 Towers have been identified as being located is seismic zone 2 or above.
- Retrofit estimated to be between $5 million and $100 million per tower.

Prior guidance (EC 1110-2-285):

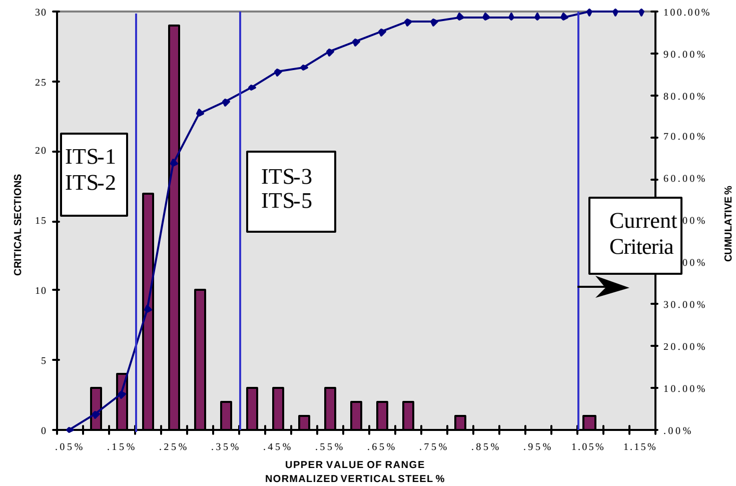
- Assumes incorrect multi-crack failure mechanism.
- Does not apply to majority of Corp's tower inventory.
- Displacement-based analysis suggested as alternative.



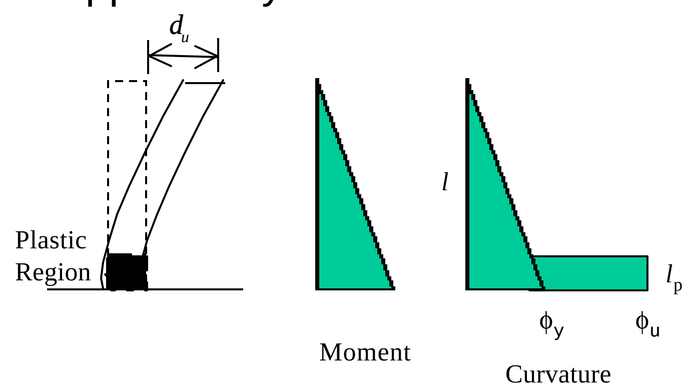
Vertical Steel % of Tower Inventory

Displacement Based Analysis

- Explicit consideration of the earthquake induced displacements of a structure.
- A modification of a response spectrum analysis that accounts for the shift of the structure fundamental frequencies with formation of plastic regions in the structure.
- Presented in EC 1110-2-285, "Structural Analysis and Design of Intake Structures for Outlet Works" as an alternative method applicable to towers with vertical steel percentages of 1 percent or less. Almost all existing towers have less than 1 percent vertical steel.



Applicability of Current Guidance



$$d_u = \frac{f_y l^2}{3} + (f_u - f_y) l_p (l - \frac{l_p}{2})$$

Classic Assumed Deflection Response

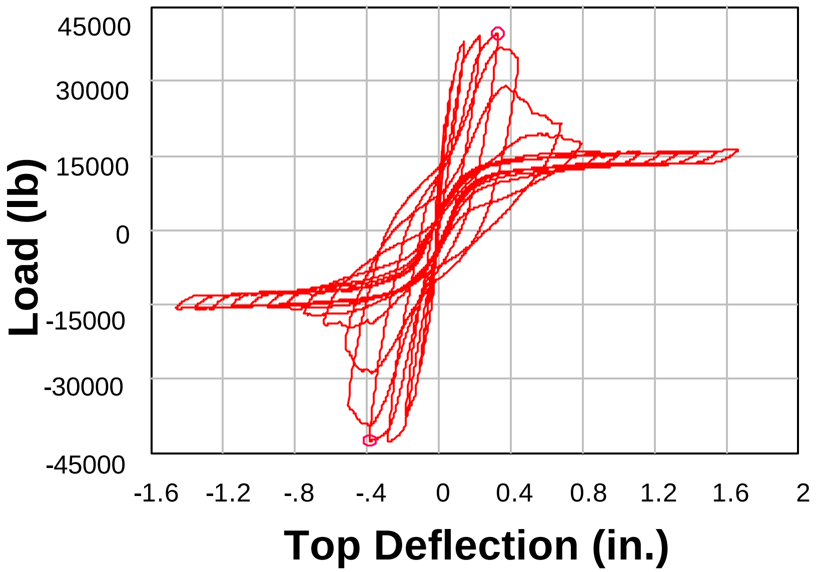
Direction of Research

Approach:

- Inventory analysis.
- Experimentation.
- Development/Evaluation of ductility evaluation procedures.

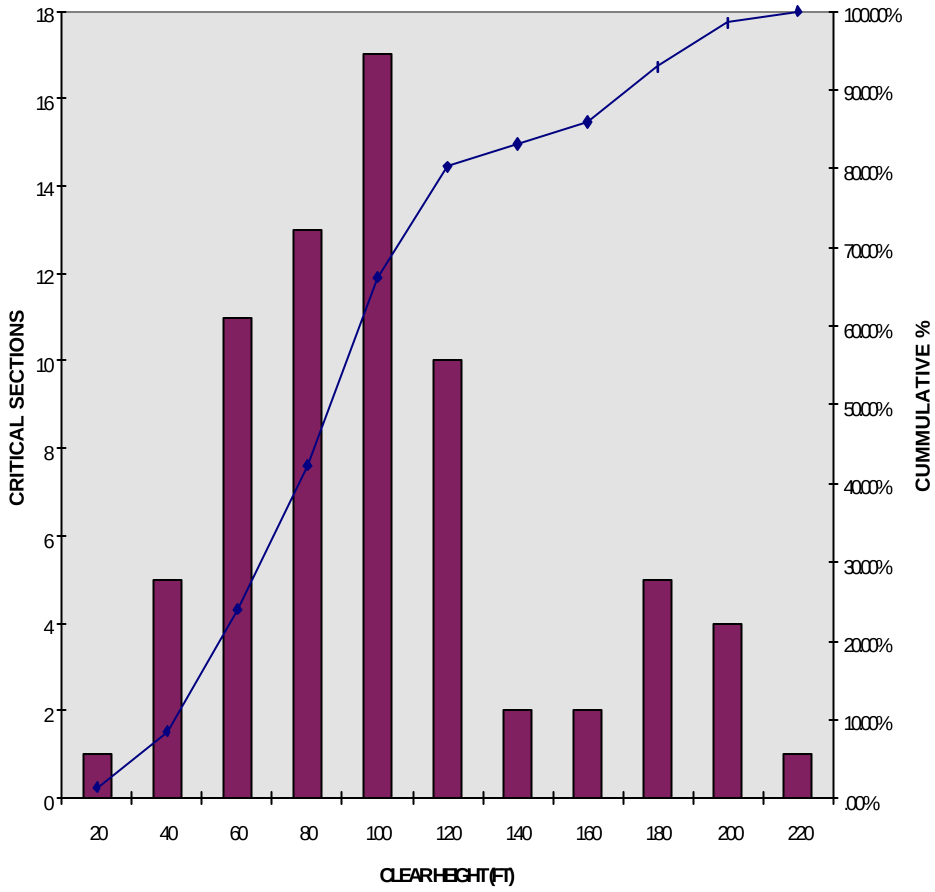
Scope of Effort:

- Experimentation has included cyclic loading of three 1/8-scale and fourteen 1/2-scale models.
- Results show substantial ductility available.
- Displacement-based analysis modified to reflect results.
- Dynamic 1/8-scale model experimentation will validate procedure.



Inventory Analysis

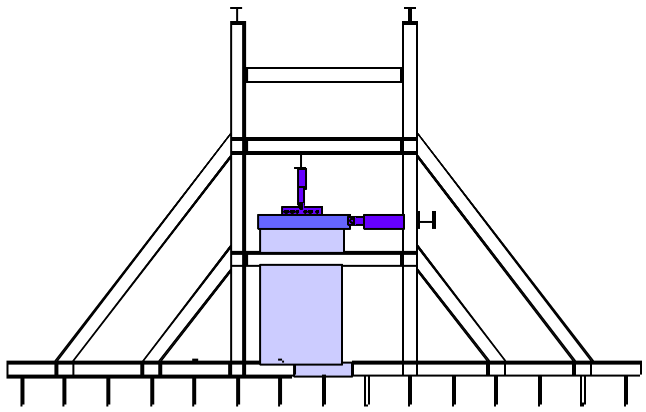
- Drawings of 72 existing towers were obtained.
- A data base of tower 36 characteristics was developed and analyzed.
- Characteristics included:
  - Descriptive (Location,Seismic Zone, Age)
  - Geometric (Shape,Height, Thickness, Pool Heights, Critical Sections)
  - Structural (Reinforcement,Material Strengths, Section Properties)
- Information developed was used to plan experimentation effort.



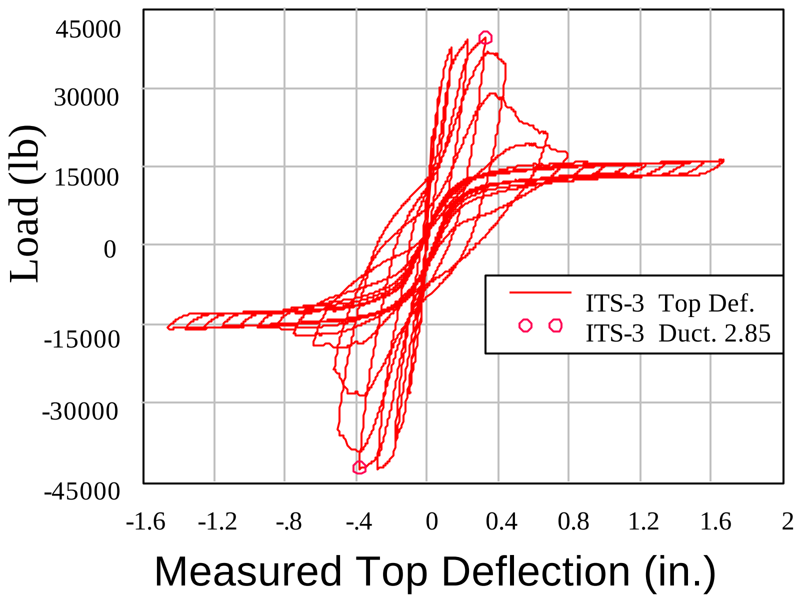
Tower Clear Height above Critical Sections

Intake Tower Substructure Experimentation

- Three 1/8-scale models of typical rectangular intake tower configuration.
- The vertical steel percentage was varied from 0.18 to 0.36.
- Static vertical dead load and the application of a one-way or cyclic horizontal and torsional loads.
- The intake towers modeled exhibited significant ductility with a very localized failure zone.
- Modification of the deflection based analysis technique is needed to model localized failure.

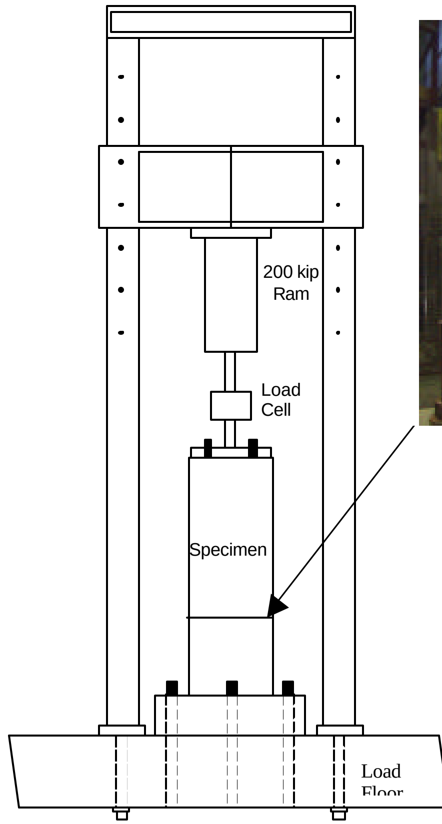


Experiment Layout

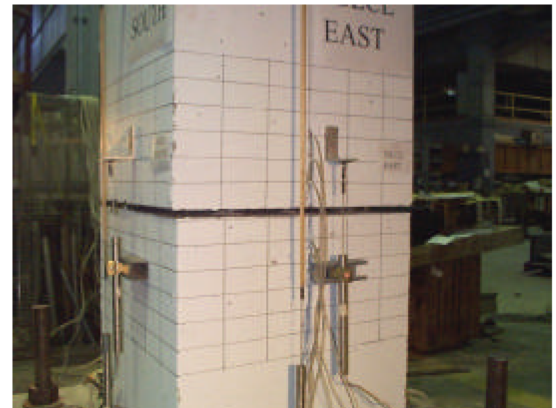


Phase 1 Strain Penetration Experimentation

- Ten 1/2-scale strain penetration experiments were conducted to determine the parameters needed for deflection-based analysis.
- Experiment design was a modified full-factorial interaction of three variables.
- Variables were bar diameter, steel strength, and concrete strength.
- Analysis of the results led to empirical relationship for ultimate crack width used in modification of the deflection based analysis technique.



Experiment Layout



Typical Failure Zone

FY 2001 Efforts

- **Phase 2 Strain Penetration Experimentation**
- **Modification of Analytical Model**
- **ITS5 Dynamic Experimentation**

Phase 2 Strain Penetration Experimentation

- Four large-bar-diameter experiments conducted to address scaling concerns and validate procedures for later experimentation.
- Variables were bar diameter, and steel strength.
- Inadequate confinement caused ambiguous results in two experiments.
- Results of two experiments were used to modify ultimate crack width model.
- Future experiments will include additional confinement.

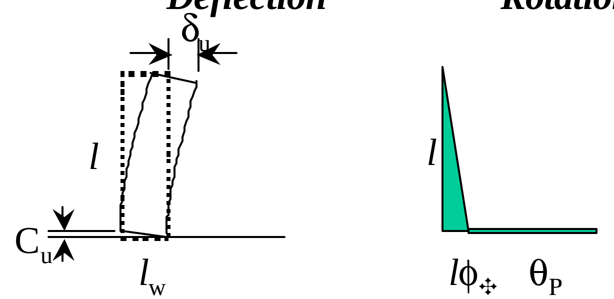
#10 Bar Failure Mode

Modified Displacement Based Analysis

- Classic assumed deflection response fails to model localized response of intake towers.
- Experimentation suggests that response can be modeled by single crack response.
- Single crack response is largely dependent upon the ultimate strain capacity and strain penetration characteristics of the reinforcing as well the geometry of the section.
- Strain penetration experiments were conducted to determine the parameters required for modification of the displacement based analysis.

<u>Modified Deflection Model</u>

Deflection ***Rotation***



$$d_u = \frac{f_E l^2}{3} + q_p l \qquad q_p = \frac{C_u}{l_w}$$

$$f_E = \frac{M}{EI_g} \qquad d_u = \frac{f_E l^2}{3} + \frac{C_u}{l_w} l$$

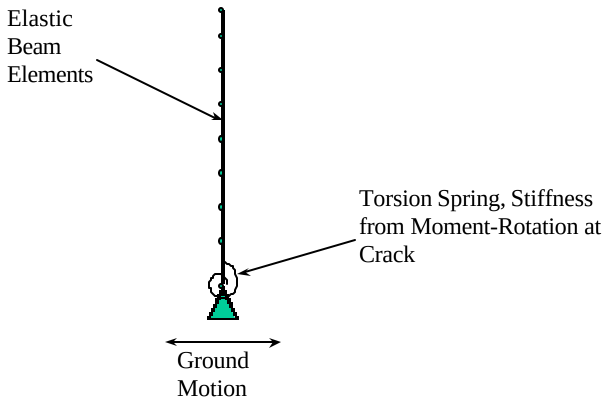
$$\mathbf{C_u = 0.12+2.47å_u + 0.79d_b}$$

where:
C_u = Ultimate Crack Width (cm.)
$å_u$ = Ultimate Bar Strain
d_b = Bar Diameter (cm.)

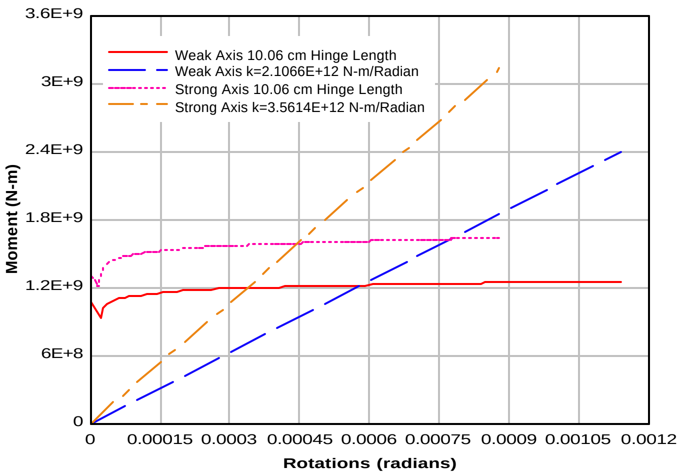
Implementation of Modified Displacement Based Analysis Procedure

- Intake tower is modeled by elastic beam elements and torsional spring.
- Torsional spring is linearized Moment-Rotation relationship of single crack failure zone.
- A response spectrum analysis is conducted to determine deflection response for given earthquake.
- Deflection capacity is calculated using modified deflection model with tower geometry and reinforcing.
- If capacity exceeds response tower passes analysis.

Structural Model

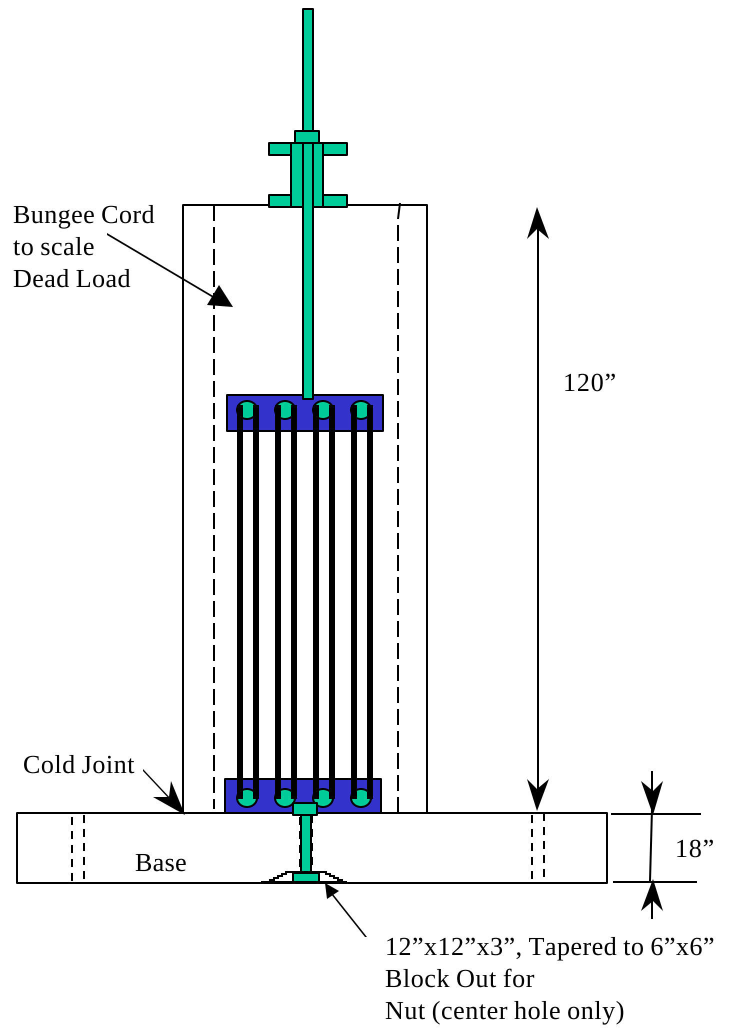


Torsional Spring Model



ITS5 Dynamic Experimentation

- Experiment will be conducted at CERL Shake Table Facility
- Objective is dynamic validation of the failure mode assumed in the displacement based technique.
- 1/8-scale model of a typical intake tower configuration, the same design as the ITS3 static model.
- Model consists of a 40-in. by 52-in., 10-ft tall tower section with 5 5/8-in thick walls, mounted on a heavily reinforced concrete base.
- The vertical steel percentage is 0.36%, horizontal steel percentage is 0.48%.



ITS5 Dynamic Experimentation

ITS5 Dynamic Experimentation

- Load to failure about weak axis by horizontal sinusoidal vibration at a frequency slightly higher than the natural frequency.
- Vertical load to model gravity will be applied using elastic "shock cords".
- Shock cords allow proper combination of inertial and gravity loads and have been used successfully in prior experiments.

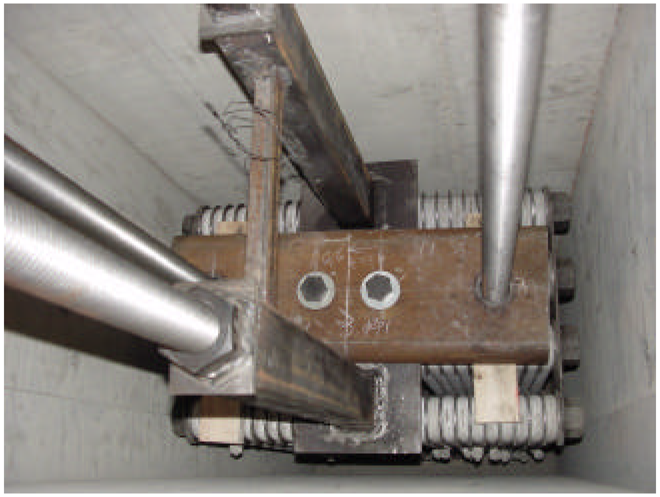
Shock cord load device

Tensioning of load device

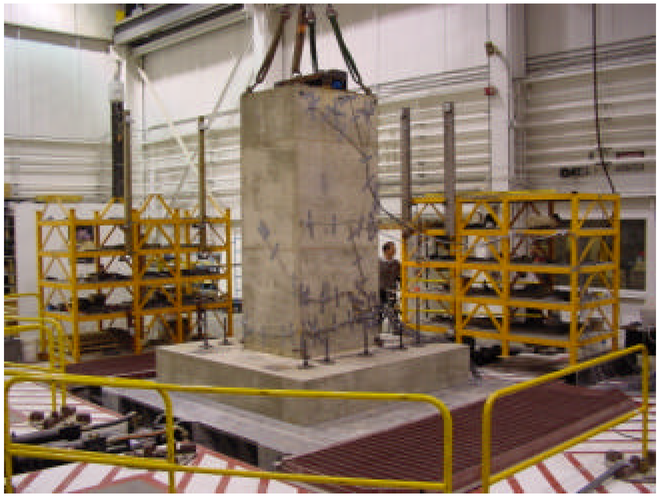
ITS5 Dynamic Experimentation

- Model was delivered to CERL in February, 2001.
- Initial modal survey was completed in April.
- Completion of experiment expected in July, pending resolution of table control issues.

Transportation of model



Installed load device



Tower model on shake table

FY 2002 Efforts – Phase 3 Strain Penetration Experimentation

- Current deflection capacity based on crack width equation derived from experimentation on #3 to #6 bars
- Bar diameters found in existing towers often reach #11 bars.
- Scalability of the experimentation is unclear.
- Additional large bar diameter experiments should substantially improve prediction of deflection capacity.

FY 2002 Efforts - Dynamic Experimentation

- The current dynamic experiment (ITS5) will model the failure mode of a typical rectangular tower and determine it’s deflection capacity. This validates the calculation of the deflection capacity based on the results of static experimentation.
- The proposed dynamic experiments (ITS6) will model the response of a tower to an individual earthquake. This will validate the complete analysis process.

Milestones

Milestone:	Year:
• Phase 2 Strain Penetration Experimentation	FY01
• ITS5 Dynamic Experimentation	FY01
• Phase 3 Strain Penetration Experimentation	FY02
• ITS6 Dynamic Experimentation	FY02
• Validated Analysis Procedure for Rectangular Towers	FY02
• Design/Analysis Guidance (EM110-2-2400)	FY02

Summary

- Experimentally validated deflection-based analysis procedure accounting for available ductility in lightly reinforced rectangular intake towers
- Analysis procedures will be included in latest guidance, with potential for substantial savings in avoided retrofit costs
- Work reviewed by outside experts including Dr. Jack Moehle, EERI, UC. Berkley and Mr. Ralph Strom Structural Engineer, Portland, OR
- Further research needed to expand application to other tower shapes and investigate other failure mechanisms
- Recent USACE Workshop on Seismic Evaluation and Rehabilitation of Civil Works Infrastructure identified continued need for development of deflection-based (pushover) analysis
- District need for capability to perform analyses of lock-walls, intake towers, spillway piers, and retaining walls specifically identified
- Current experimental and analytical efforts will provide this capability for rectangular intake towers
- This capability will be included in latest design/analysis guidance
- Future work can expand this capability