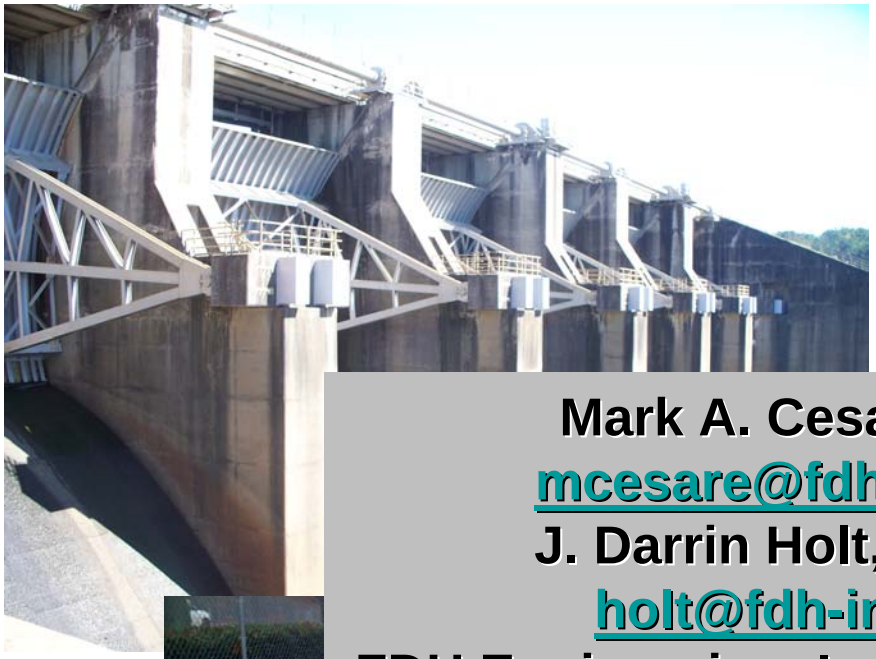
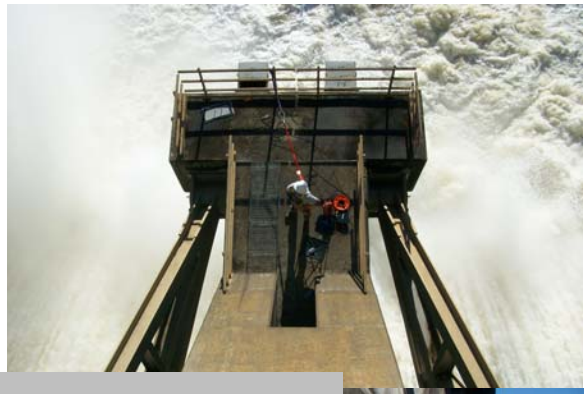
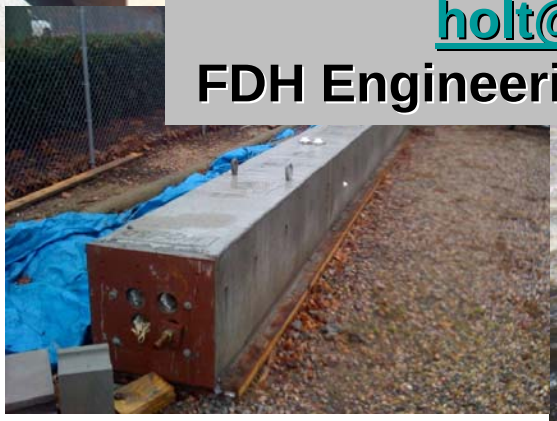
Testing Post-Tensioned Steel Trunnion Rods for the U. S. Army Corps of Engineers







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Trunnion Anchor Rods

The Problem

- Some Catastrophic Rod Failures
- Loss of Pre-Stressing (grip nut slippage, relaxation, etc.)
- Unknown Initial / Existing Tensions

- Typical Solution = Mechanical Lift-Off
- New Solution = Nondestructive Testing (NDT) by *Dispersive Wave Propagation (DWP)*

Approach to the Problem

- Feasibility investigation at West Point: Can this even be done?
- Lab models and full-scale trunnion assembly prototype.
- Wide spread testing.
- Mechanical lift-off.
- Calibration / Validation

- *Dispersive Tension Equation* (DTE).

Background on the Testing Method

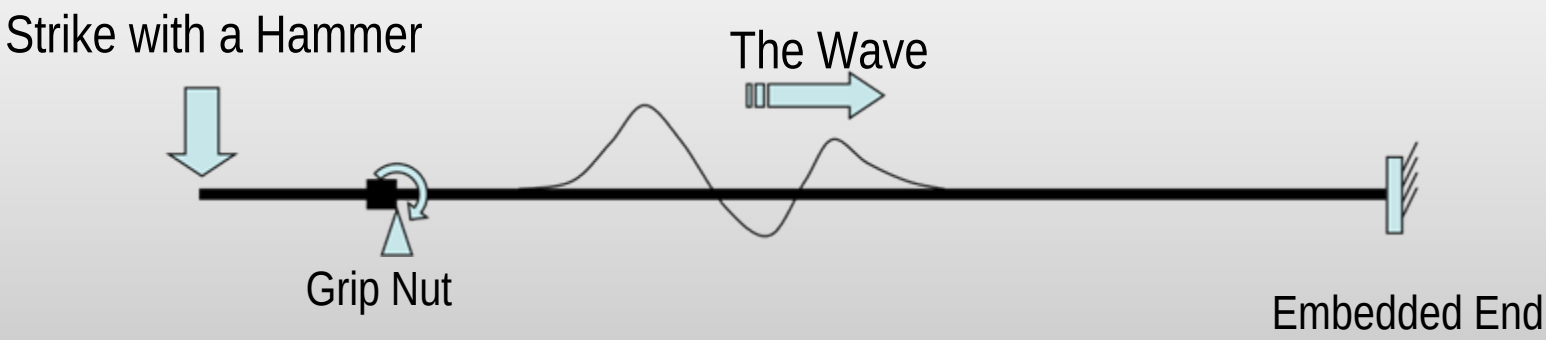
- *Dispersive Wave Methods*

as used for foundation testing

- FHWA / NCDOT Research in 1989 for Bridge Piles
- Used in 50 States, PR, USVI, El Salvador
- Used by several States and many private corporations

The “Idea”

Dispersive Flexural Wave Motion



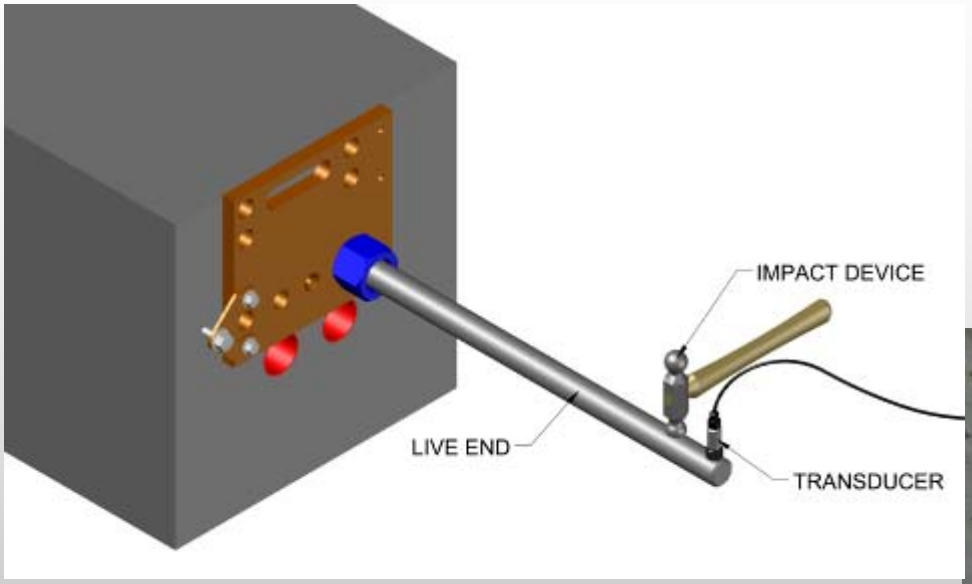
Flexural wave velocities and response depend upon:

Material

Cross-Section

<u>Tension</u>

The Nondestructive Field Testing



"Light" impacts create the dispersive waves.

Wave motion captured and recorded.

Data analyzed for response.

Tension determined from response curves.

Field Testing

Accessibility Issues

Modeling the Steel Covers

- Built full size cover box with PVC for rods
- Helped develop custom strikers (“Hammer on a stick”)
- Developed and practiced testing procedures

Tackling Accessibility

Each rod had to be measured & “pinged”

- non-trivial problem thru the port hole openings
- Remote camera had to be used

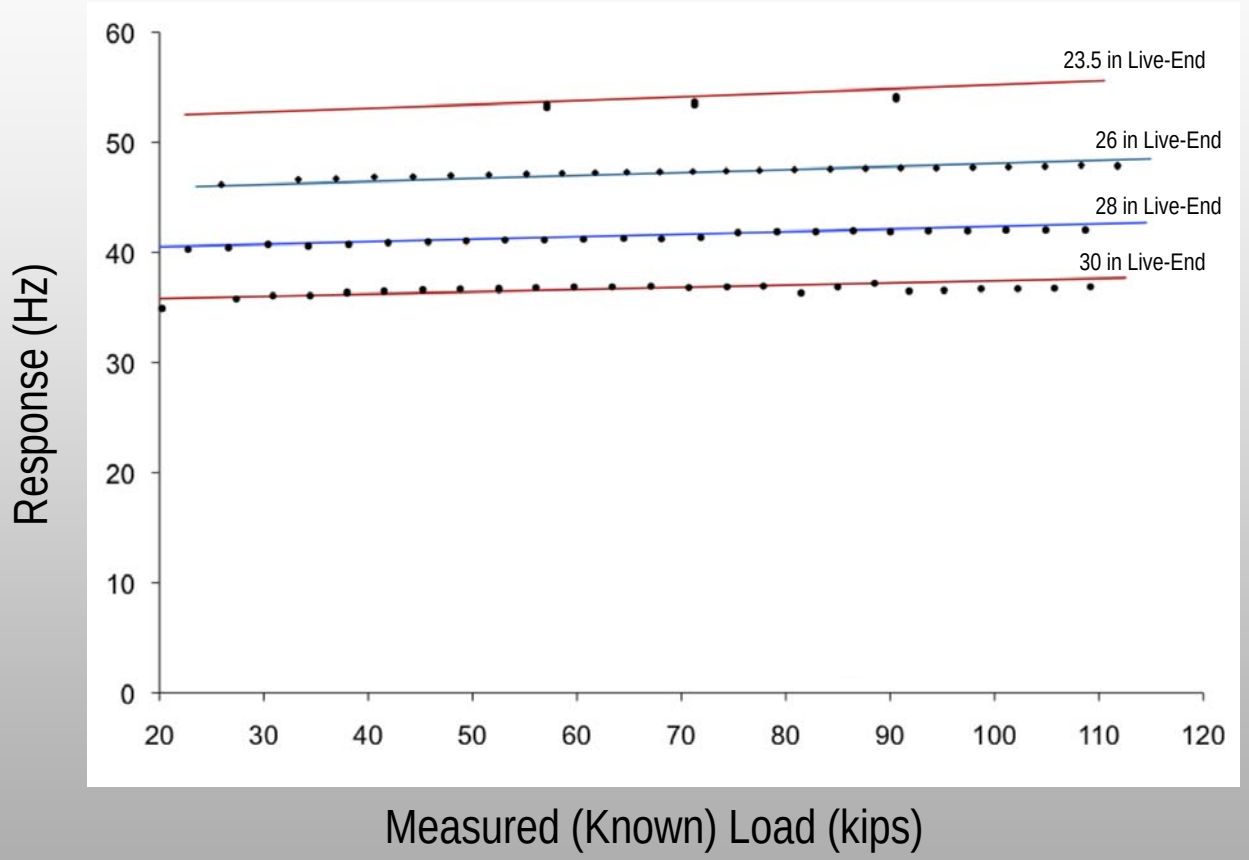
Trunnion Assembly Prototype

- Reinforced concrete with tubes for rods and test equipment.
- Designed and built at FDH

Trunnion Prototype

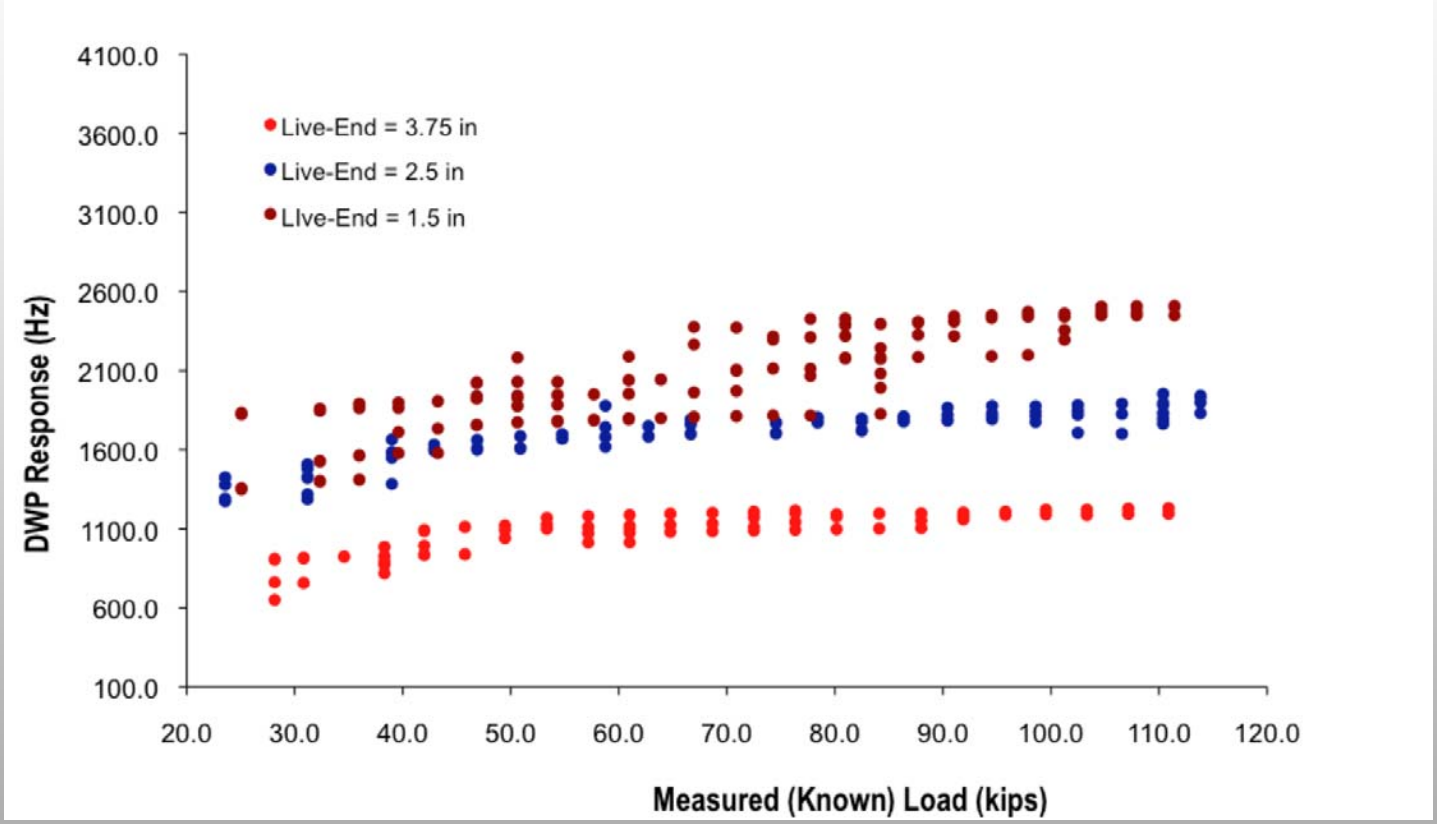
Allows for modeling of many dam configurations.

DWP Response with Tension



West Point Configuration

DWP Response with Tension



Robert F. Henry Configuration

Dispersive Tension Equation

After performing lift-off tests, the **Dispersive Tension Equations (DTE)** were derived (1st generation):

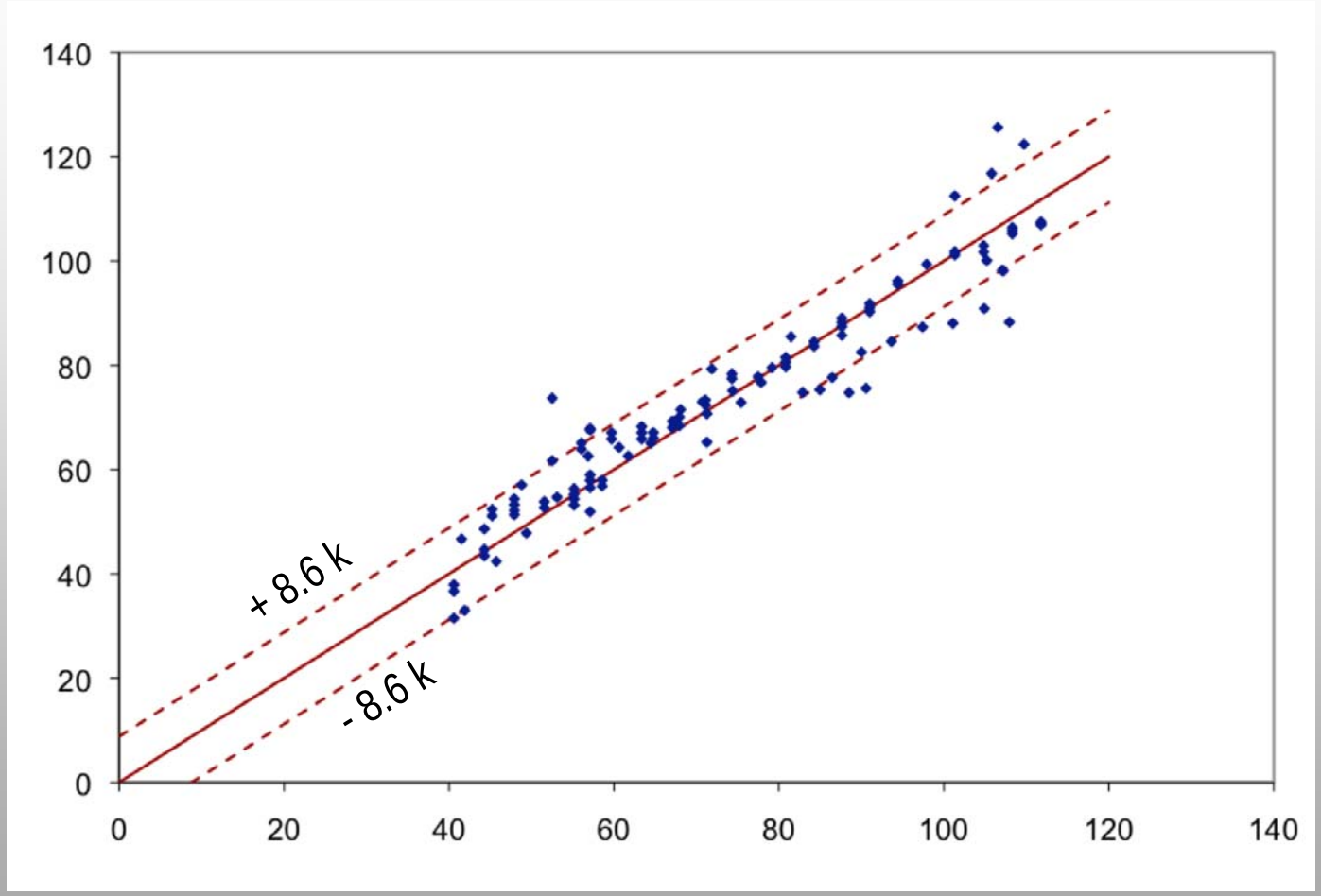
"Long" Live-End Lengths (as West Point)

$$T = 181.8 * f1 + 123.1 * C - 24.55 * f1^2 - 0.67 * f2^2 + 1099 * \left(\frac{f2}{f1}\right) + 7.73 * f1 * f2 + 2.272 * f1 * \left(\frac{f2}{C}\right) - 14746.56$$

"Short" Live-End Lengths (as RF Henry)

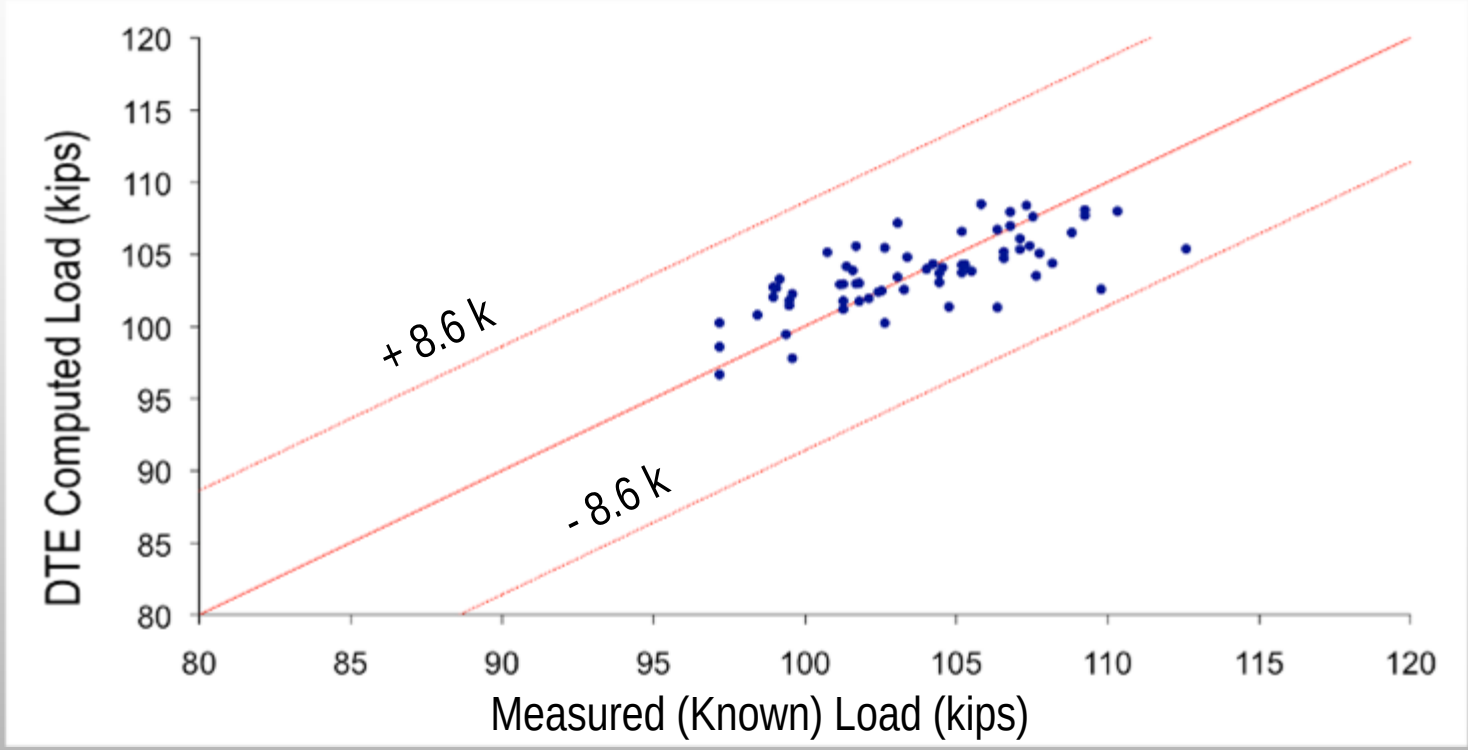
$$T = 12245.4 + 10.4C + 0.0027 f_1 + 0.0019 f_2 - 4.9615\left(\frac{f_1}{f_2}\right) + 0.0179L - 18888.0d + 7314.7d^2$$

DTE Results – West Point, GA



West Point Standard Error : +/- 8.6 kips

DTE Results – Robert F. Henry



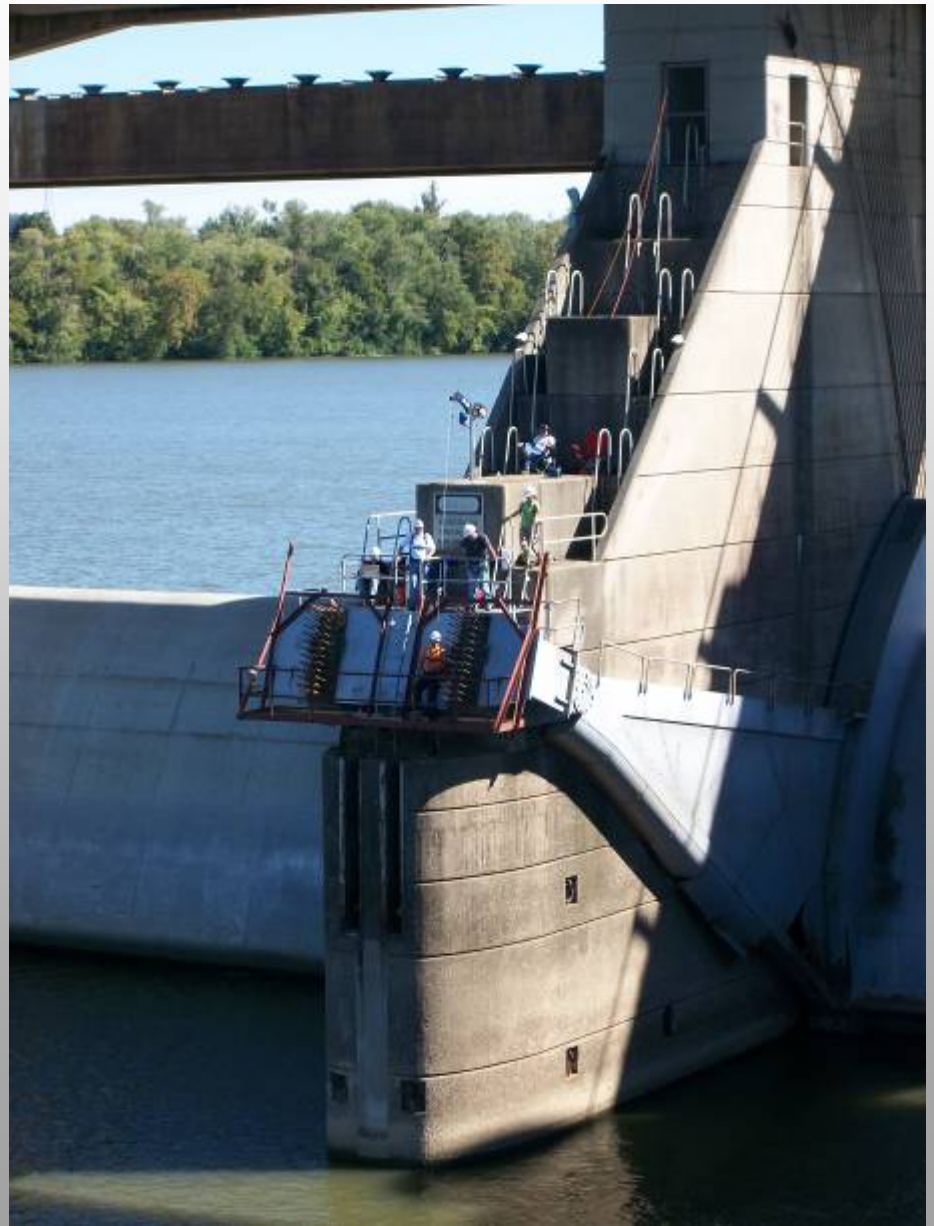
R.F. Henry Standard Error : +/- 2.6 kips

Greenup, KY

104 rods tested

Identified one failed rod

No lift-offs as of yet



Advantages

- Can be preformed w/ high level of safety.
- No standing in front of rods.
- Easily applied.
- No additional stress added to the rods.
- Can test 80 to 100 rods per day (approximately).

Thank You !

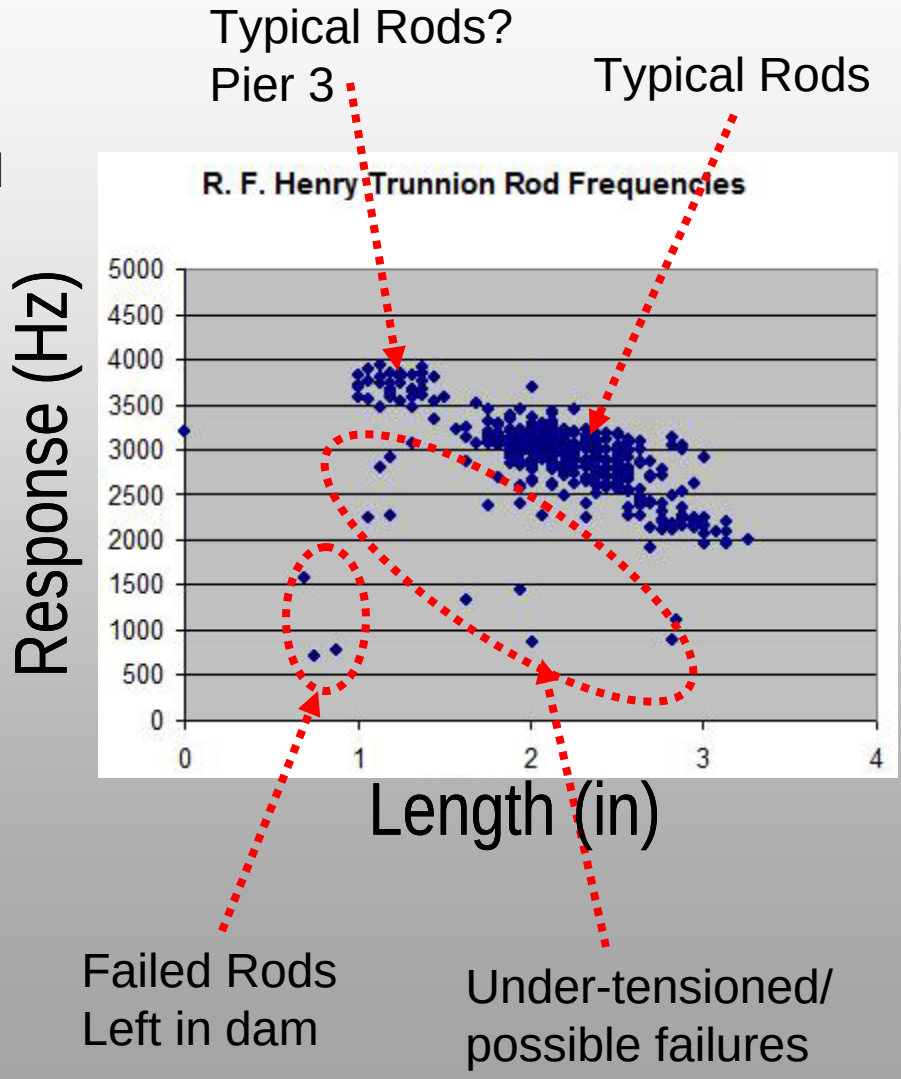
Response Results - R. F. Henry

Observed frequency correlated to exposed length

Known failures are outliers

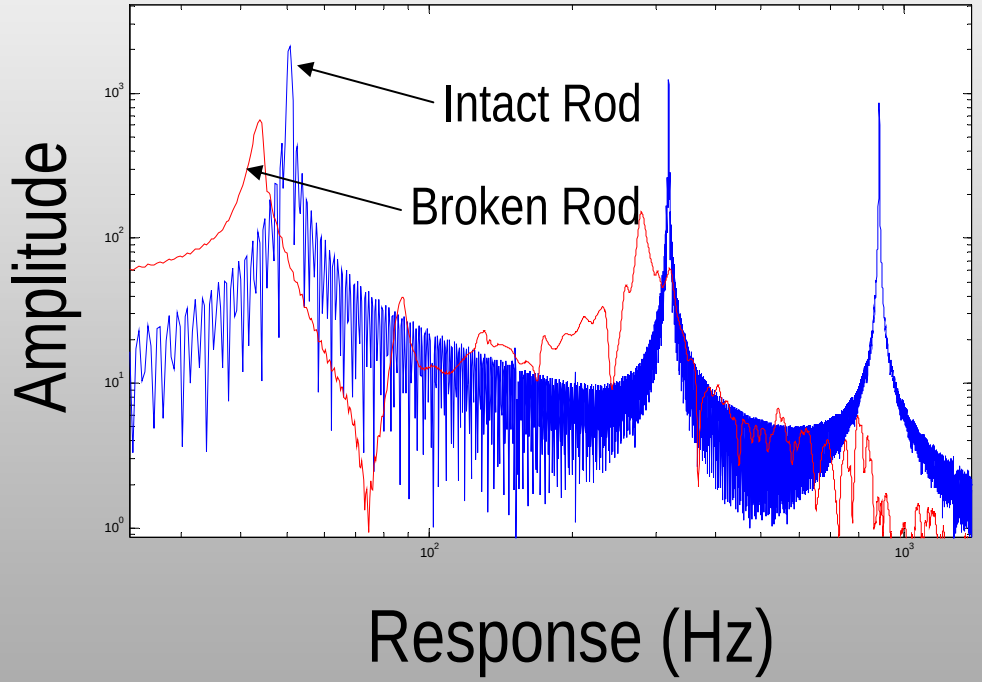
Others are well below the “Typical” rods

Piers 1, 2, and 3 built by different contractor than 4 thru 12, and several years apart



Greenup Results

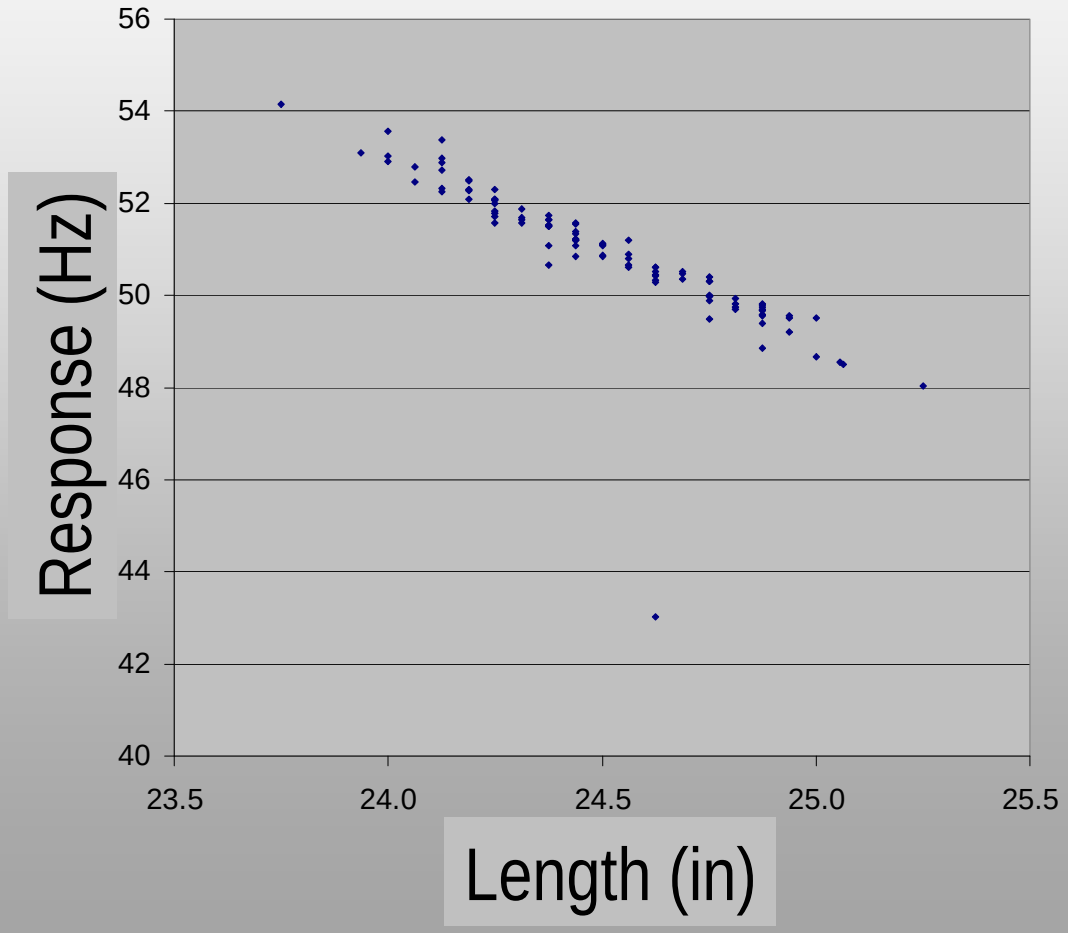
- Most rods ~50 Hz
- Broken rod 43 Hz
- Lift-off test in planning phase



Greenup, KY Results

Observed response correlated to exposed length

One extreme outlier for broken rod



Trunnion Assembly Results

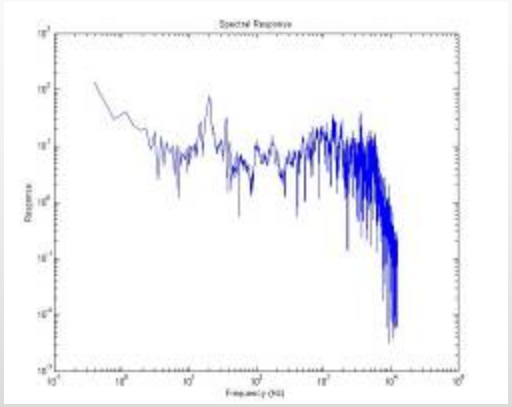
Rod typically tested at 25 different loads from 0 to 115,000lb per setup

At no load – we get noisy FFTs

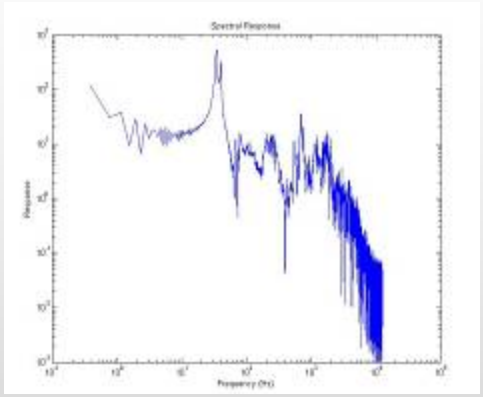
Small load start to bring out peaks

Mode of vibration of cantilever clear

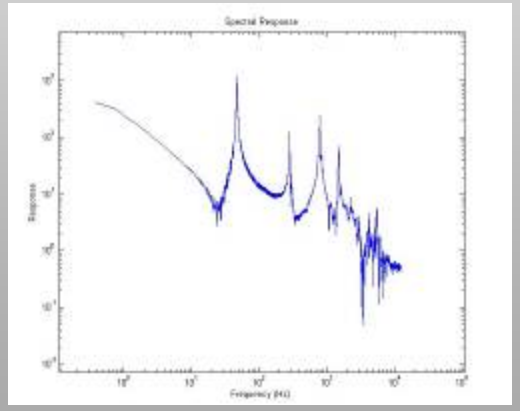
All f's increasing with load



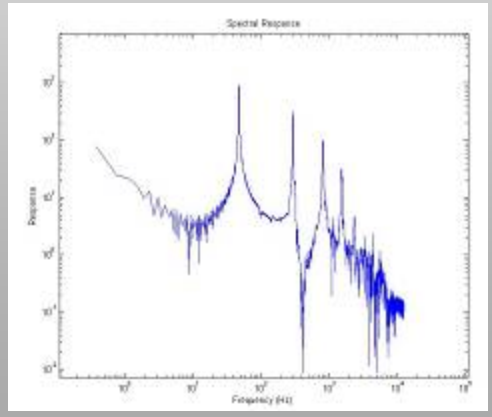
No Load
19.8 Hz



5000 lb
33.95 Hz



55,150 lb
46.92 Hz

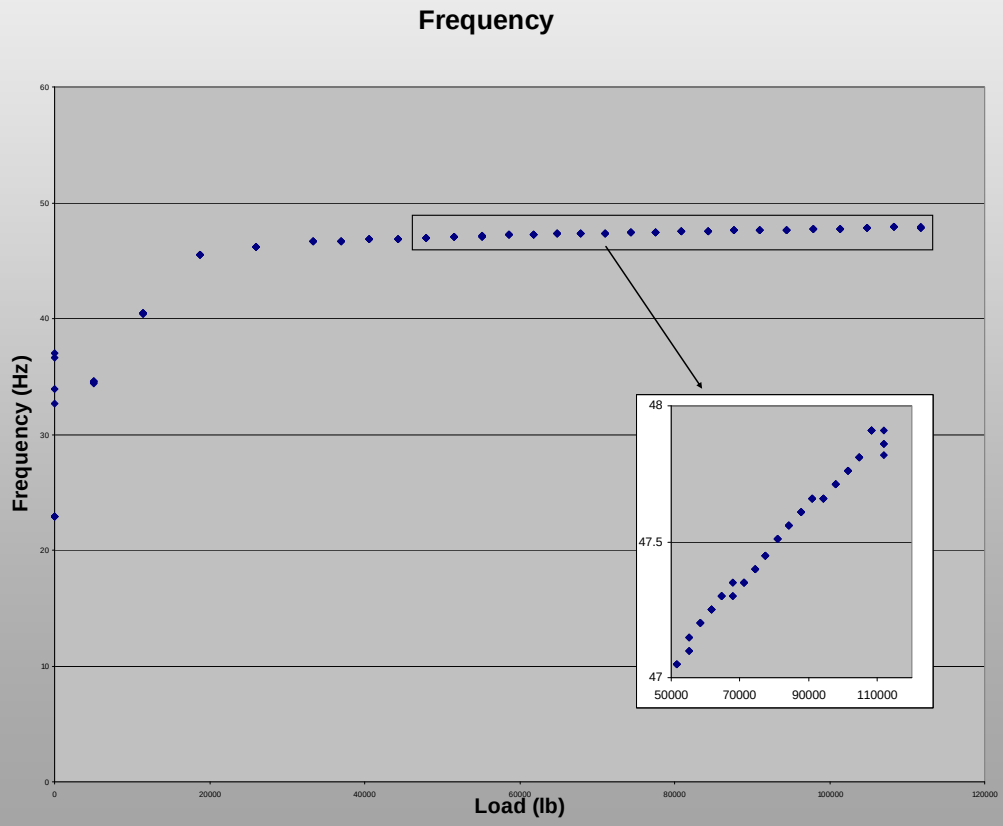


111,780 lb
48.06 Hz

Results – Trunnion Prototype

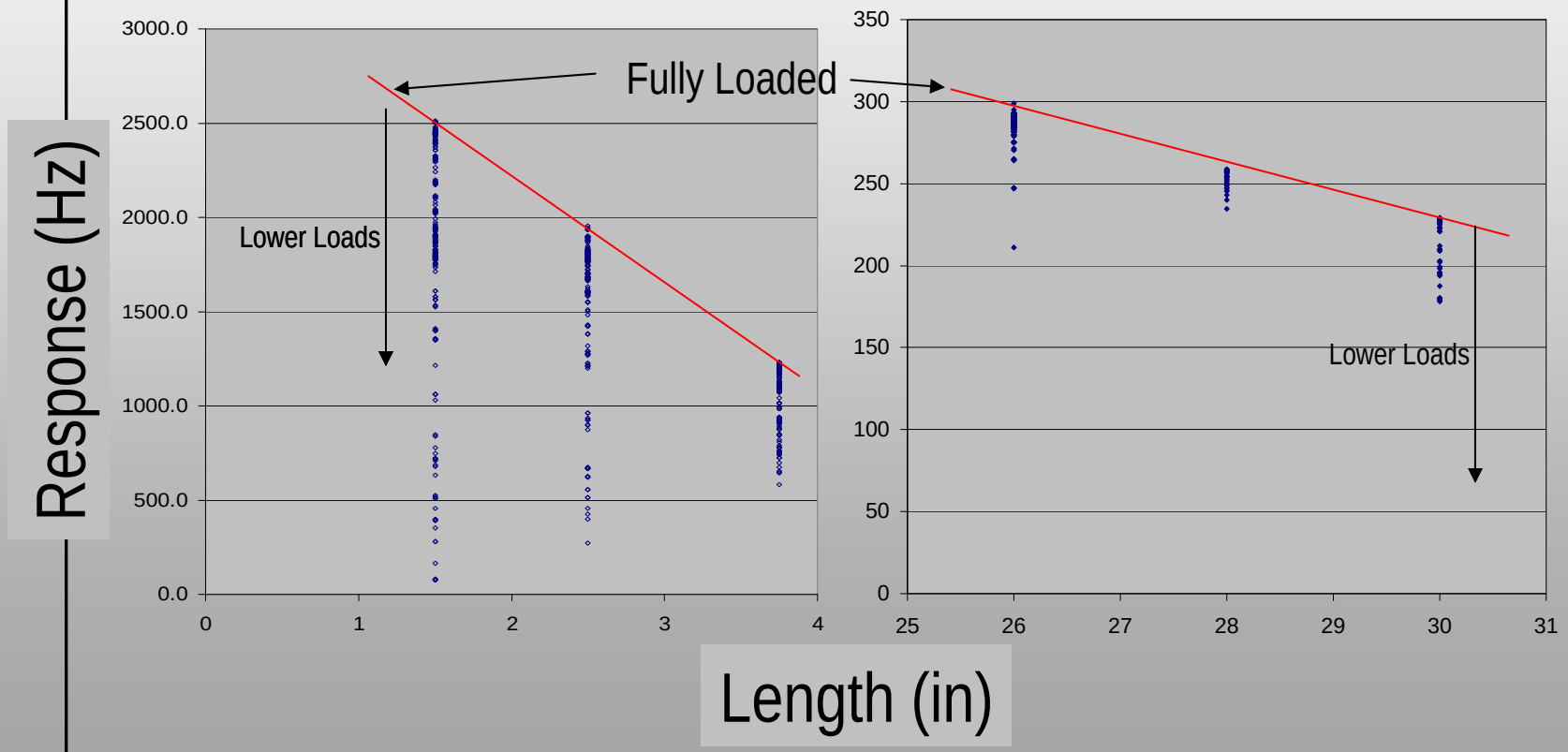
Large increases in frequency at low loads

Above ~20,000 lb pattern of slow but steady increase in frequency with tension



Results – Trunnion Prototype

Many tests done at different lengths and loads



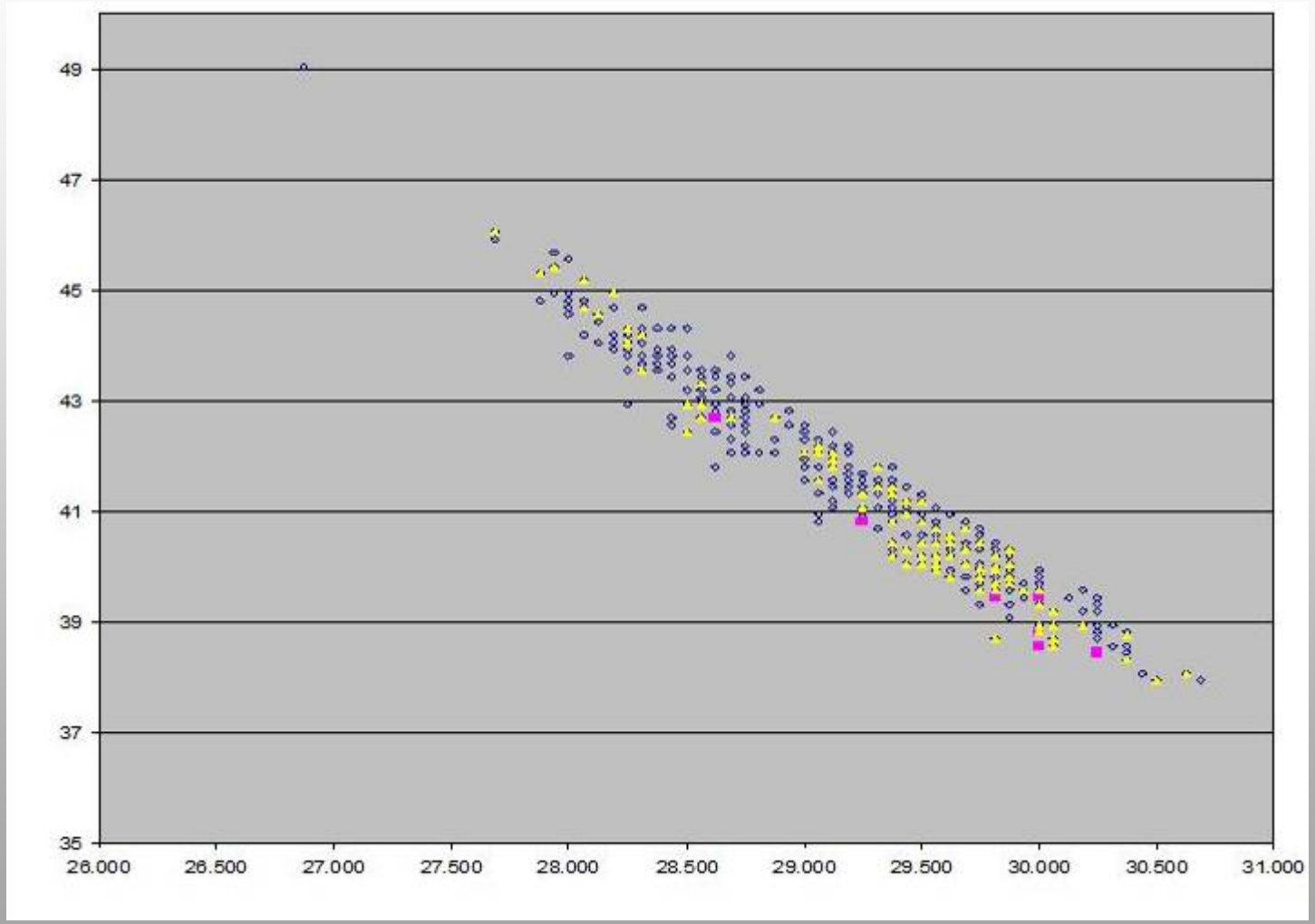
Preparing for liftoff tests

- Test custom made gripping devices
- Strain gages to determine actual pre-stress in rods
- Generated mathematical relation between reported liftoff load and preset load in rod

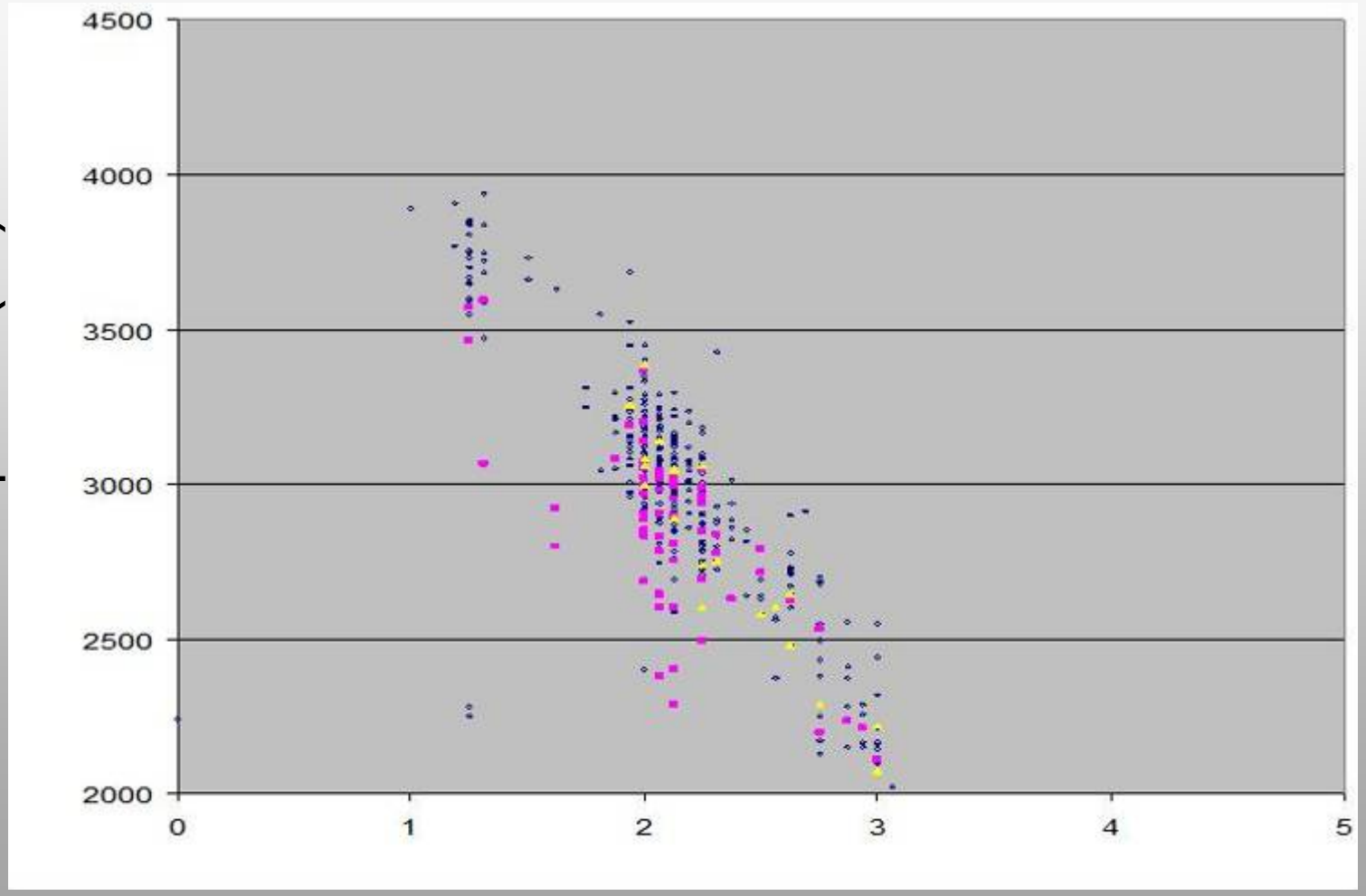
Liftoff Tests Results

- West Point - 109 rods liftoff tested
  - 7 lifted (110k to 115k)
  - 102 did not lift
- R. F. Henry – 90 rods liftoff tested (not all data reviewed)
  - 70 lifted !!!! (99k to 113k)
  - 20 did not lift
- Greenup – 10 tests planned for 2011

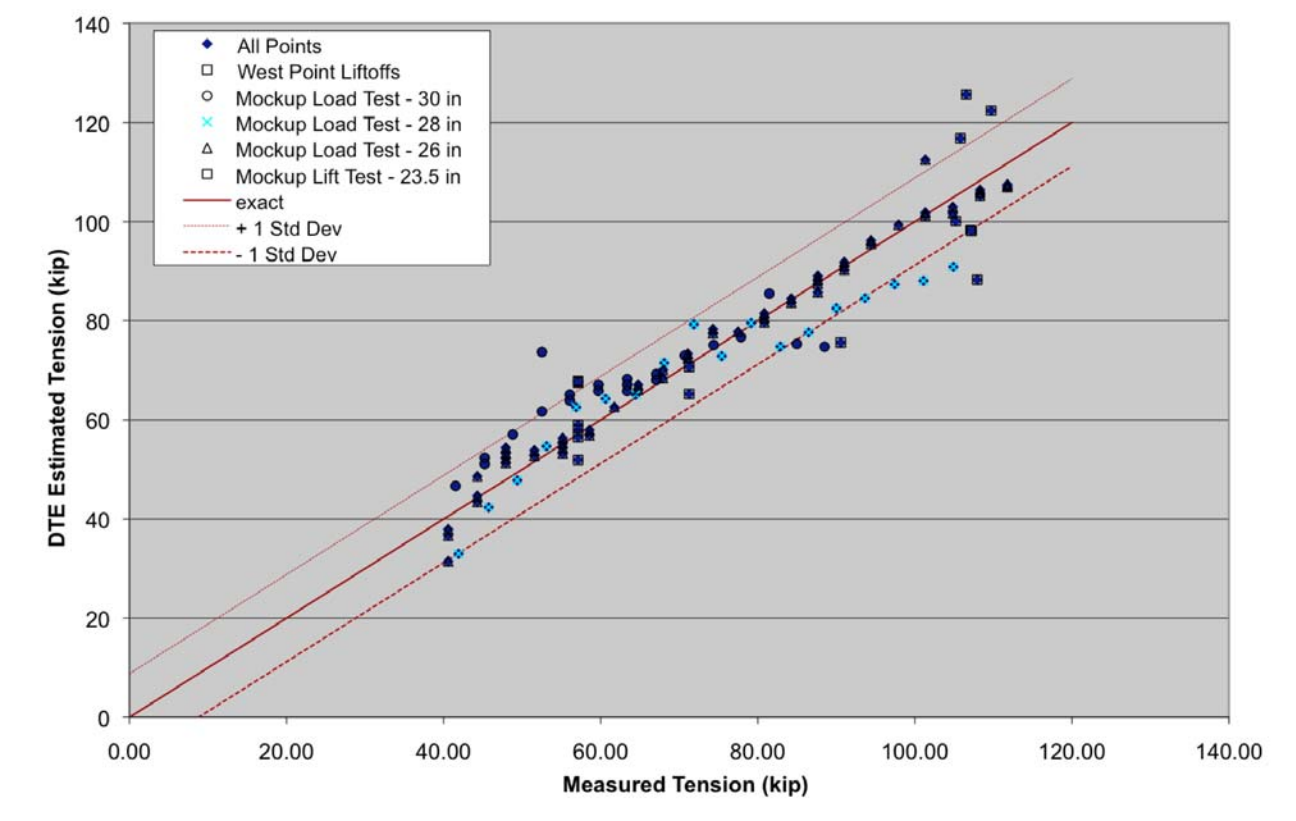
West Point Data



R. F. Henry Data



The Dispersive Tension Equation



An equation relating tension to DWP response

The “DTE” estimated tension with +/- 1 Std. Dev. (+/-8.0 K)

FDH Approach to Trunnion Rods

- Non destructive to rods
  - Widespread lift-off not required (in general)
  - Load in rod never changes
- Low risk to rods and personnel
  - Crews need only access to side of rods
  - Danger zone in front of rod avoided

FDH Approach to Trunnion Rods

- Low impact on operations
  - Temporary structures not needed
  - Crane not needed
- About 1/10 the cost of liftoff testing
- Results +- 7.5 k

Current Approach

- Measure all rods (length and diameter)
- Record lateral acceleration from impact
- Do liftoff tests on 5-10% of rods
- Use Liftoff tests and analytic model to create a calibrated equation (specific to the dam)
- Estimate loads in rods not liftoff tested

Future

- With better modeling and ongoing data collection eliminate need for liftoff tests
- Once liftoff test are done calibration curves and be reused for same dam
- Real time monitoring of vibration frequency (passive test still had useable frequency content)

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Thank you

Modeling the Rods

Beam Finite Element Model of Rod

Simple supports at face of trunnion beam and far end

Additional rotational springs

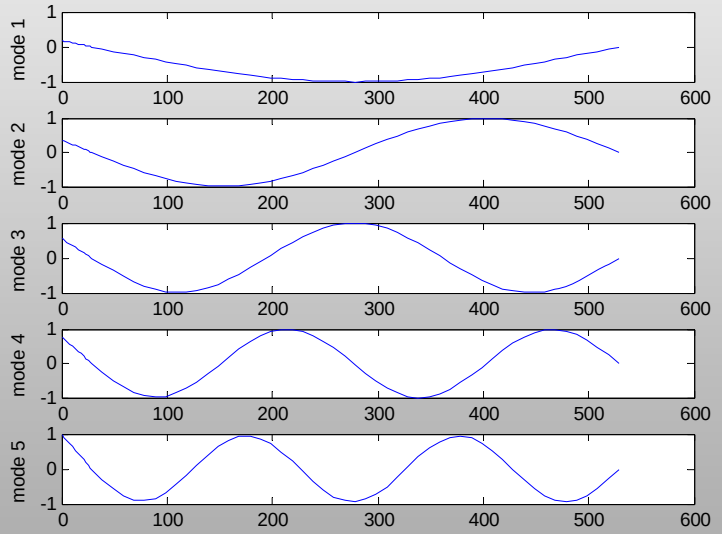
Tension between supports only

Increased thickness for grip nut

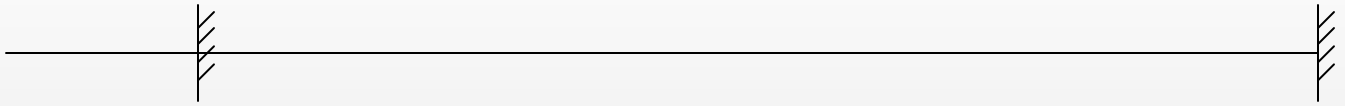
Modal Analysis

Mode Shapes

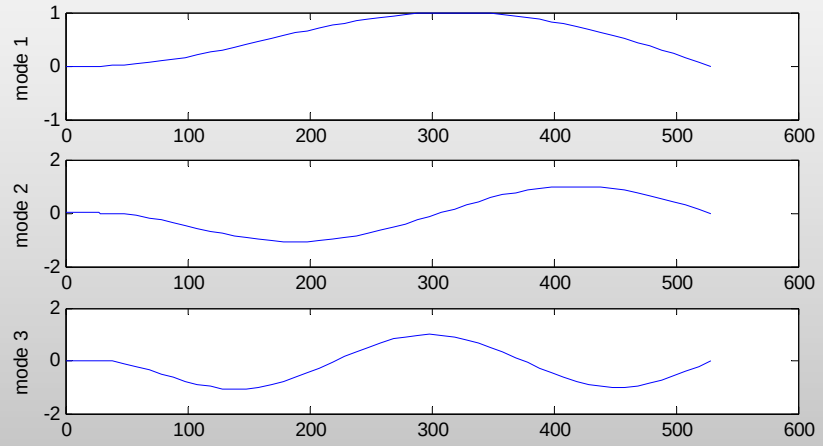
- Pinned connection at grip nut and far end
- Consistent modal frequency spacing
- All modes share cantilever and embedded motion



Mode Shapes



- Fixed connection at grip gut
- Acts like two independent systems



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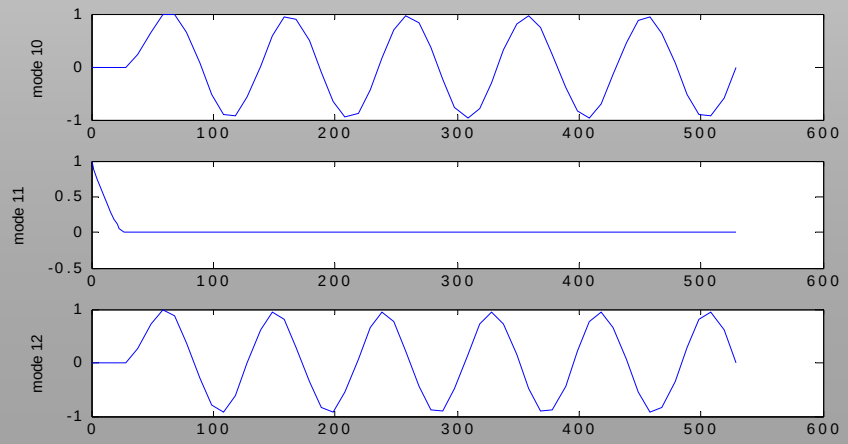
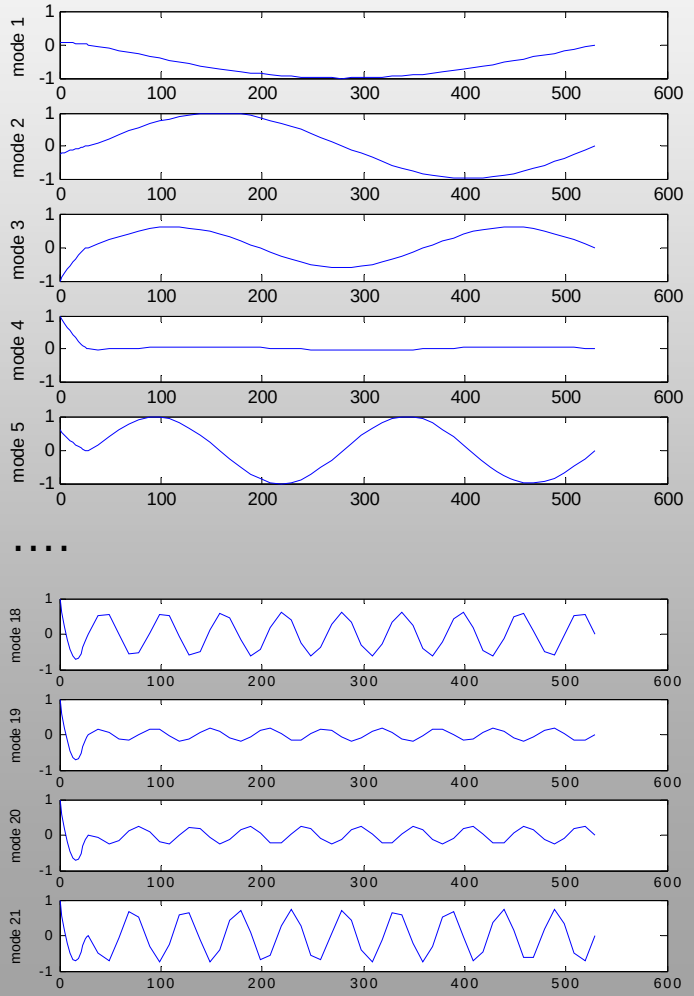


Analysis

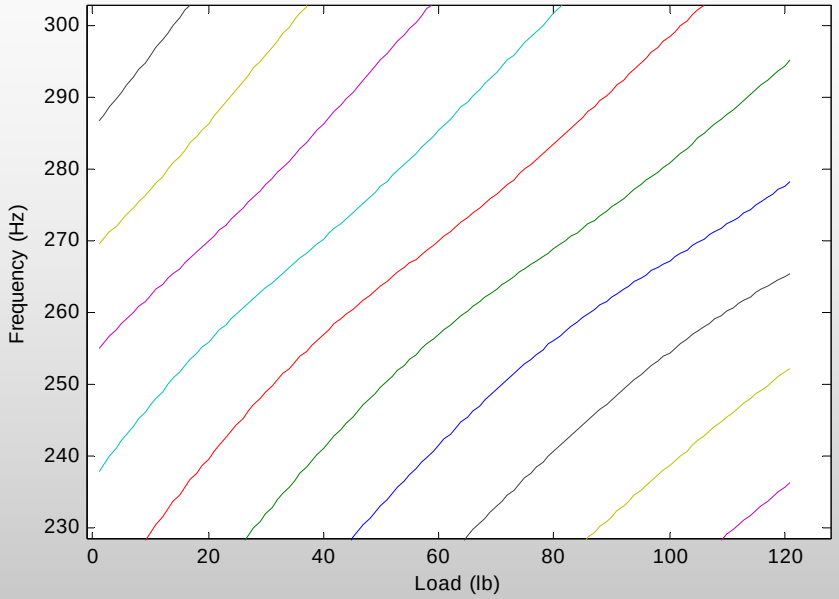
More Mode Shapes

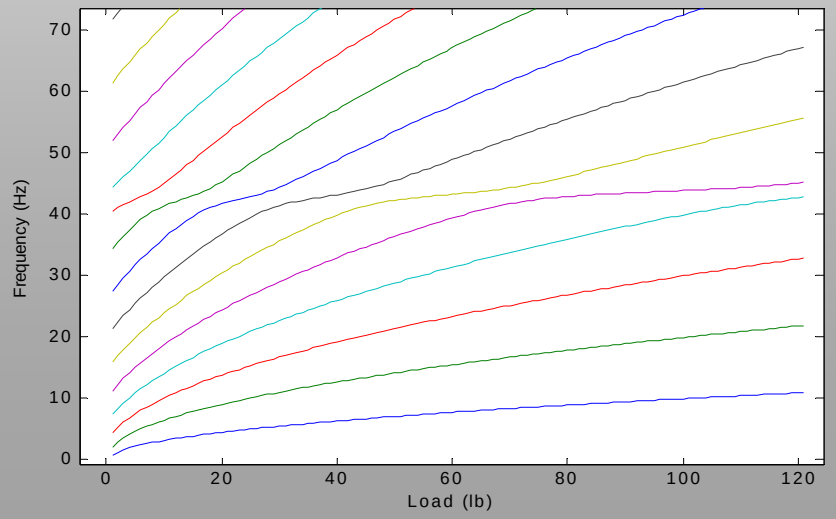
- Semi-flexible grip nut
- Tension
- Some modes dominated by cantilever motion
- Some modes dominated by tensioned portion motion



Modal Frequencies with Tension

- As tension increases each mode takes a turn “Acting” like the cantilever mode





Preliminary Tests

- Built prototype test setups
- Gathered data for proof of concept

Greenup Rods

- Grip nut integral with face plate
- “Insert” directly in face plate

Who we Are and What We Do

- Consulting Engineering / NDT / R&D
- 102 person Firm
- Offices: Raleigh, St. Louis, Baton Rouge

- NDT, Research & Development
- Structural, Geotechnical Engineering
- Hydraulics, Water Resources
- Failure / Forensic Investigations

Failures at West Point Dam

Background

All brittle failures

Flaw size at failure very consistent

Failures between 5 and 15 feet from dead end

What happens when a rod having 115K of tension catastrophically fails?

Slipped Grip Nuts at R. F. Henry

- Two with Grip nut separated from face plate
- One slipped
- Three with brittle failures & ejection.
- Rods were found to be intact

A Methodical Research Project

- FDH approached by Corps in 10/2008 with problem.
- Preliminary experiments on Lab models
- West Point – Feasibility tests (April 2009) – 37 rods
- A Trunnion Assembly Full-Scale Model – Extensive testing
- Collect field data at West Point (376 rods) and RF Henry (476 rods)
- FDH testing / DYWIDAG demonstration lift-off tests on prototype
- Liftoff Testing (West Point & RF Henry - 216 rods)
- Greenup Dam, Greenup, KY testing (one pier)
- Calibration of FDH results = *Dispersive Tension Equation (DTE)*

West Point Dam

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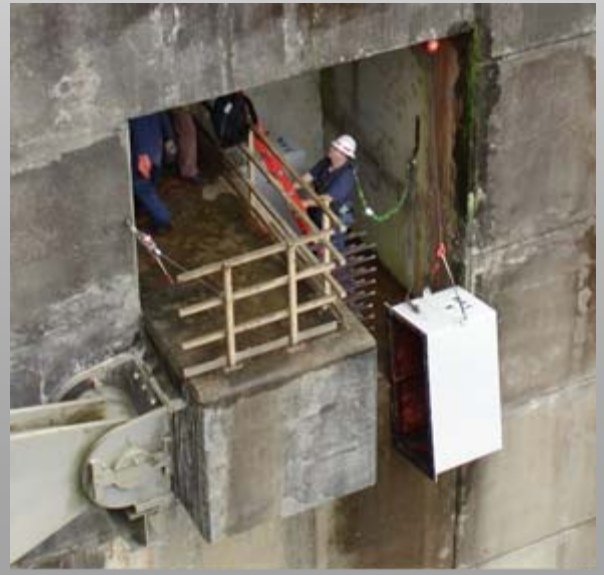
Robert F. Henry Dam

Greenup, KY Dam

West Point Trunnion Rods

26 to 30 inches exposed

Rods accessed through 24” by 12” opening



R. F. Henry Trunnion Rods

21 rods per group
2 groups per Tainter Gate
11 Gates

2 end groups of 7 rods

476 rods total

ASTM A322-64, Grade 5160

1 ¼” Diameter

145k Ultimate Tensile Strength

Anchor plate at far end

Rod Length 412” to 508”

Rods are in tubes w/ NO-OX-ID Grease

Rods from same manufacturer and lot as West Point rods

Trunnion Model Rods

- Various rod lengths
- Couplers to attach actual rod fragments from West Point Dam

Lift-Off Tests

On site practice liftoff tests at FDH facility in Raleigh, NC

- Dorsey & Dorsey
- DYWIDAG
- Corps of Engineers

Preparing for liftoff tests

- Close up of custom (DSI) grip-nut gripper

- Feeler gage checks for stretch in free part of rod

Testing the Rods

- Rods also tested by “Listening” as gates were opened and closed
- Same dominant responses observed
- In fact, same responses observed by just attaching sensors

Modeling the Rods

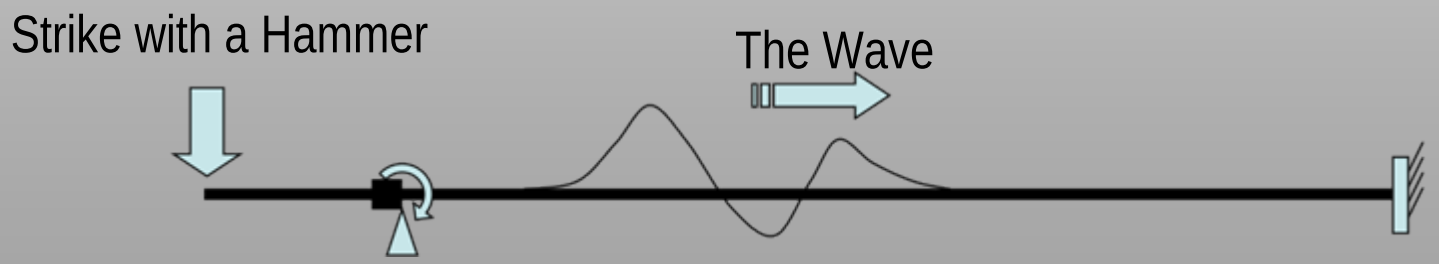
2-D, 3D (future) Beam Finite Element Model of Rod

Simple supports at face of trunnion beam and far end

Additional rotational springs

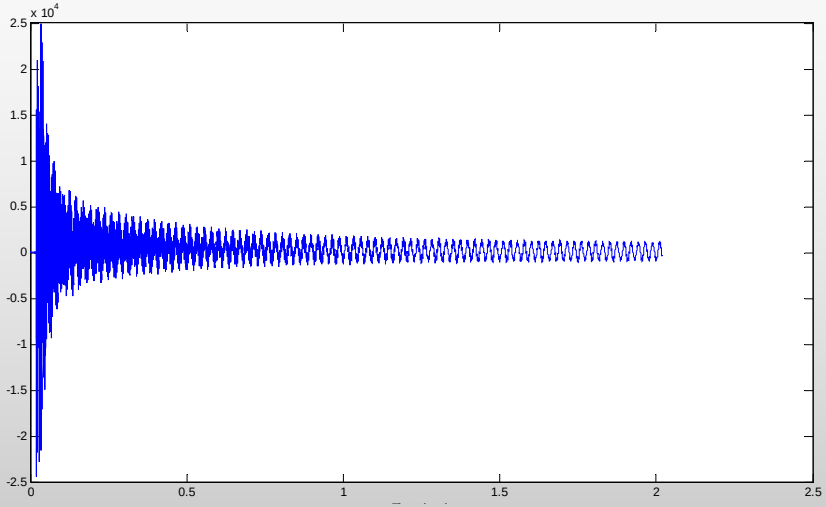
Tension between supports only

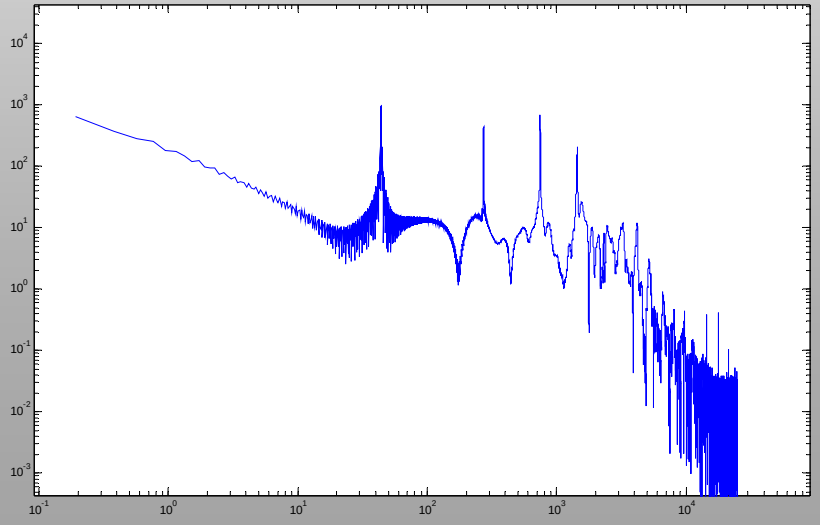
Dispersive Data Analysis



West Point Results

- Collected acceleration time histories of impacts
- Use DWP to find response content
- Identify first dominant modes of motion





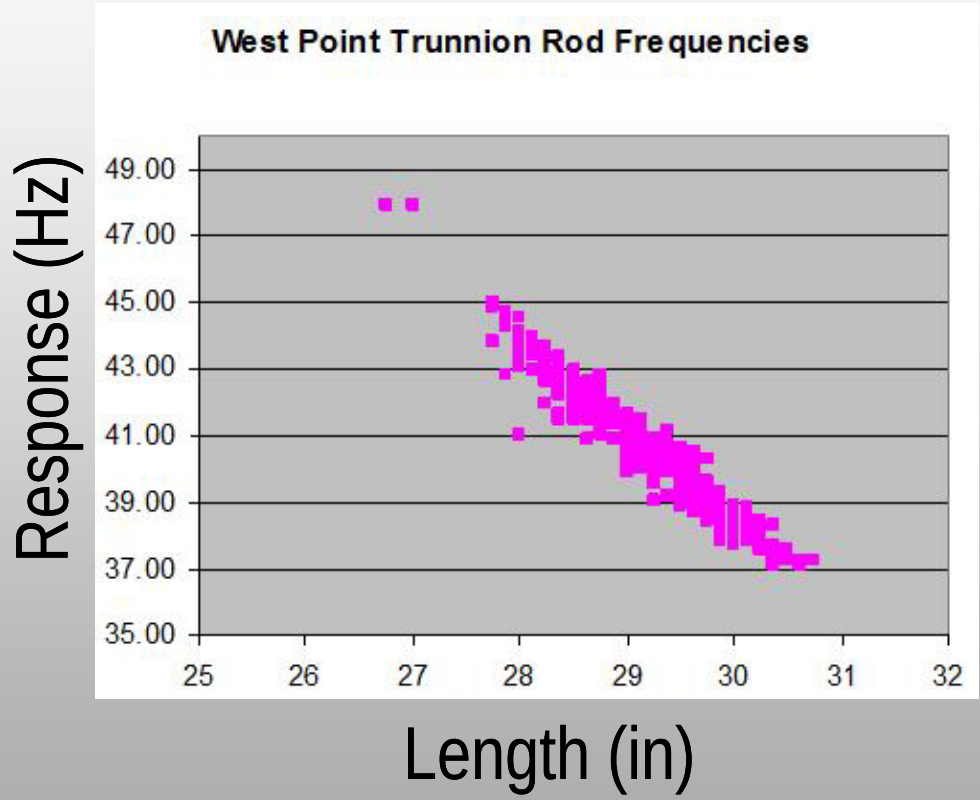
West Point Results

Observed response correlated to exposed length

Two rods are much shorter but appear to fall in line with response

No extreme outliers

All rods appear to be intact

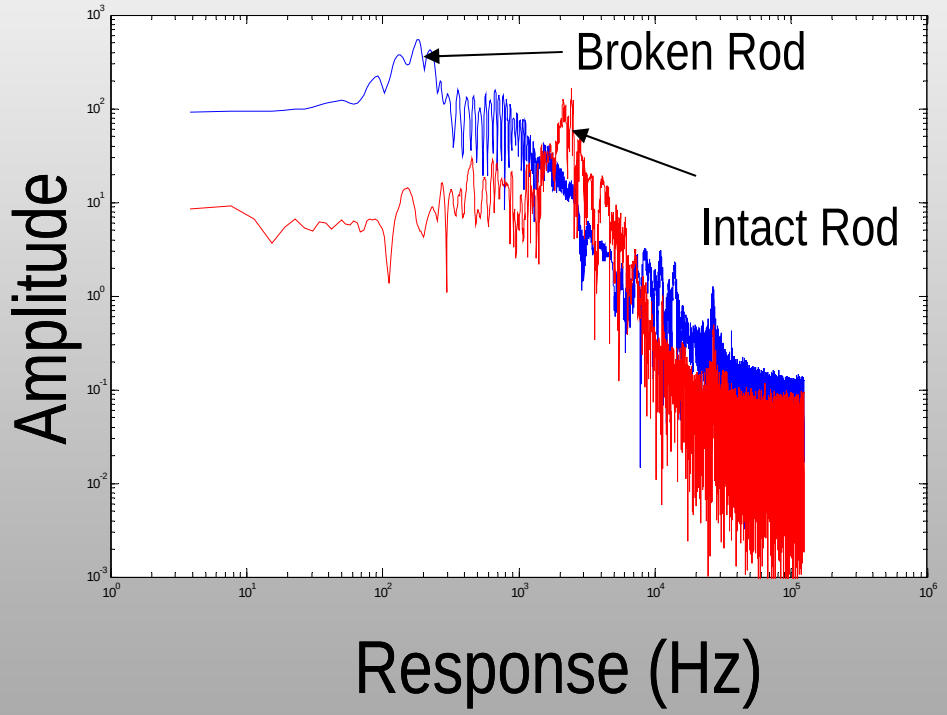


R. F. Henry Dam

R. F. Henry rods have many modes that are close to the live-end response

Clear, single response peaks may not be seen

DWP from broken and intact rods at R. F. Henry show same pattern as no load and fully load case from mockup



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Trunnion Assembly Full-Scale Model

Greenup Trunnion Rods

52 rods per group

2 groups per Tainter Gate

Only 1 pier tested

1 1/8” Diameter

~125,000 lb tensile capacity

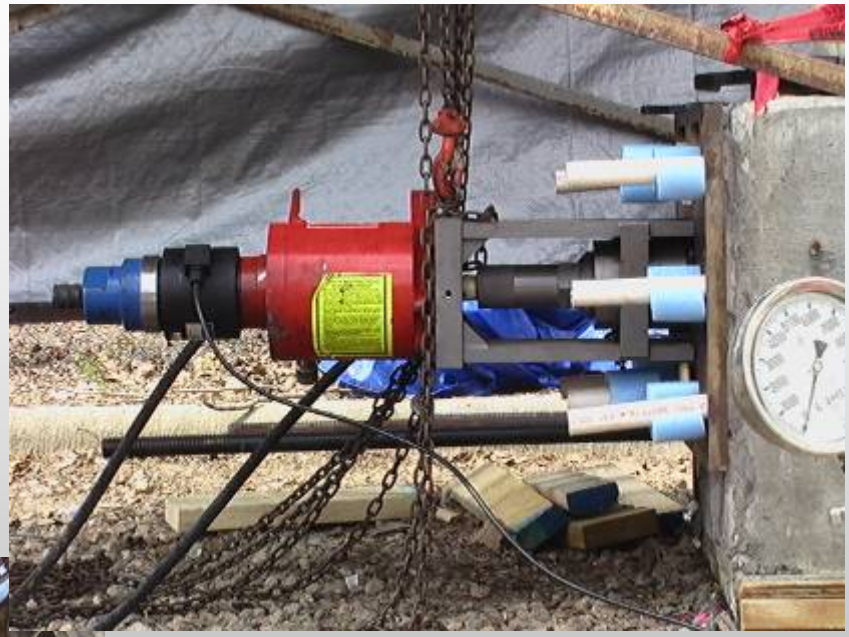
Anchor plate at far end

All rods same length (924”)

Rods are in tubes with NO-OX-ID Grease

Preparing for Field Lift-Off Tests

- West Point tests simulated (below)
- 28 inch rods
- Actual Rod salvaged from West Point



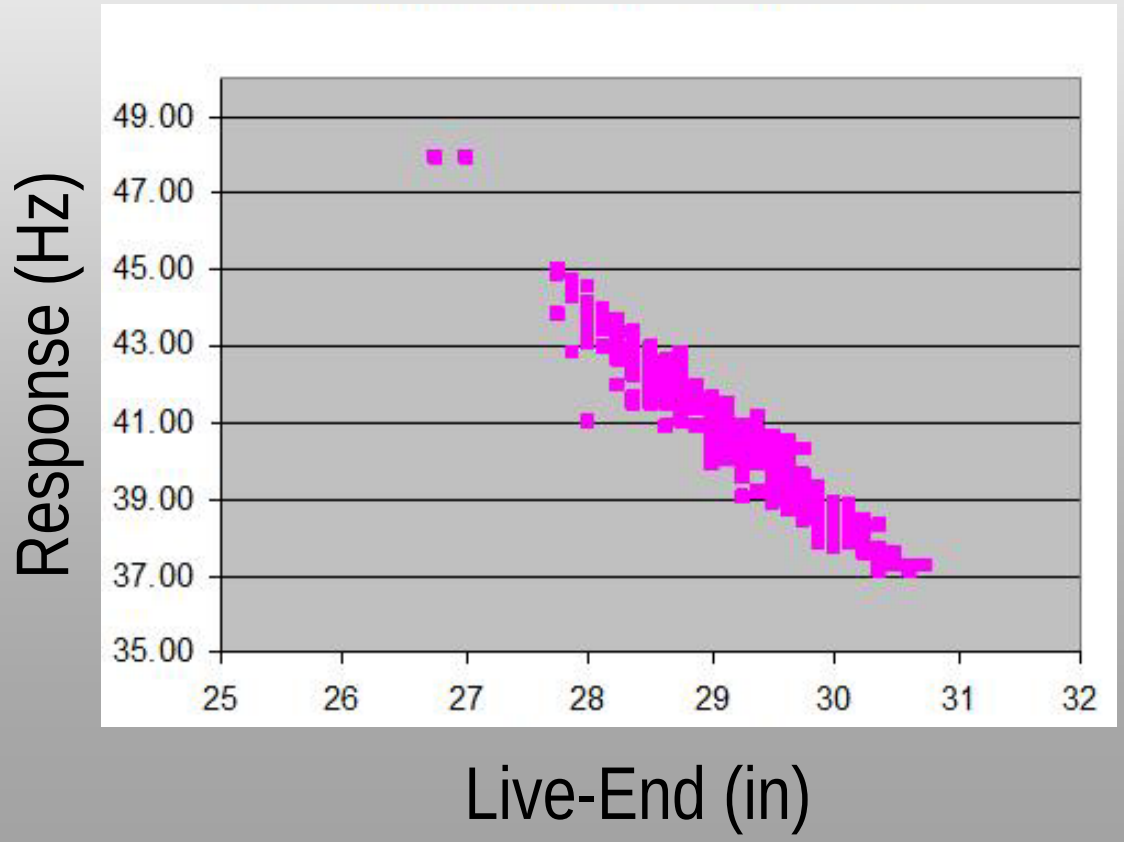
- R. F. Henry tests simulated (above)
- 2-4 inch rods
- Gripper attaches to grip nut NOT rod directly

West Point Results

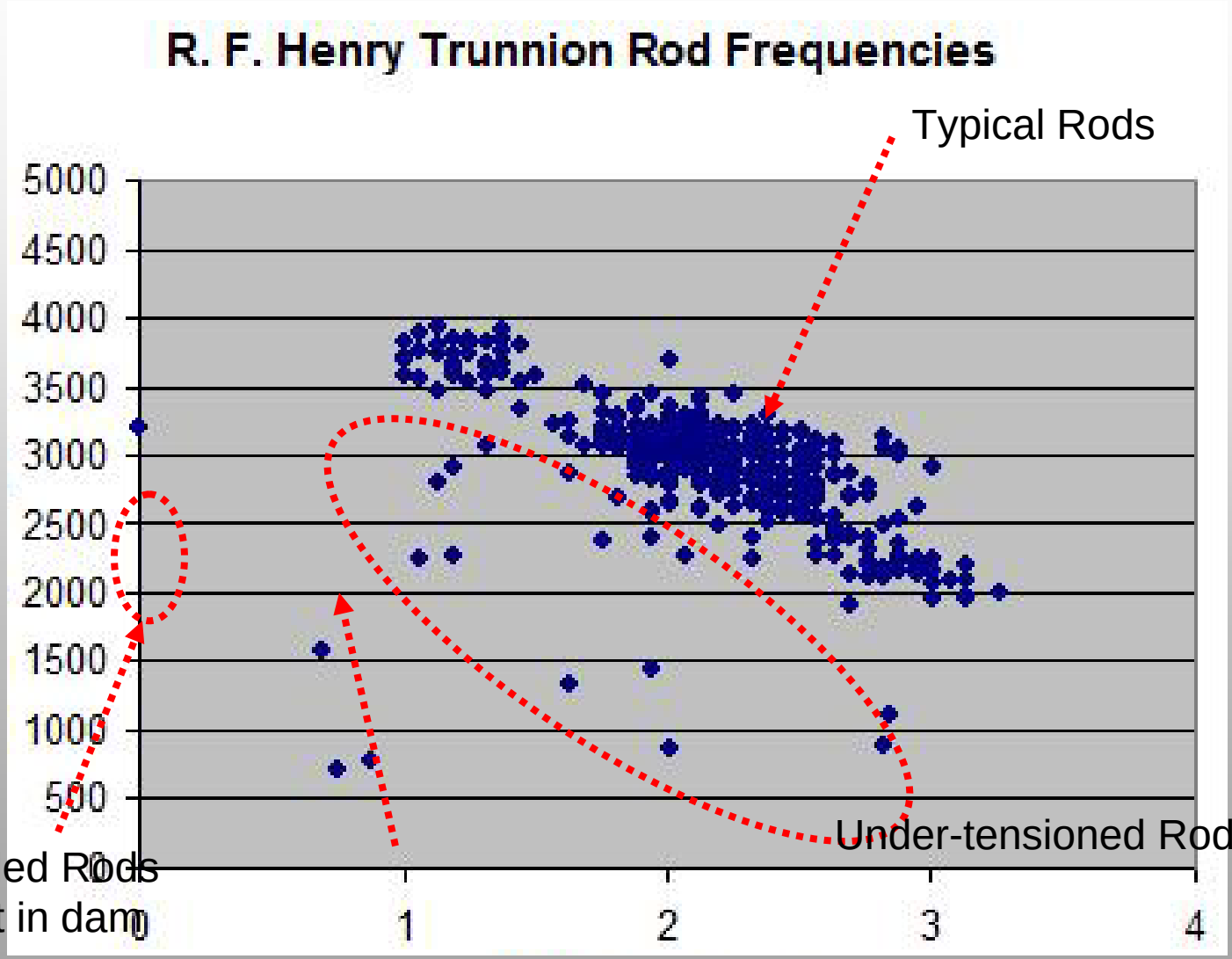
Observed response correlated to exposed length

No extreme outliers

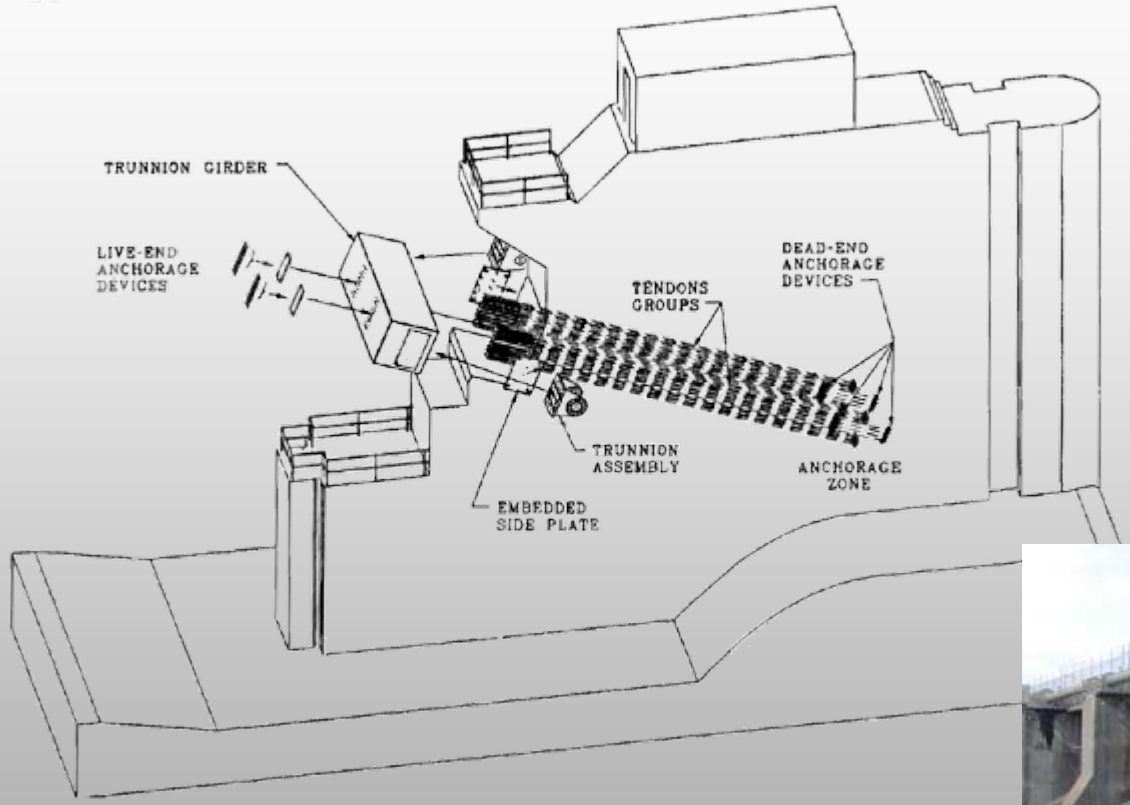
All rods appear to be intact



Robert F. Henry Results



Trunnion Anchor Rod Assembly



Transfers Tainter gate forces to dam.

Upwards to 115K post-tension load.