Hydraulic Mechanisms of Concrete-Tie Rail-Seat Deterioration

William W. Hay Seminar

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ASSOCIATION OF AMERICAN RAILROADS

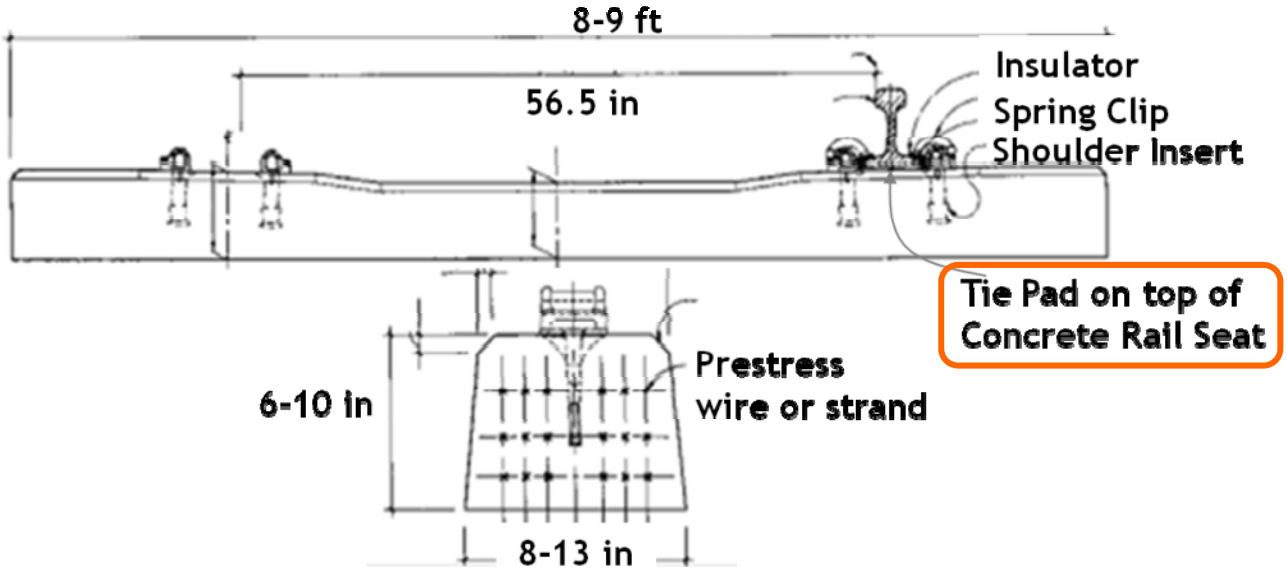
ILLINOIS
RAILROAD ENGINEERING PROGRAM

Outline

- Concrete ties
- Rail seat deterioration (RSD)
- Hydraulic mechanisms of RSD
  - Hydraulic pressure cracking
  - Hydro-abrasive erosion
  - Cavitation erosion
- Laboratory experiments
  - Load tests
  - Uplift tests
- Conclusions and tie pad design
- Future concrete tie research at Illinois

Concrete Ties

- Prestressed concrete crossties, part of ballasted track structure
- Basic functions:
  - Support train loads and distribute loads to ballast
  - Stabilize the rails to maintain safe track geometry
  - Electrically isolate the rails for the track circuit



Concrete Ties for Heavy Haul Railroads

- Freight lines with high annual traffic, curvature, and axle loads use concrete ties
- Promising alternative to traditional timber ties
  - Concrete ties have higher initial cost in North America
  - Concrete ties should have longer service life and require less maintenance – lower life-cycle cost

Concrete Tie Failures

Rail Seat Positive Cracking

Center Negative Cracking
(Center Binding)

Derailment Damage

Concrete Tie Failures

Yielded (Sprung) Clip

Tie Pad Degradation

Rail Seat Deterioration

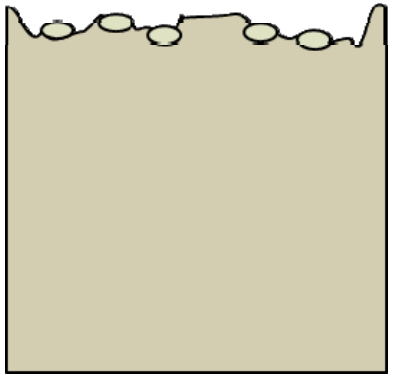
2008 Survey of Class I Railroads

Most Critical Concrete Tie Problems	Average Rank
Rail seat deterioration (RSD)	6.83
Shoulder/fastener wear or fatigue	6.67
Derailment damage	4.83
Cracking from center binding	4.58
Cracking from dynamic loads	1.83
Tamping damage	1.83
Other (ex: manufactured defect)	1.33
Cracking from environmental or chemical degradation	1.25

Rail Seat Deterioration (RSD)

- Degradation under the rail on a concrete tie
- Also “rail seat abrasion”
- Leads to track geometry problems and damage of fastening components
- Difficult to detect without lifting the rail
- Increases maintenance costs and shortens service life of the tie

Severe Examples



Causes of RSD

	High Stresses at Rail Seat	Relative Motion at Rail Seat	Presence of Moisture	Presence of Abrasive Fines
Internal Factors	• Loss of proper rail cant	• Looseness of fastening system (loss of toe load) • Scrubbing action	• Tie pad seal • Concrete saturation	• Tie pad seal • Fines from wear of rail seat components
External Factors	• High vertical loads • High L/V ratio • High longitudinal loads • Poor load distribution among adjacent ties	• Uplift action • Lateral action • Longitudinal action	• Climate	• Environment • Track maintenance • Train operations

Concrete Deterioration Mechanisms

Potential Mechanisms	High Stresses at Rail Seat	Relative Motion at Rail Seat	Presence of Moisture	Presence of Abrasive Fines
Abrasion	✓	✓	✓	✓
Crushing	✓	✓	✓	
Freeze-Thaw			✓	
Hydraulic Pressure	✓	✓	✓	
Hydro-Abrasive Erosion	✓	✓	✓	✓
Cavitation Erosion			✓	

Hydraulic Mechanisms = Theories

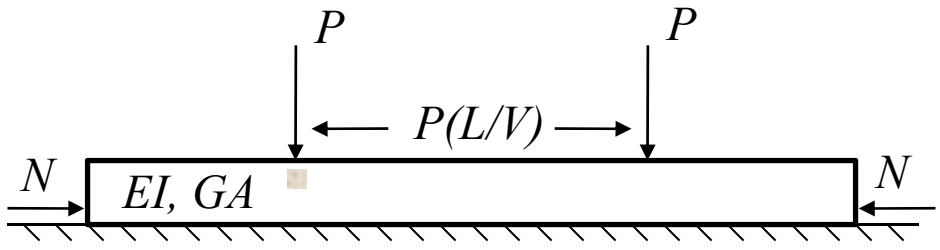
- The hydraulic mechanisms require the presence of moisture between the tie pad and the rail seat
  - Are these mechanisms feasible?
  - If so, how to mitigate these mechanisms?
- **Hydraulic Pressure Cracking** – load creates high pressure that causes tensile cracking in the concrete
- **Hydro-Abrasive Erosion** – load accelerates water and suspended-particles to high velocity, causing wear on the surface
- **Cavitation Erosion** – rail uplift lowers pressure until water cavitates, and the resulting vapor bubbles collapse and damage the surface

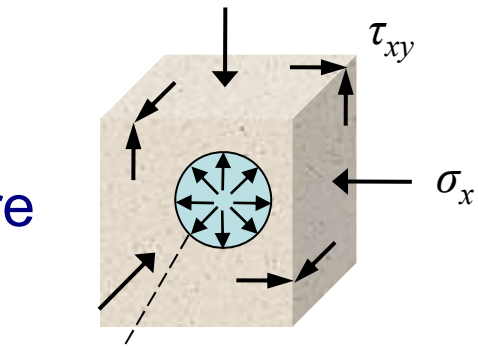
Hydraulic Pressure Cracking

- Modeled state of stress:
  - Elastic stress distribution
  - Beam on an elastic foundation
- Modeled pore water pressure as a function of the surface water pressure
- Compare effective stress with tensile strength of concrete (700 psi)

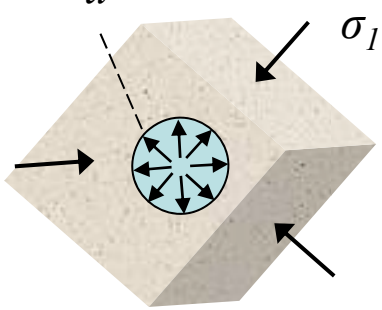
Effective Stress = σ – u

Elastic Stress Models





State of Stress, xyz



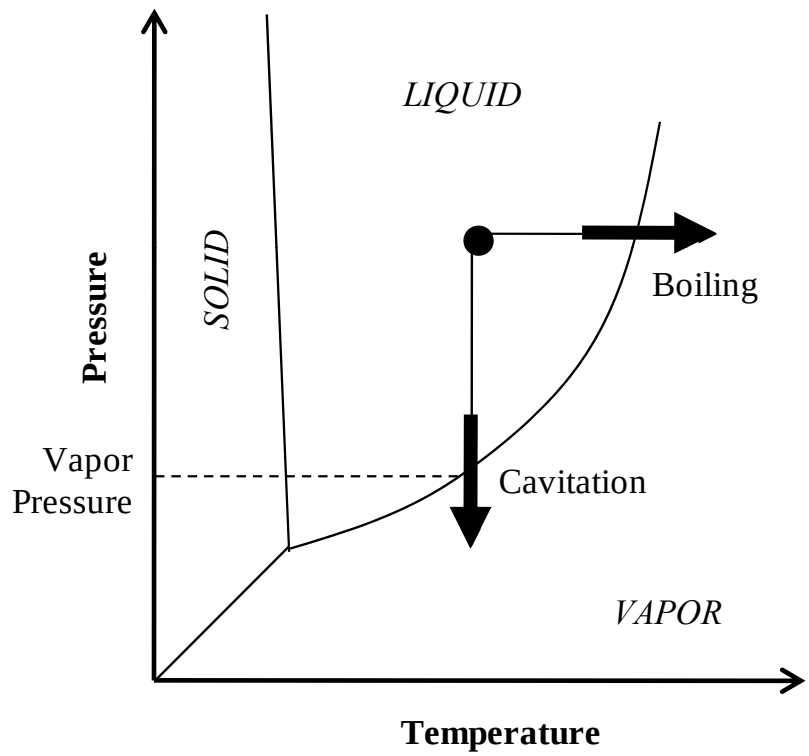
Principal State of Stress

Hydro-Abrasive Erosion

- Erosion rate depends on
  - Velocity of water and suspended particles
  - Angle of impact with the surface
  - Concentration of suspended particles
  - Particle size, shape, and hardness
- Erosion due to high-velocity water or particles
  - Critical water velocity ~ 400 ft/s
  - Critical particle velocity ~ 165 ft/s
  - Particle velocity could be 60-72% of the water velocity

Cavitation Erosion

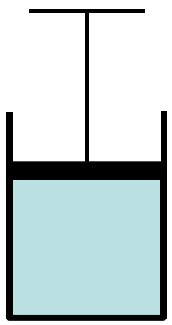
1. Drop in pressure to vapor pressure (-14.3 psig)
2. Air bubbles form (0.5-10 mm diameter)
   - Internal pressure ~ -14.3 psig
     - Unstable
3. Bubbles collapse rapidly
   - Collapse pressure depends on:
     - Initial size of bubble
     - Surrounding water pressure
   - Pressure up to millions of psi

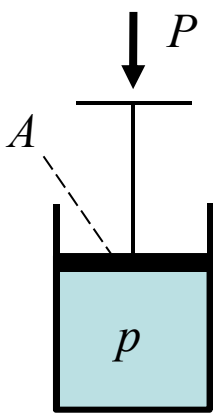


Sealing: Pressure vs. Velocity

- Consider ideal situations in order to frame the problem
  - Water inside a rigid piston chamber
- The applied load transfers energy to the water
  - Water energy is in the form of pressure or velocity
    - Bernoulli's equation for pipe flow:

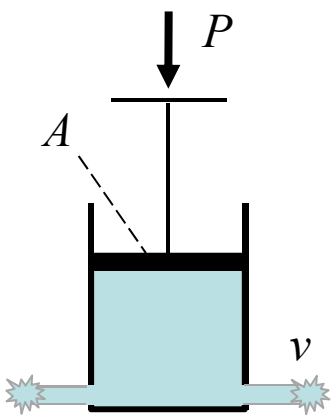
$$p + \tfrac{1}{2}\rho v^2 = \frac{P}{A}$$





Perfect Seal

$$p = \frac{P}{A}$$



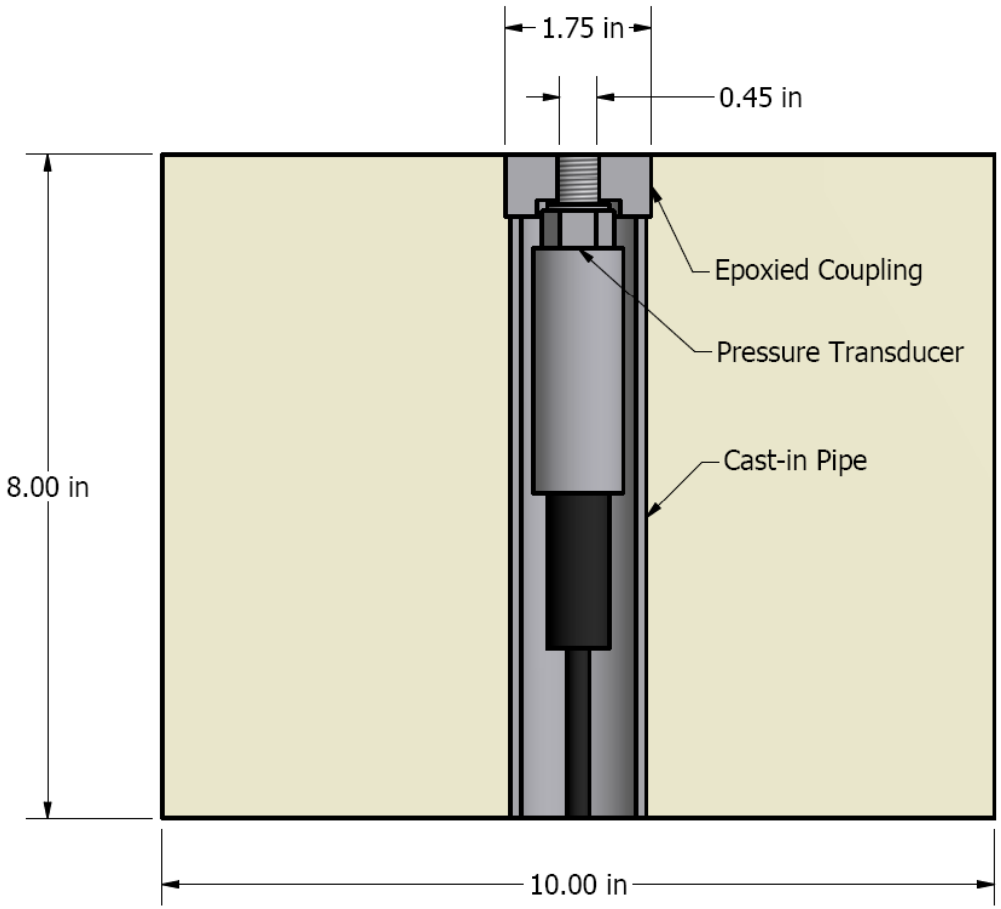
No Seal

$$v = \sqrt{\frac{2P}{\rho A}}$$

Concept behind Laboratory Tests

- Measure water pressure at the rail seat surface in the laboratory
  - Test on blocks of concrete instead of full ties, but maintain full-scale tie pads and loads
  - Measure the potential for wear, not the actual wear
- Treat the load (down-stroke) and uplift (up-stroke) separately
  - **Load Tests:**
    - Hydraulic pressure cracking
    - Hydro-abrasive erosion
  - **Uplift Tests:**
    - Cavitation erosion

Instrumented Concrete Block

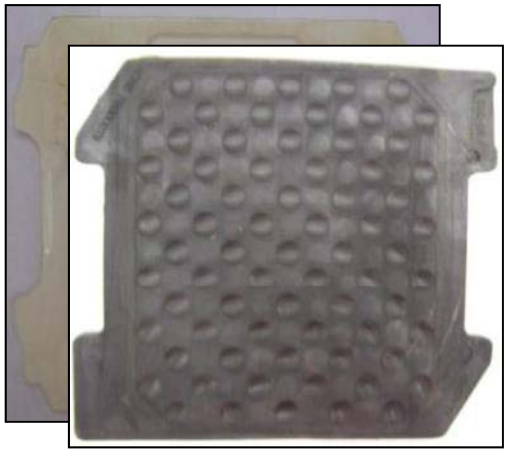


Cross-section of the design

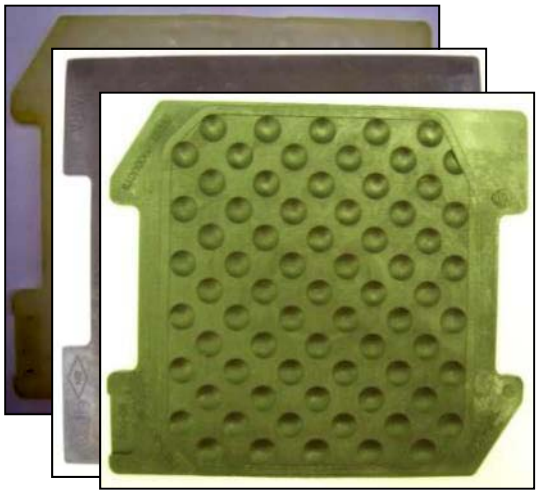
Finished block

Tie Pads and Pad Assemblies

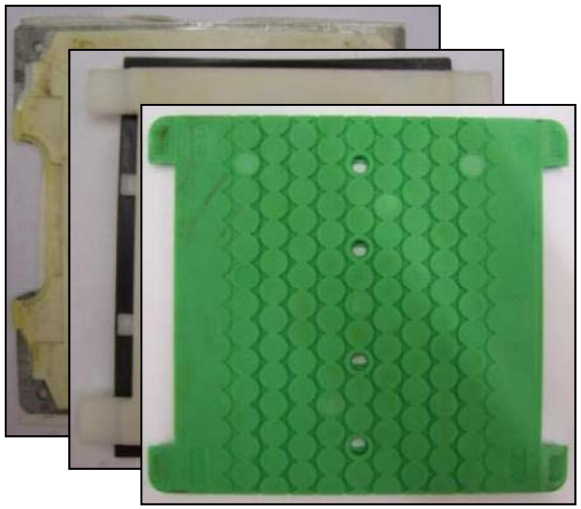
- Thermoplastic pads: polyurethane, santoprene rubber, EVA
- Surface geometries: flat, grooved, dimpled, studded
- 2-part or 3-part assemblies contain steel or plastic layer
- Varying compressibility, flexural rigidity, and hardness



Flexible Pads

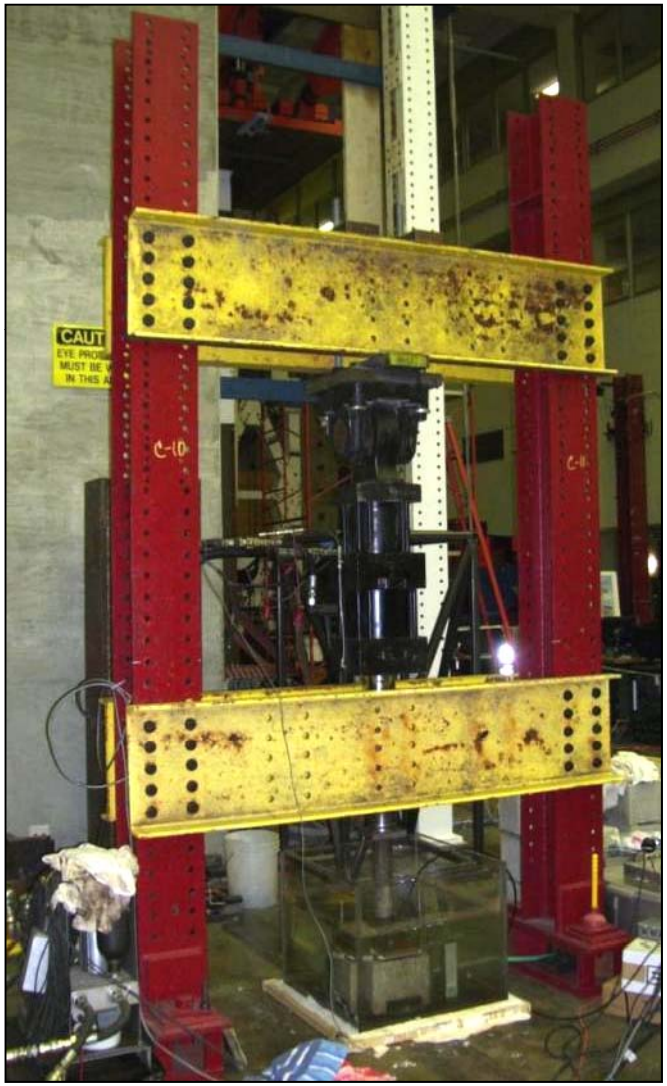


Semi-rigid Pads



Pad Assemblies,
Rigid Layer

Test Setup

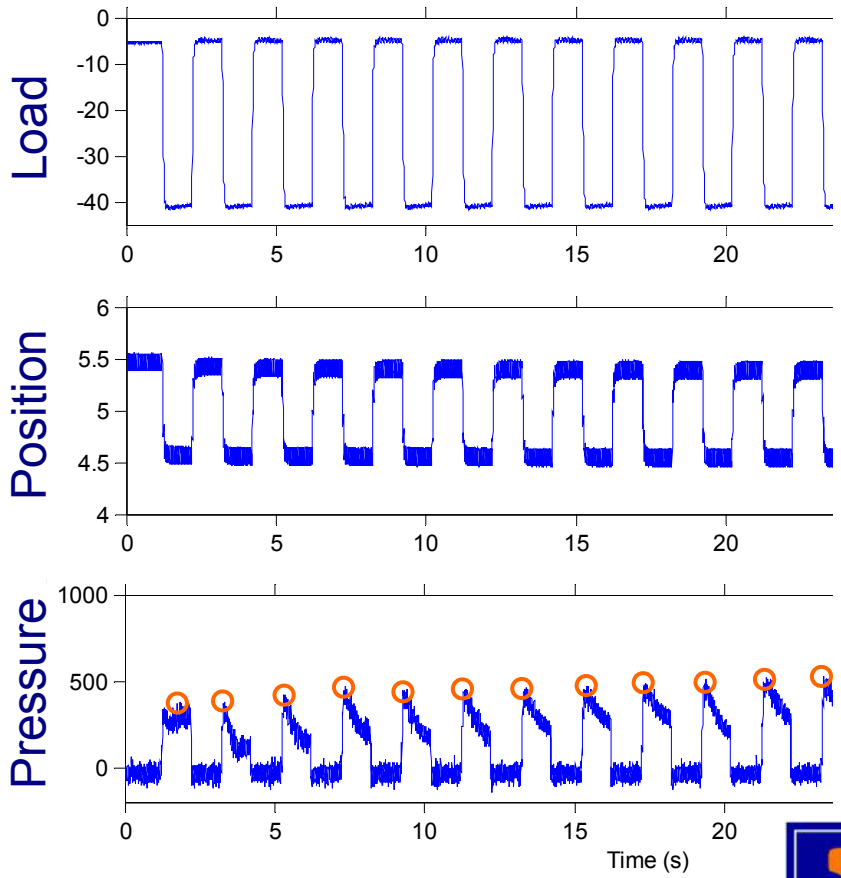


Steel-based, plexiglass water tank

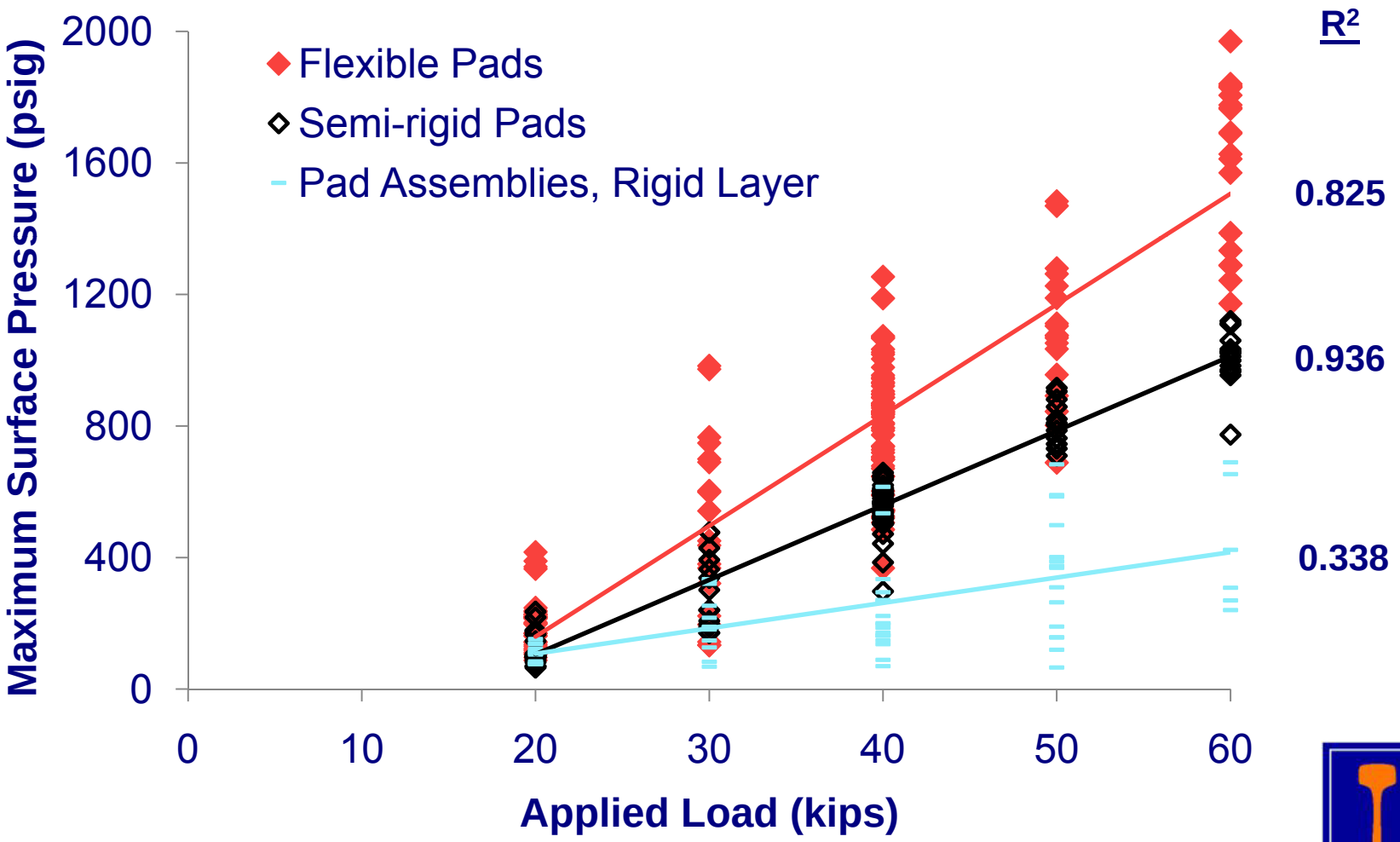
100-kip MTS servo-hydraulic actuator,
10 gpm servovalve
Measured force, displacement, acceleration

Load Test Procedure

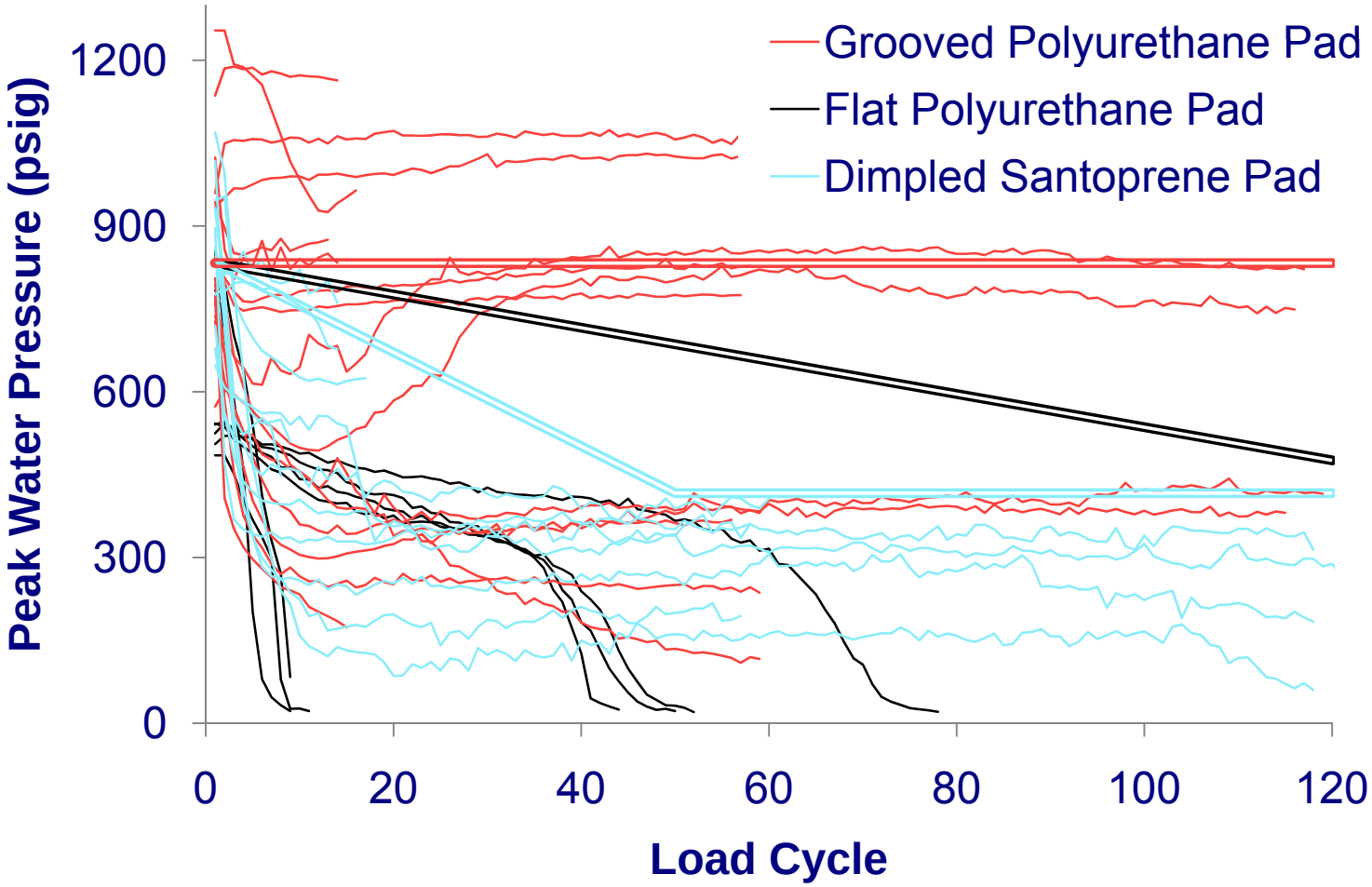
- Load-control mode
- Variables:
  - Tie pad
  - Max load
    - 20-60 kips
    - 20-kip static rail seat load
  - Waveform
    - Loading rate



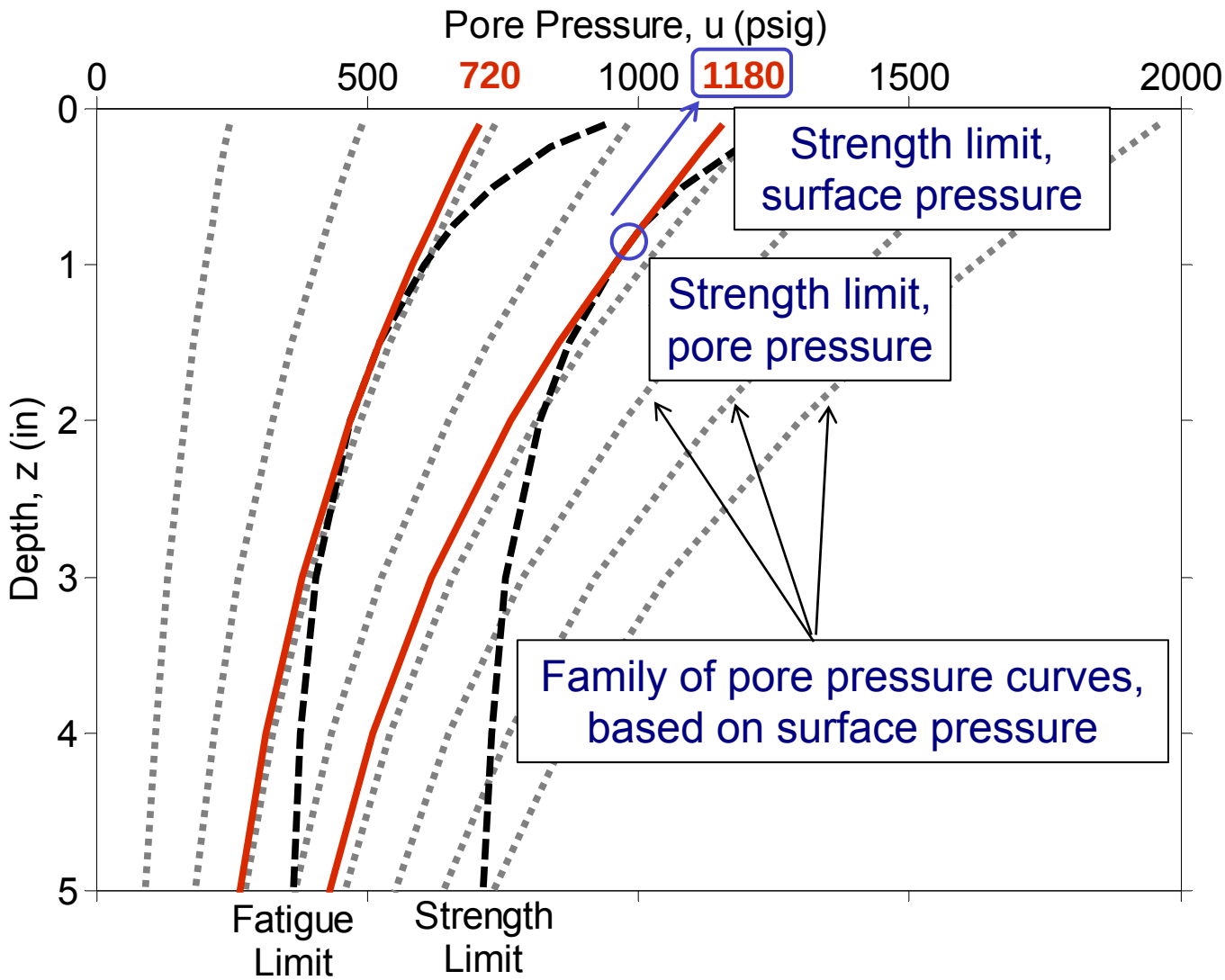
Pressure vs. Load, All Trials



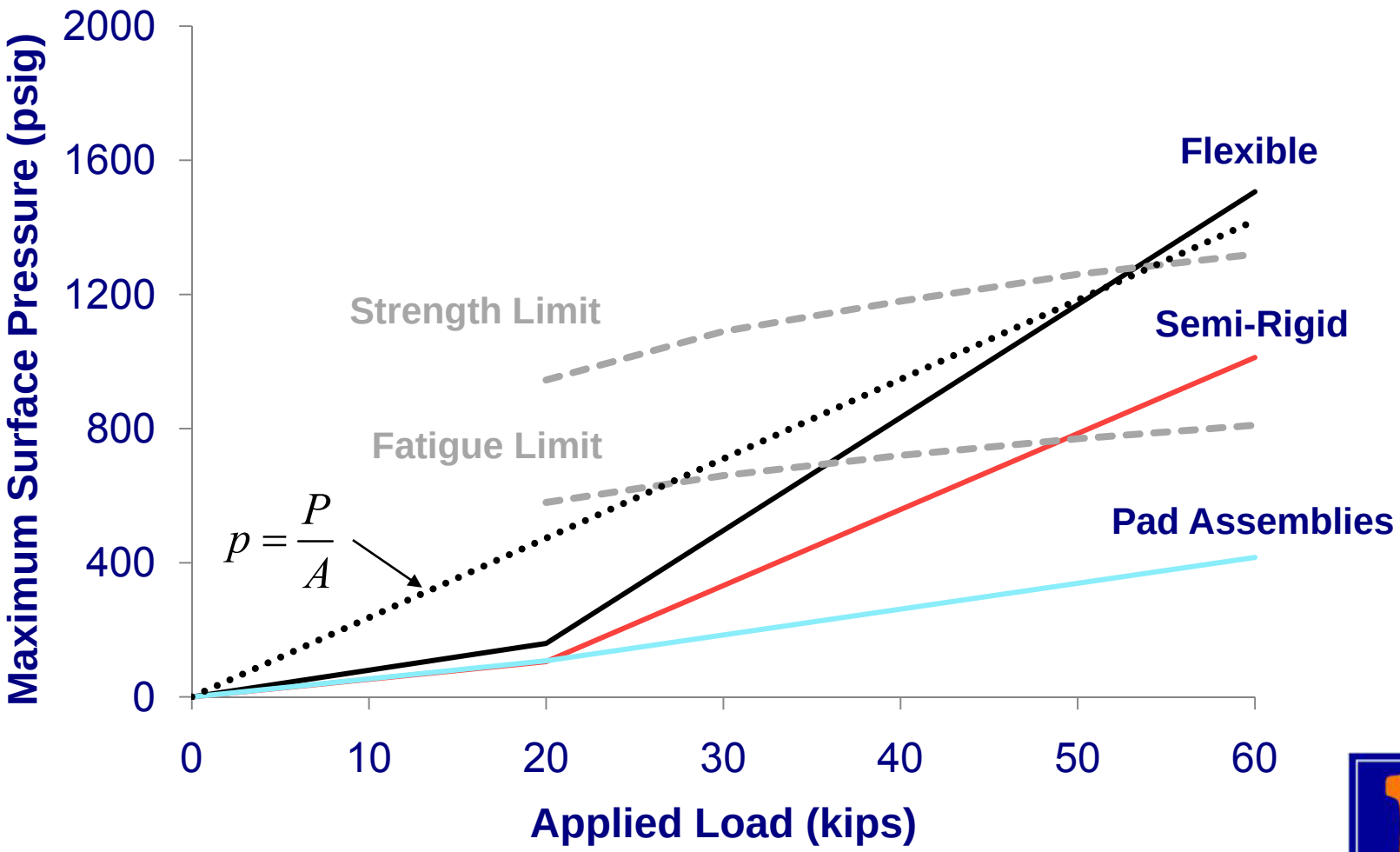
Pressure vs. Cycles, Flexible Pads, 40 kips



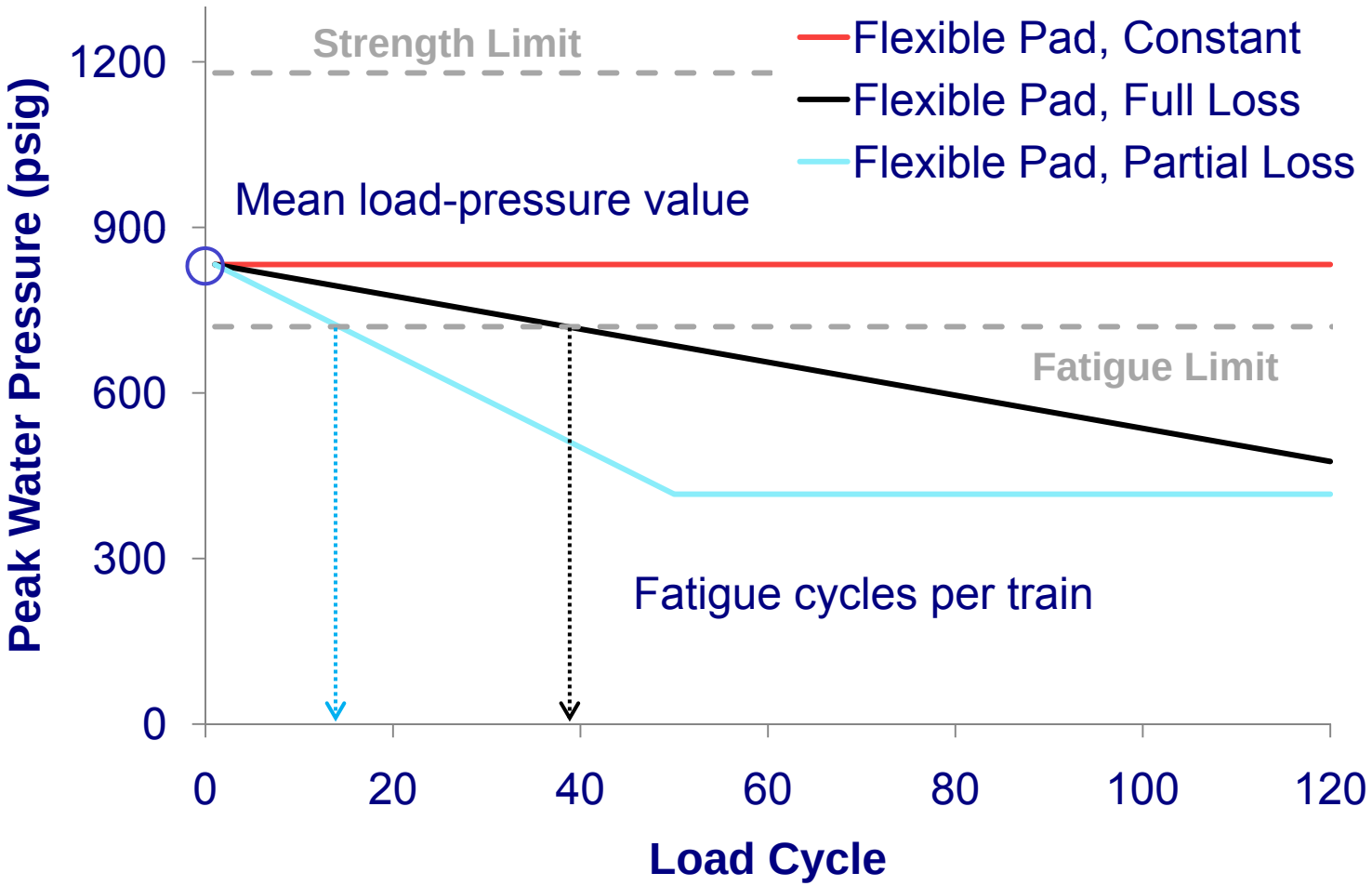
Concrete Damage Limits, 40 kips



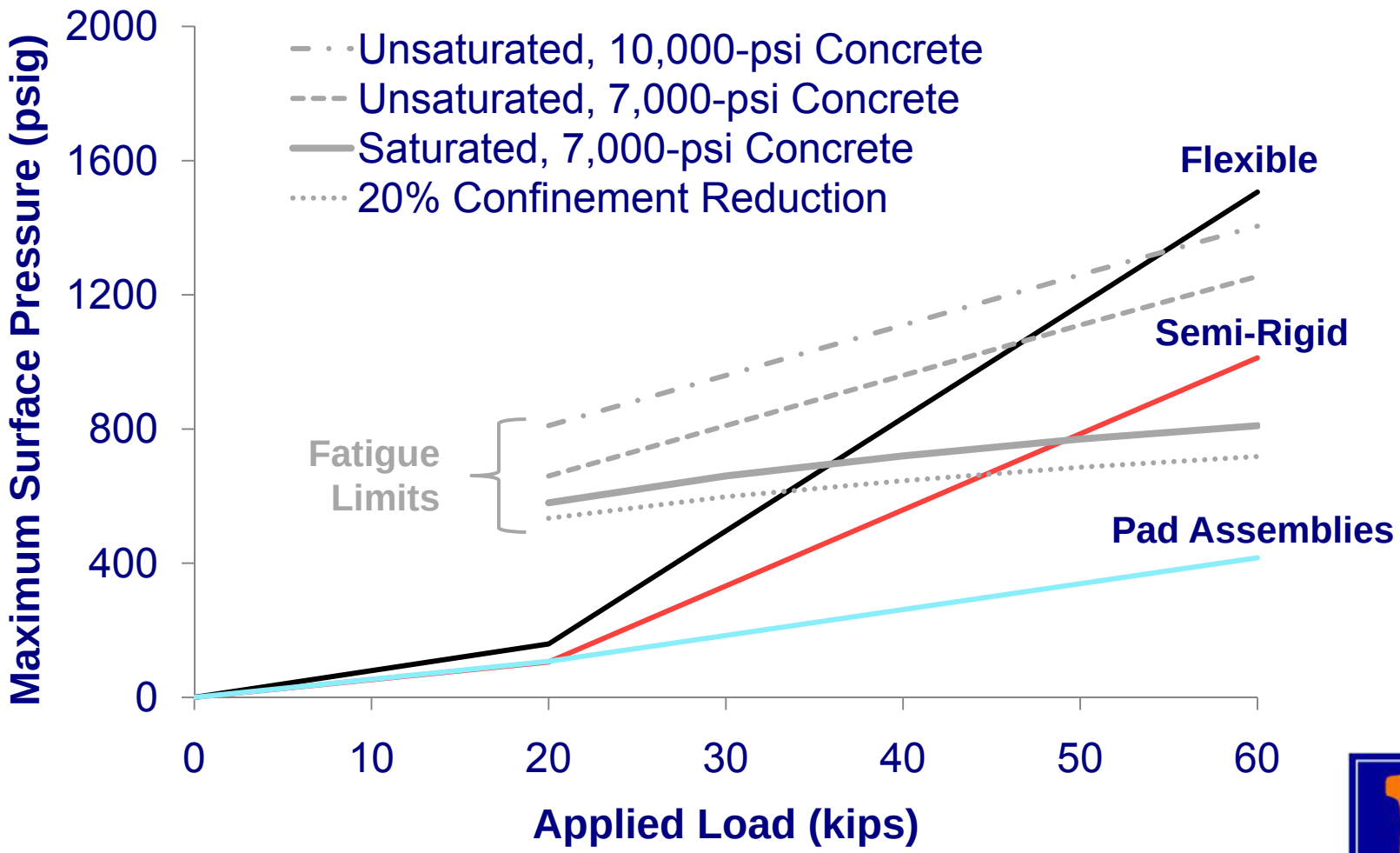
Damage Limits and Mean Regression Lines



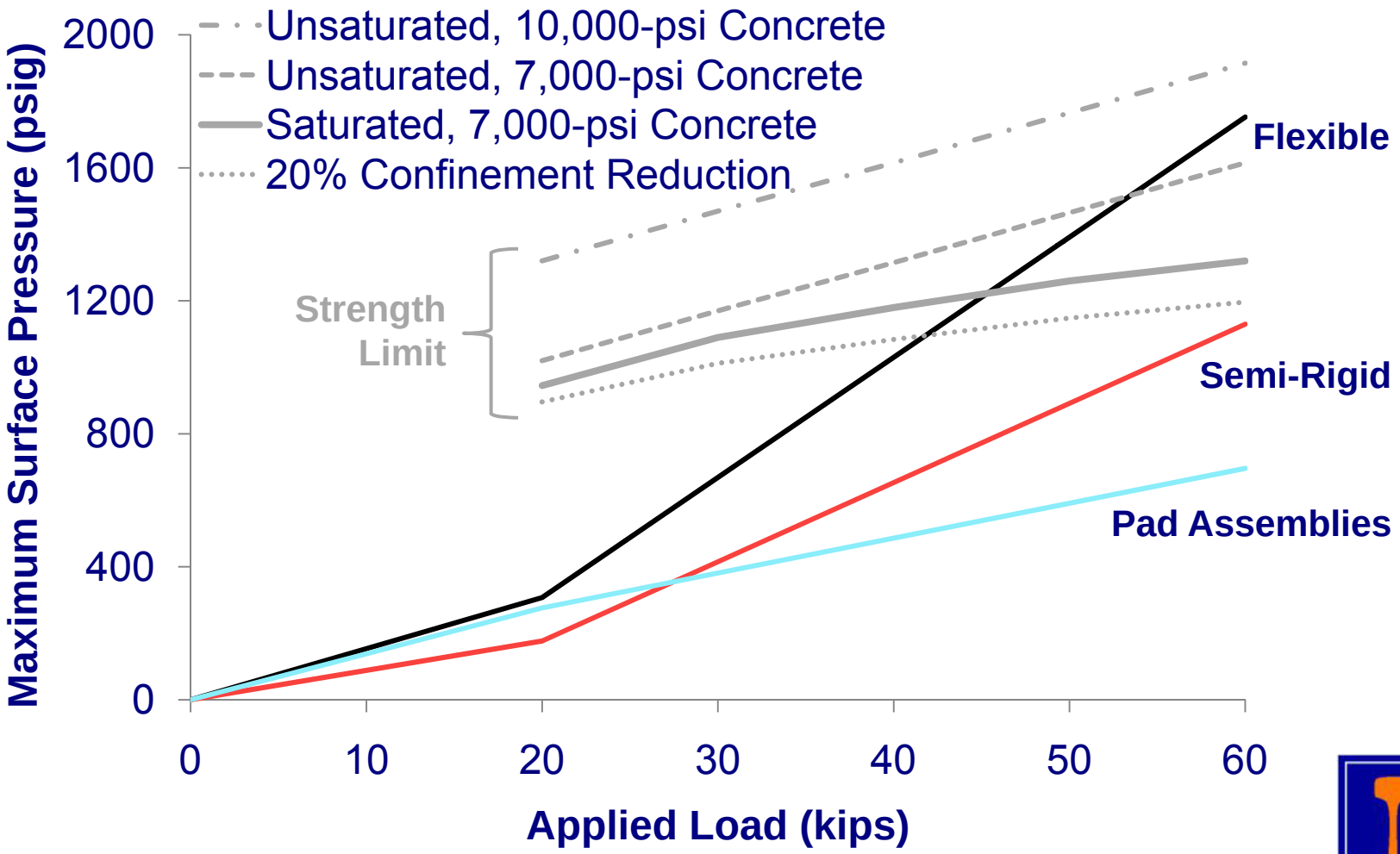
Damage Limits and Load Cycle Envelopes, 40 kips



Sensitivity of Fatigue Limit, Mean Pressure



Sensitivity of Strength Limit, Upper 95% Pressure



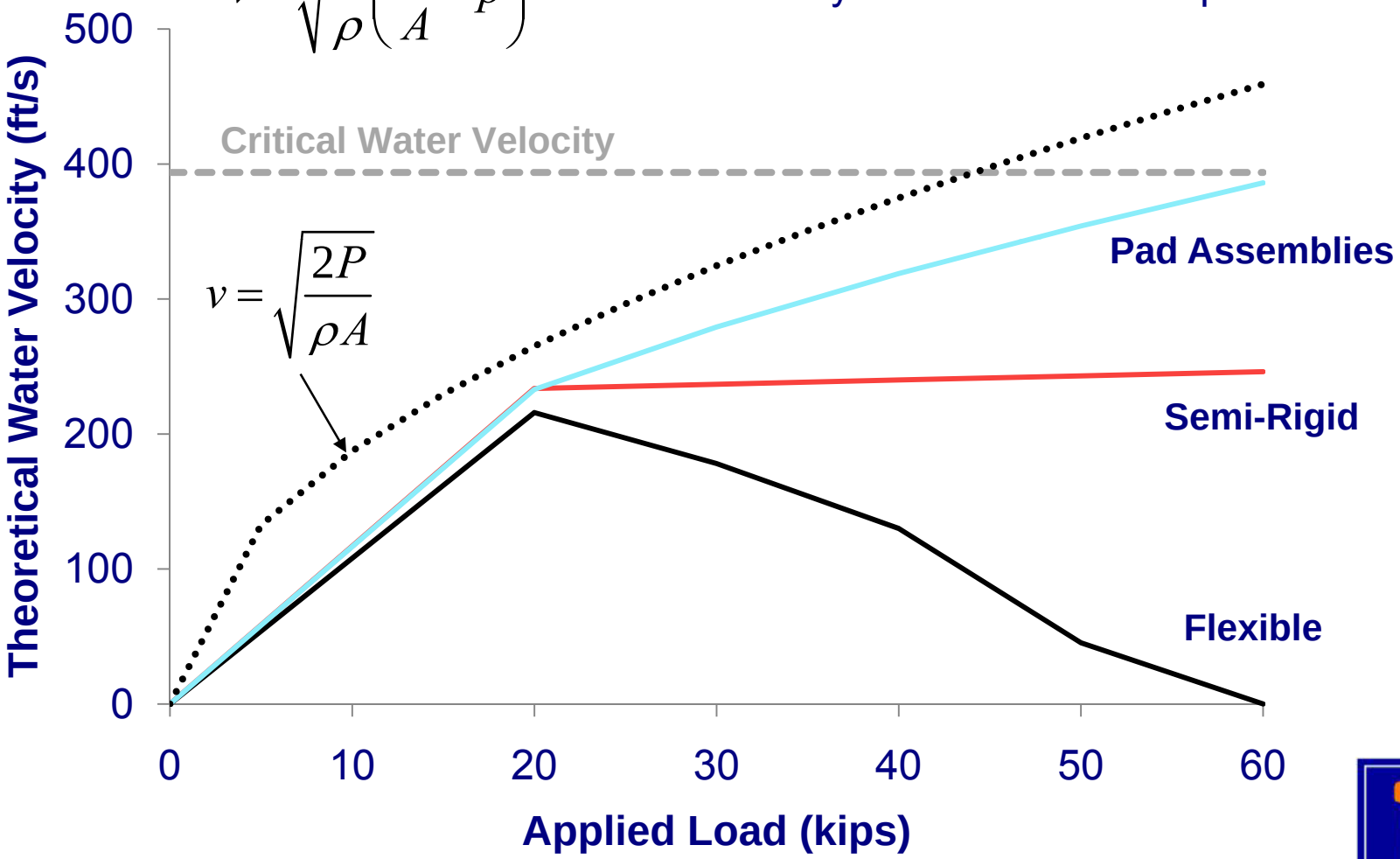
Estimations of Fatigue Damage Potential

- Assumptions:
  - 100-MGT line
  - 120-car coal trains
  - 286-kip gross car load
  - 7,000-psi concrete
  - Saturated concrete 50 days of the year
  - Wet, unsaturated concrete 100 days of the year
- Worst-case pad: grooved polyurethane
  - Flexible pad = high pressure
  - No loss of pressure with load cycles
- **2003** WILD distribution: **14 years** to 1 million fatigue cycles
- **2008** WILD distribution: **182 years** to 1 million fatigue cycles

Theoretical Water Velocity from Mean Pressure

$$v = \sqrt{\frac{2}{\rho}\left(\frac{P}{A} - p\right)}$$

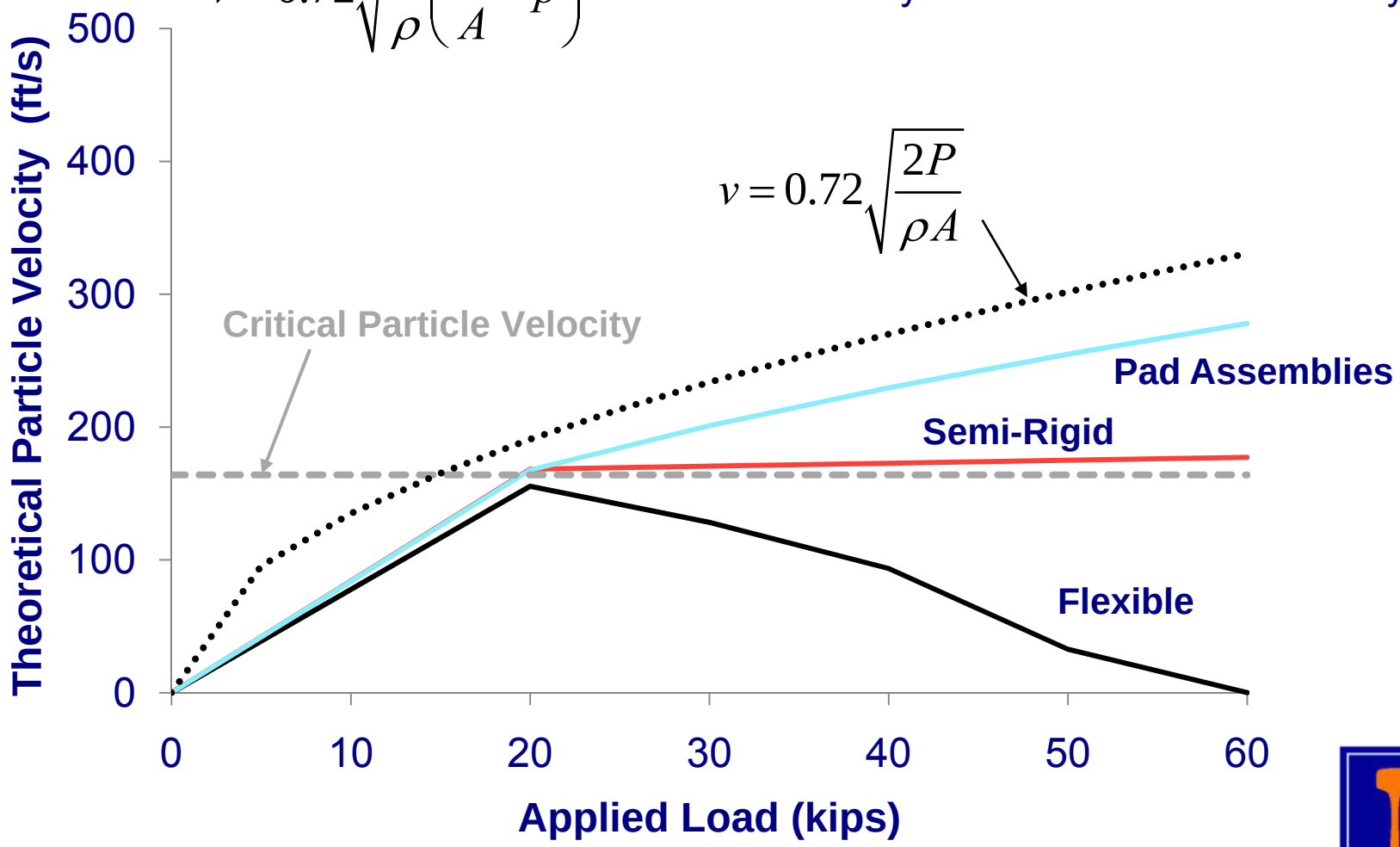
Water velocity from Bernoulli's equation



Potential for Hydro-Abrasive Erosion

$$v = 0.72\sqrt{\frac{2}{\rho}\left(\frac{P}{A} - p\right)}$$

Particle velocity scaled from water velocity

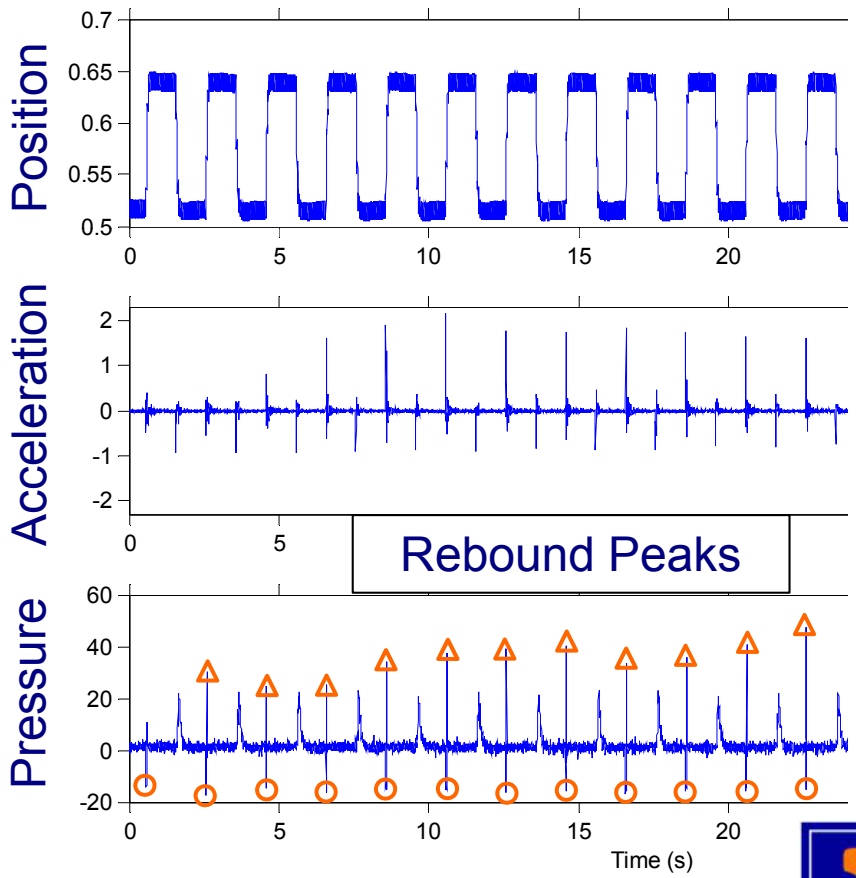


Conclusions from the Load Tests

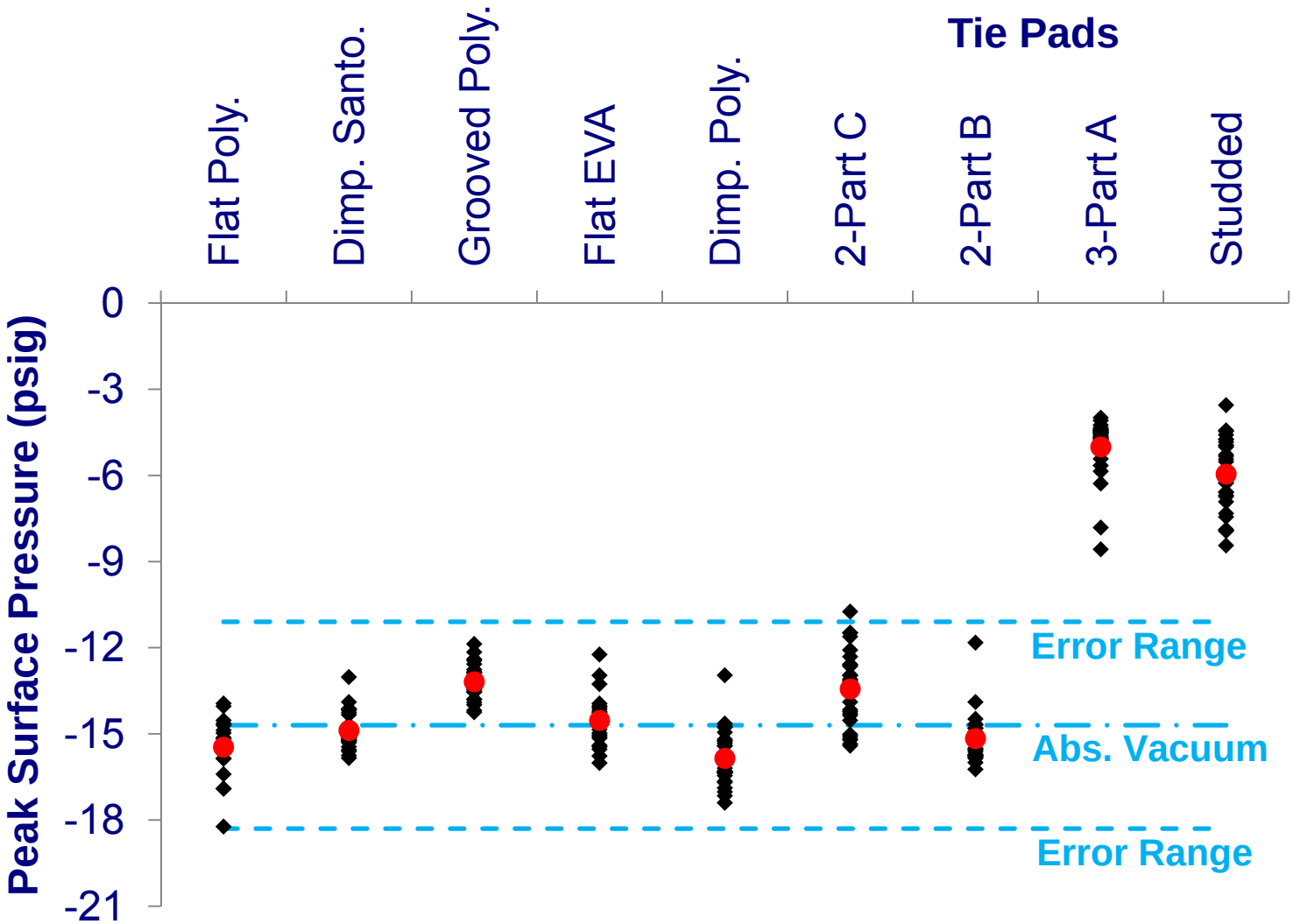
- Hydraulic pressure cracking is feasible; effectively mitigate with
  - Tie pad that does not seal water
  - Low frequency of high impact loads
  - High-strength, air-entrained, low permeability concrete
- Hydro-abrasive erosion appears to be feasible
  - Would mitigate with a sealing tie pad
    - Conflicts with mitigation of hydraulic pressure cracking
  - Needs further study before recommendations can be made

Uplift Test Procedure

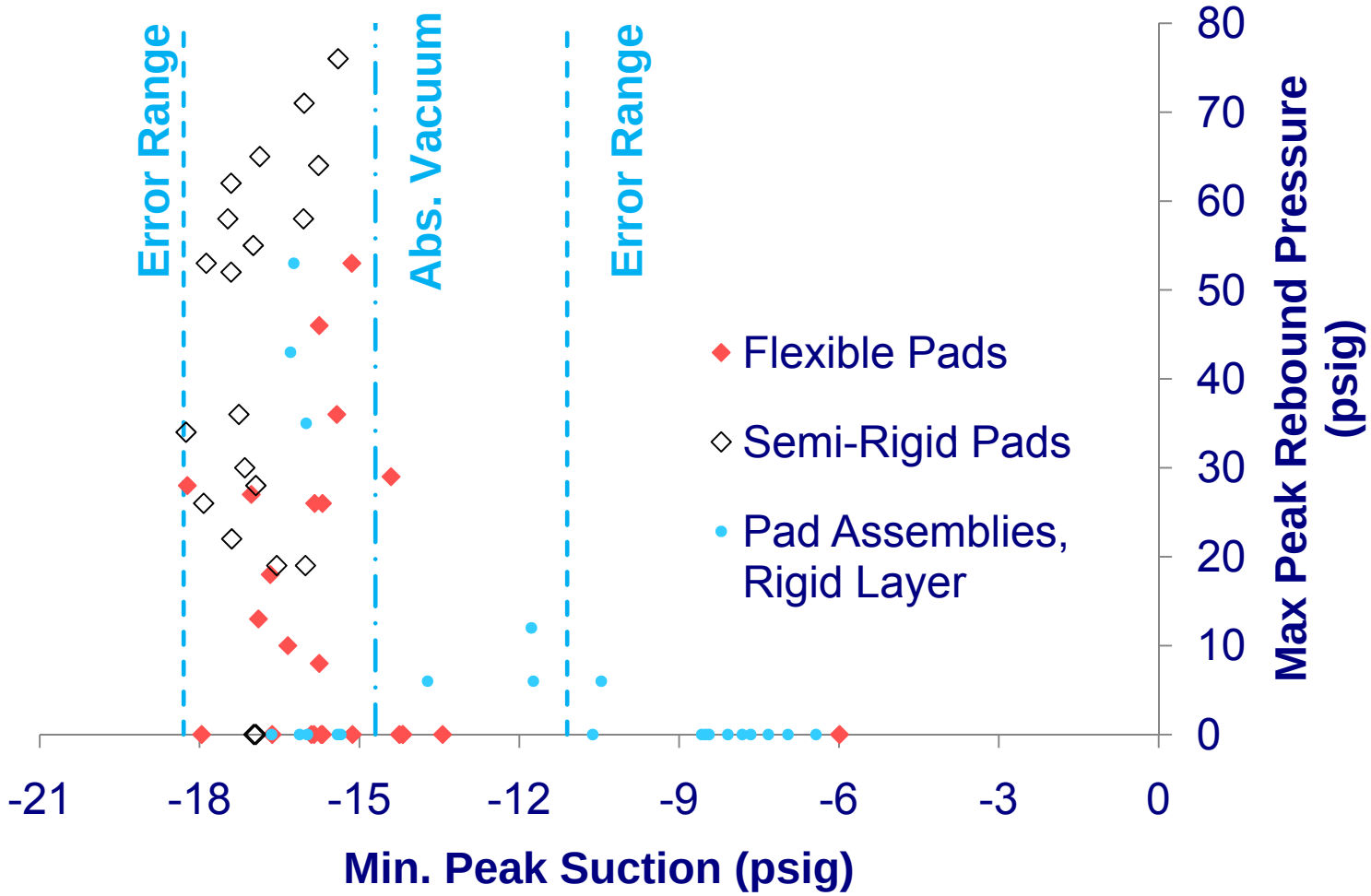
- Position-control mode
- Variables:
  - Tie Pad
  - Uplift
    - 0.03” to 0.09”
  - Waveform
    - Displacement rate



Suction and Cavitation Potential

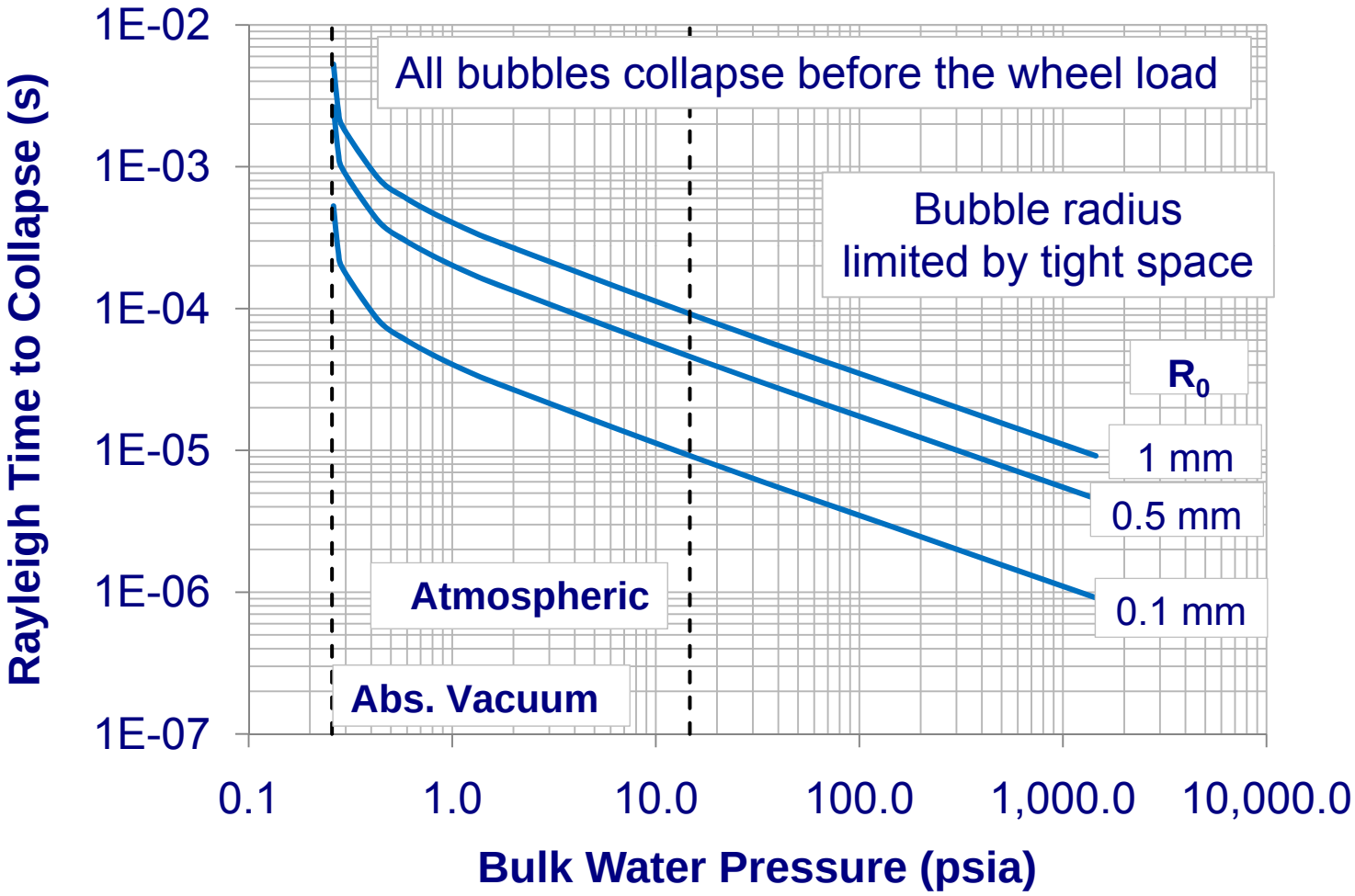


Rebound Pressure and Collapse Pressure



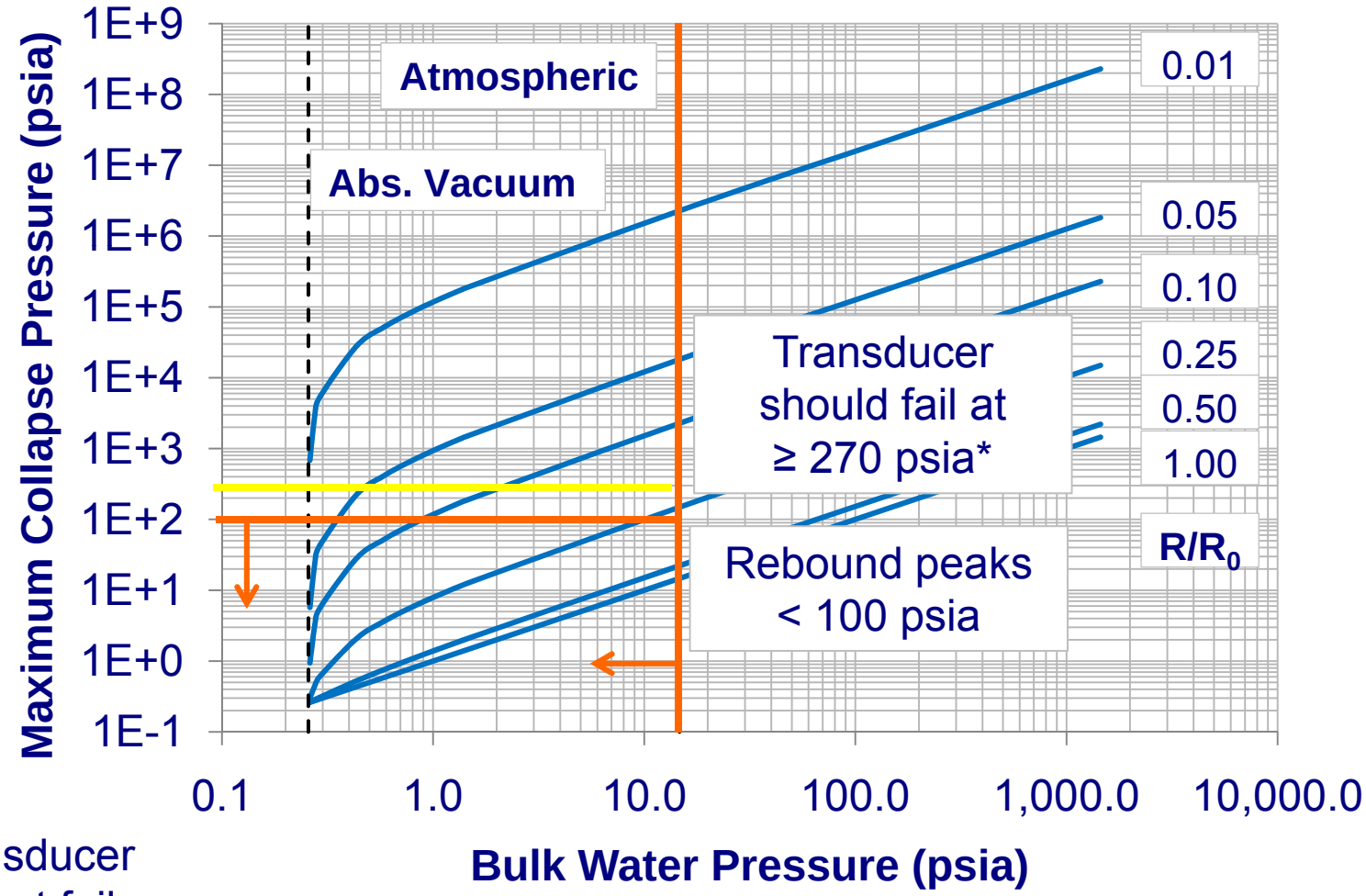
Cavitation Erosion Potential

Talbot equation predicts that uplift stroke lasts 1E-01 s for 60-mph train



Cavitation Erosion Potential (cont.)

Due to rapid collapse, bulk water pressure ≤ atmospheric pressure



*Transducer did not fail

Conclusions from the Uplift Tests

- Cavitation erosion appears to be an infeasible RSD mechanism
  - Cavitation may occur in the rail seat surface water
    - Can prevent with tie pads that do not seal water
      - Same conclusion for hydraulic pressure cracking
  - Analysis and results suggest that collapse pressure will not damage the concrete
    - Bubbles are too small and collapse too rapidly

Revised Understanding of RSD

Potential Mechanisms	High Stresses at Rail Seat	Relative Motion at Rail Seat	Presence of Moisture	Presence of Abrasive Fines
Abrasion	✓	✓	✓	✓
Crushing	✓	✓	✓	
Freeze-Thaw			✓	
Hydraulic Pressure	✓	✓	✓	
Hydro-Abrasive Erosion	✓	✓	✓	✓

Conclusions Related to Pad Design

- The sealing potential of a tie pad or assembly depends on
  - Tie pad material properties and surface geometry
  - Clip toe load
  - Uniformity of rail seat surface
- To prevent sealing and the potential for hydraulic pressure use
  - Pad assembly with rigid layer, preferably hard plastic bottom
  - Thermoplastic pad in contact with rail seat should have escape channels for water
- Balance hydraulic considerations with abrasion/erosion mitigation
  - Intrusion of moisture and abrasive fines
    - Better to have flow in and out rather than risk trapping the moisture?
  - Pad durability and stiffness

Remaining Questions

- How much could hydro-abrasive erosion contribute to RSD?
  - Appears to be a feasible mechanism
  - Would have to measure velocity and wear in another setup
- How much of a seal do tie pads produce on a fully assembled concrete tie?
  - Different sealing potential than with the laboratory blocks?
  - Measure intrusion of moisture and fines under different conditions

Future Concrete Tie Research at Illinois

- Full-scale abrasion tests on concrete ties
- Fastening system design
  - Load path
  - Elasticity and damping
- Simple abrasion tests with polymers and abrasive slurry
- Characterize the demands on insulators
- Effects of curing techniques on global and local concrete properties

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Questions?

Sample WILD Distributions

Rail seat load, half of wheel load (kips)	Percent of loads, Freight Car Company (2003)	Percent of loads, Class I railroad (2010)
0-25	80.932%	94.210%
25-35	12.383%	4.692%
35-45	4.500%	0.944%
45-55	1.586%	0.135%
>55	0.599%	0.018%
Sample size:	0.03 million	59.6 million

Sample Calculations for Fatigue Damage Potential

$$\text{Daily Traffic} = \frac{(100\times10^6\ \frac{tons}{year})(2\ \frac{kips}{ton})}{(120\ \frac{cars}{train})(286\ \frac{kips}{car})(365\ \frac{days}{year})} = 16\ \frac{trains}{day}$$

$$\text{Annual Load Cycles} = (120\ \frac{cars}{train})(4\ \frac{axles}{car})(1\ \frac{cycle}{axle})(16\ \frac{trains}{day})(365\ \frac{days}{year}) = 2.8\times10^6\ \frac{cycles}{year}$$

$$\frac{\text{fatigue cycles}}{\text{year}} = \frac{\text{load cycles}}{\text{year}}\left[\sum_{i=1}^{2} P(\text{moisture}_i)\sum_{j=1}^{5} P(\text{load}_j)\left(\frac{\text{fatigue cycles}}{\text{load cycle}}\right)_{ij}\right]$$

2003 WILD:

$$\text{Grooved Poly.: } 2.8\times10^6\left[0.14\left(0.06+0.03+0.01\right)+0.27\left(0.03+0.01\right)\right] = 69,400\ \frac{\text{fatigue cycles}}{\text{year}}$$

$$\text{Time to 1 million cycles} = \frac{1\times10^6}{69,400\ \frac{\text{fatigue cycles}}{\text{year}}} = 14\,years$$

2008 WILD:

$$\text{Grooved Poly.: } 2.8\times10^6\left[0.14\left(.94\%+.14\%+.02\%\right)+0.27\left(.14\%+.02\%\right)\right] = 5,500\ \frac{\text{fatigue cycles}}{\text{year}}$$

$$\text{Time to 1 million cycles} = \frac{1\times10^6}{5,500\ \frac{\text{fatigue cycles}}{\text{year}}} = 182\,years$$