Introducing Dr Ed Clukey

the

5th McClelland Lecturer

Who’d a thunk?

with thanks to

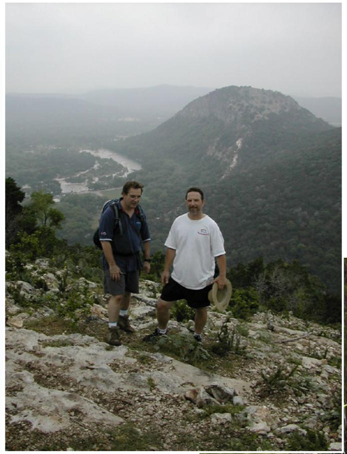
Jack Templeton, Alan Young, Mark Randolph, Don Murff, Ryan Phillips, Philippe Jeanjean and Chuck Aubeny

Exxon Chad-Cameron PL shore crossing
(w/Gardline team and Cameron reps)

Start of Amoco-BP career

Inspecting ‘long box’ for SCR testing @ C-CORE

Inside Holstein SC with Jean Audibert



Hiking in hill country, Texas

Hiking in upper Yosemite

Thunder Horse suction caisson
Installation (aboard Balder)

w Alan Young and friends in Angel Fire New Mexico

Sightseeing during Japanese centrifuge facility tour

Visiting Italy

w/ Ms. Sanford @ Versailles

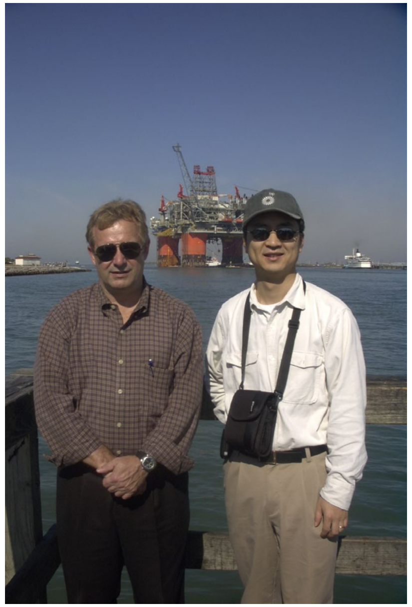
inspecting Japanese centrifuge facility

Inspecting construction of Cornell Wave tank facility

Preparing silt test in Cornell wave tank facility

w/ native villagers in highlands of Papua New Guinea

First golden retriever Jesse



watching Thunder Horse launch from
Corpus Cristi. w/colleague George Li

Finishing at BP

- Alaskan Resource Sciences
- United States Geological Survey
- McClelland Engineers
- Exxon Production Research Company
- Amoco → BP America
- GeoMaxEd

- Tenacious
- A communicator
- Practical
- Influential
- Passionate
- Insightful

Ed – the geotechnical profession is in your debt

The Role of Physical Modeling in Offshore Geotechnical Engineering

5th McClelland Lecture

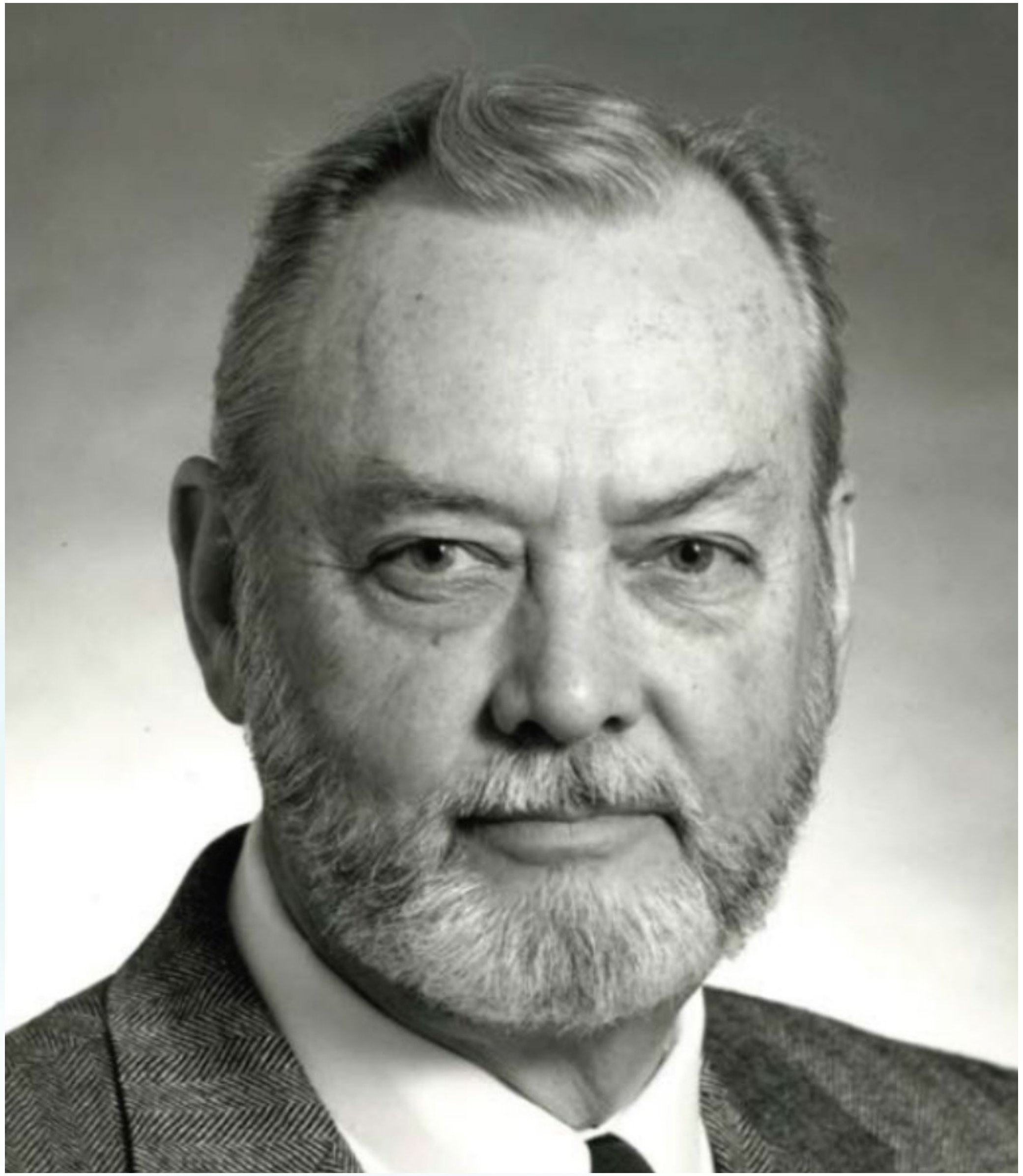
by:

Ed Clukey

GeoMaxEd

Austin, TX
August, 2022

Father of offshore geotechnical engineering



Bramlette McClelland

Geotechnical Practice in Offshore Engineering, Austin TX, 1983

Keynote address: ‘Overview of Offshore Practice’

Purpose of model tests

- Calibrate designs
- Increase understanding – research
- Verify numerical/analytical approaches
- Aim - test under field conditions, well as close as possible

A proxy for the real world

Types of model tests

- Segment
- Sectional
- Full soil & structure

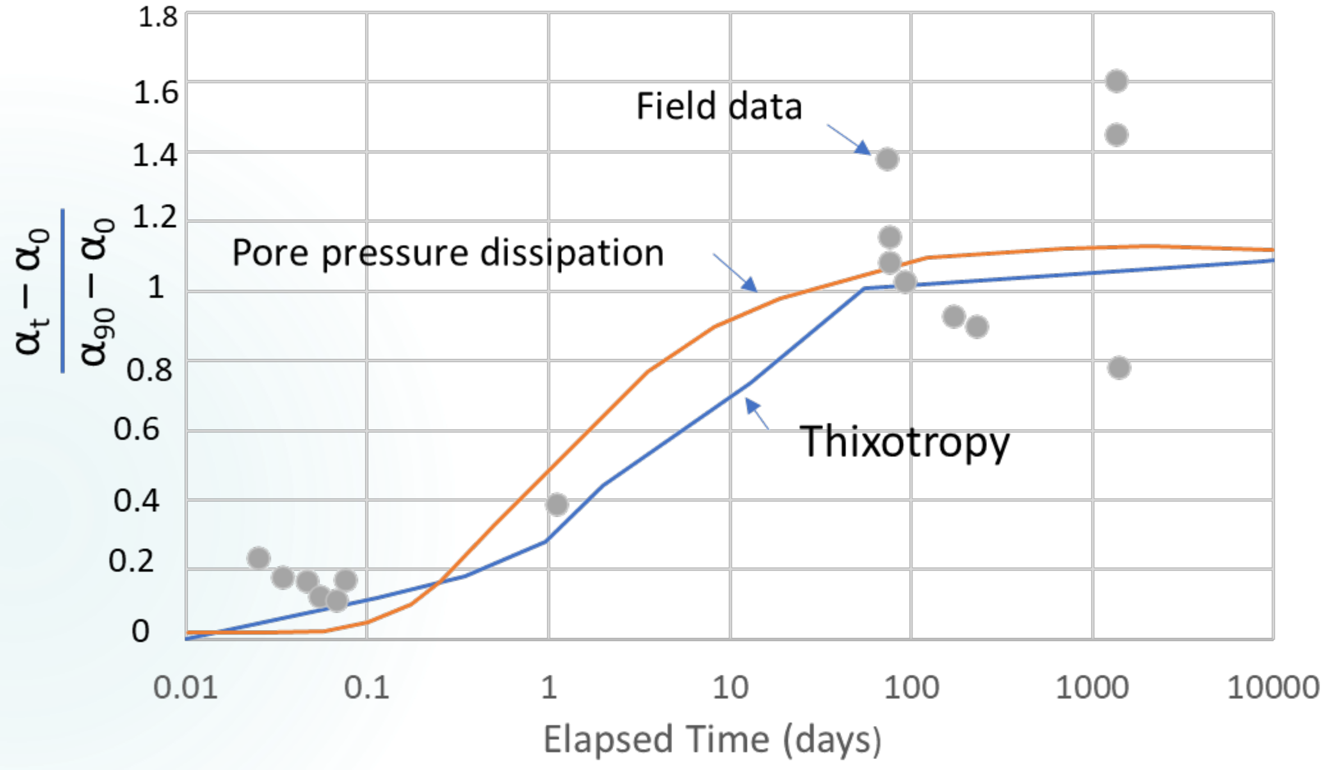
Scaling

- Dimensional Analyses
  - Buckingham Pi –dimensionless parameters
  - Soils, body forces
  - centrifuge vs. 1g model tests

- Challenges, costs & feasibility
  - consolidation time
  - model size
  - Large extreme loads

Sample preparation-reconstituted, remolded clay soils

Pull out tests on suction caissons used for MODUs



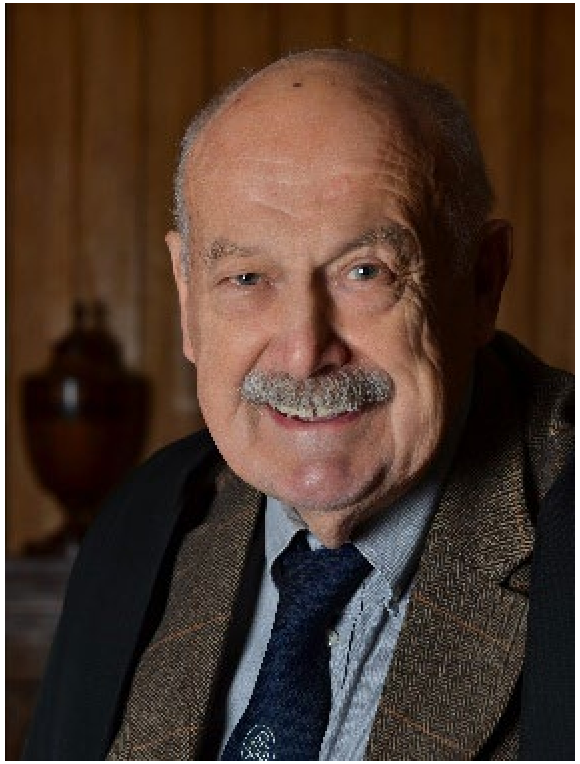
(modified from Jeanjean, 2006)

Centrifuge testing

Professor Ron Scott

Correct stress gradients

Professor Andrew Schofield



Correct body forces

Dr. Don Murff

Appropriate failure mechanisms

Centrifuge scaling

Parameter	Scale Factor
Length	$L_m N = L_p$
Stress	$\sigma_m = \sigma_p$
Density	$\rho_m = \rho_p$
Time -consolidation	$T_m N^2 = T_p$
Time acceleration	$T_m N = T_p$
Acceleration	$a_m / N = a_p$
Force	$F_m N^2 = F_p$
Strain	$\epsilon_m = \epsilon_p$
Mass	$m_m N^3 = m_p$

Simulate bigger (N) prototypes

Much less time (1/(N^2) req'd. for consol.

EQ delivered much N time faster

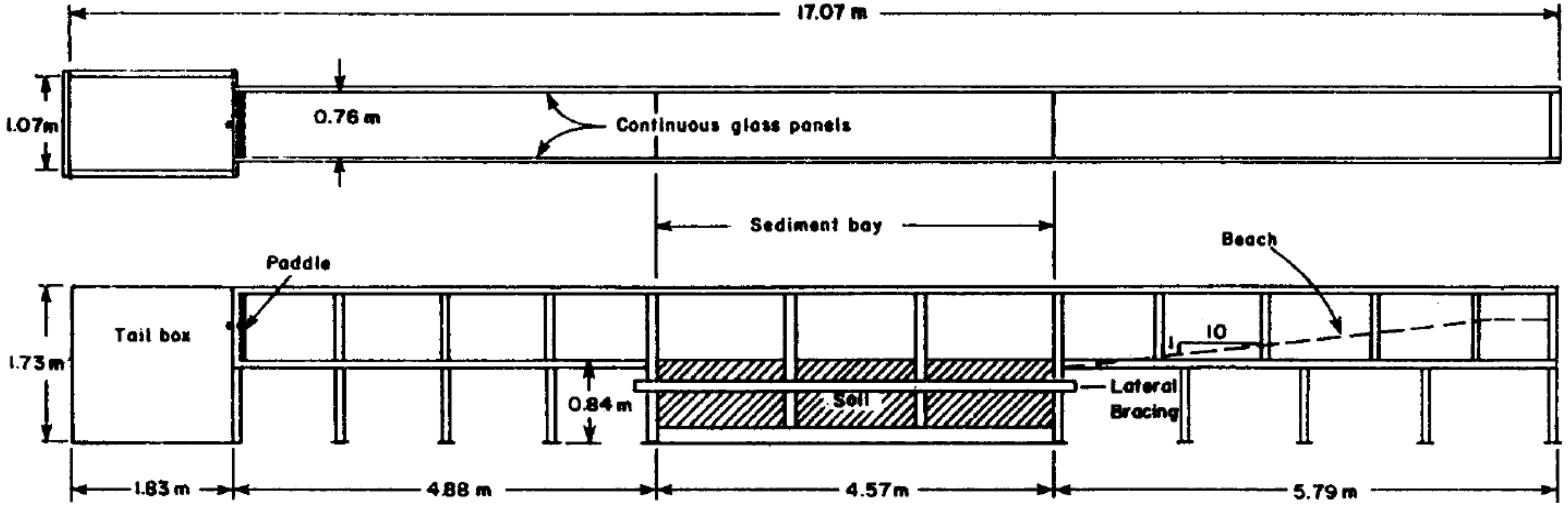
Accel levels N x higher

See: Garnier et al. paper for others

Examples

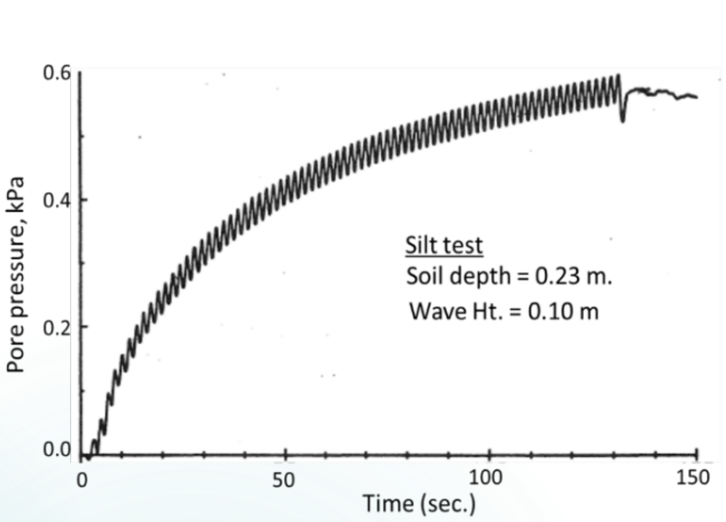
1. Wave-seafloor interaction
2. Debris flow impact on pipelines
3. Suction caissons
4. Fatigue – conductors & SCRs
5. Earthquakes, piles, SPJ, and manifold

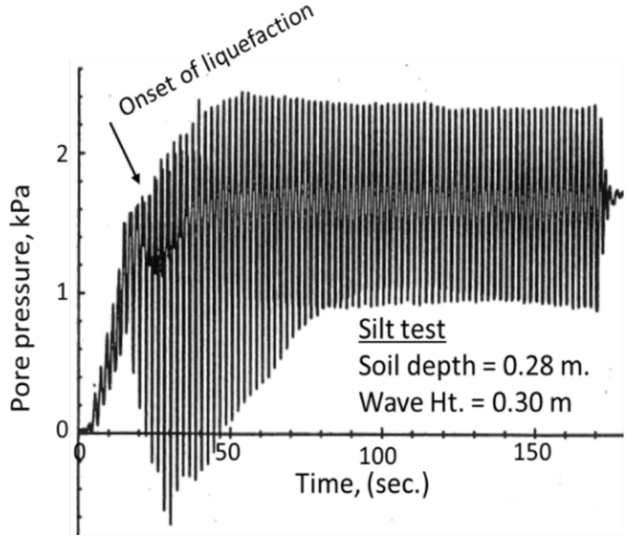
Wave-seafloor interaction

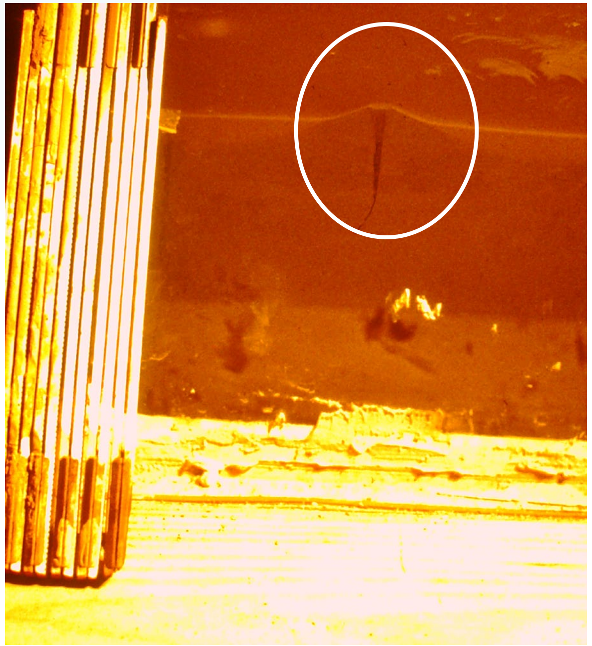


Cornell wave tank facility

Wave-seabed interaction- silt tests

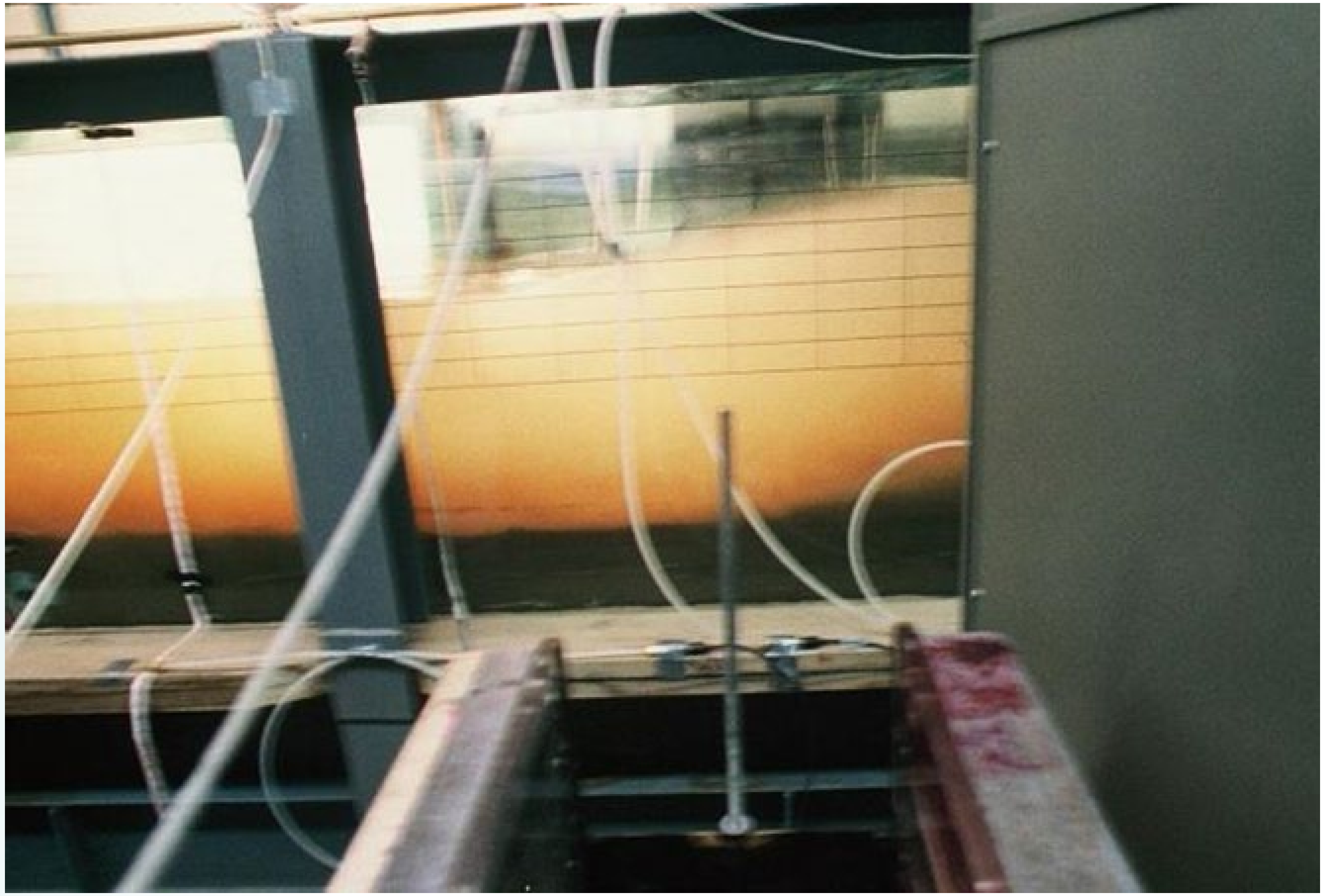






(from Clukey et al., 1985)

Failed silt bed -sloshing



Wave-seafloor interaction - sand

Pore pressures

Uncoupled solution

P L-F Liu

- $p = p_o \cosh \lambda(d_s - z)/(\cosh \lambda d_s)$

λ = the wave number ($2\pi/L$)

d_s = the thickness of the soil deposit

Assumptions

1. Rigid seabed
2. Incompressible fluid
3. Hydraulic isotropy

Coupled solution

Yamamoto –Madsen

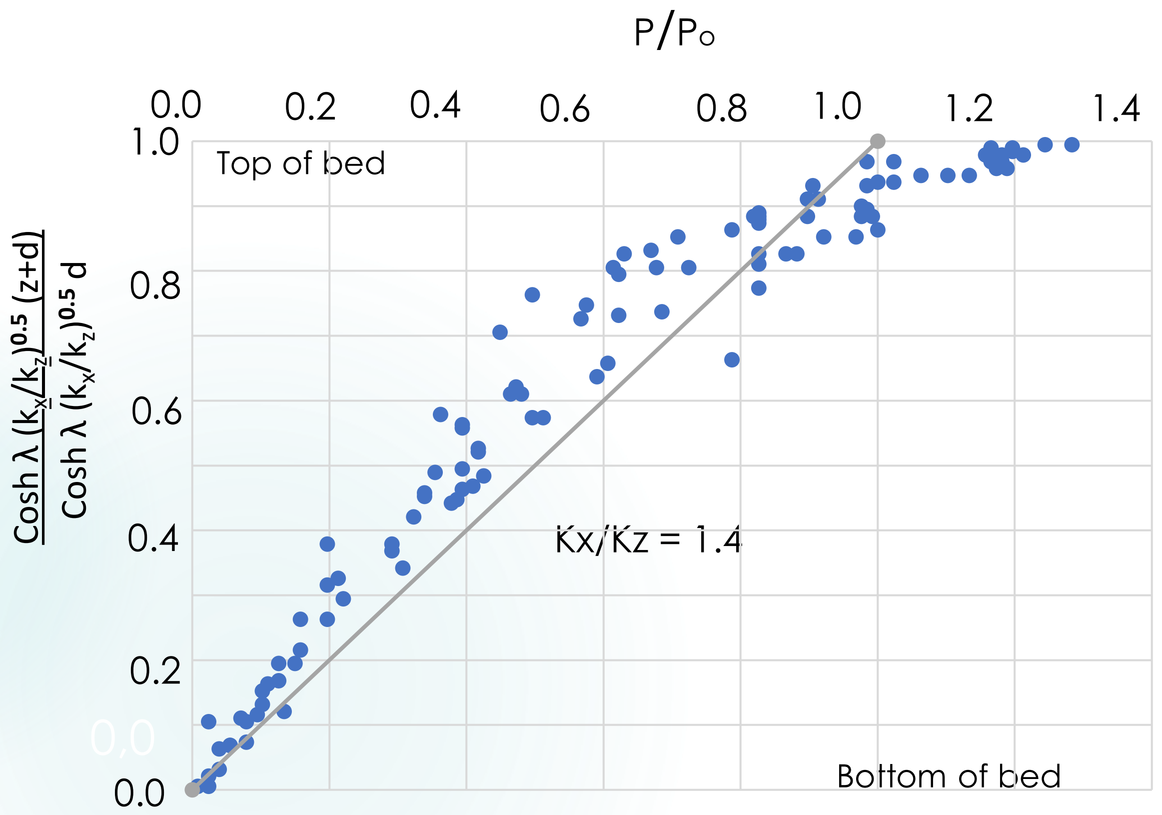
- Determine pore pressures & effective stresses

Assumptions

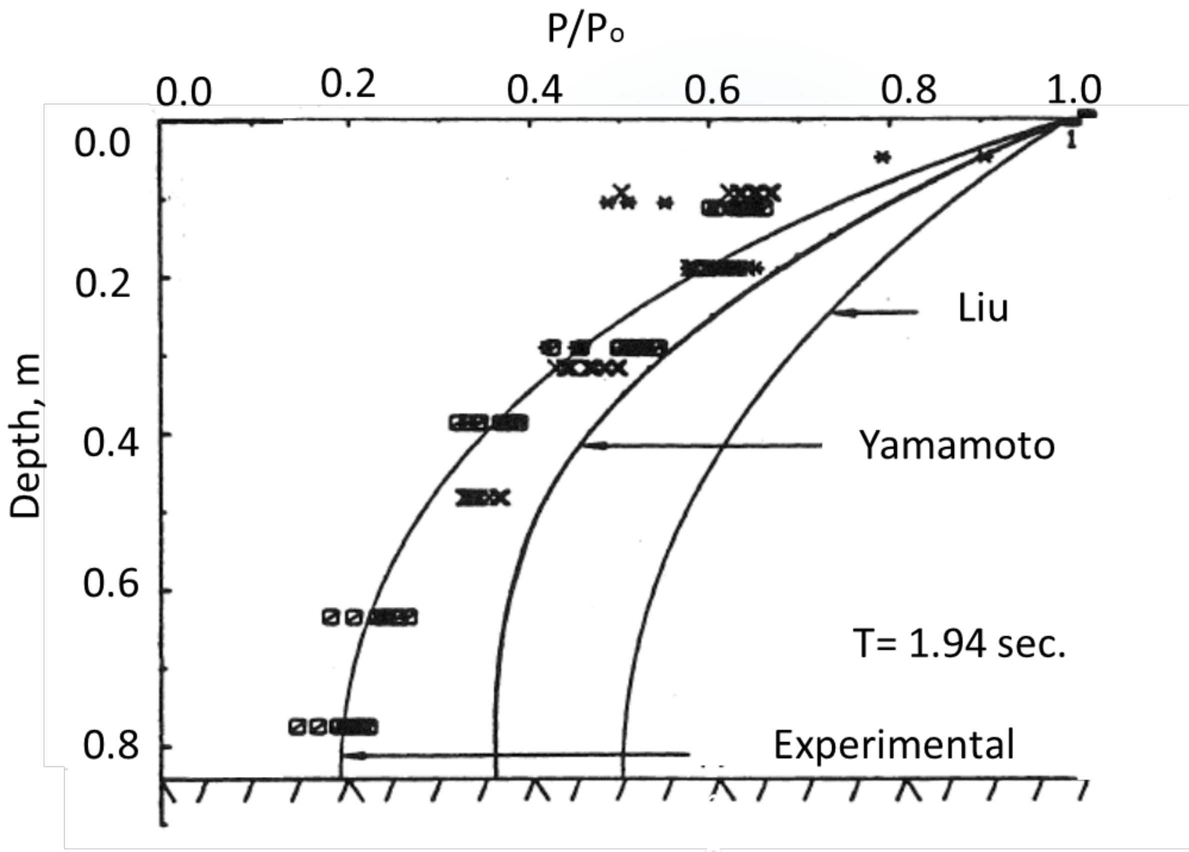
1. Elastic seabed
2. Compressible fluid
3. Hydraulic anisotropy

Block Island wind project shut down!

Model test results-pore pressures



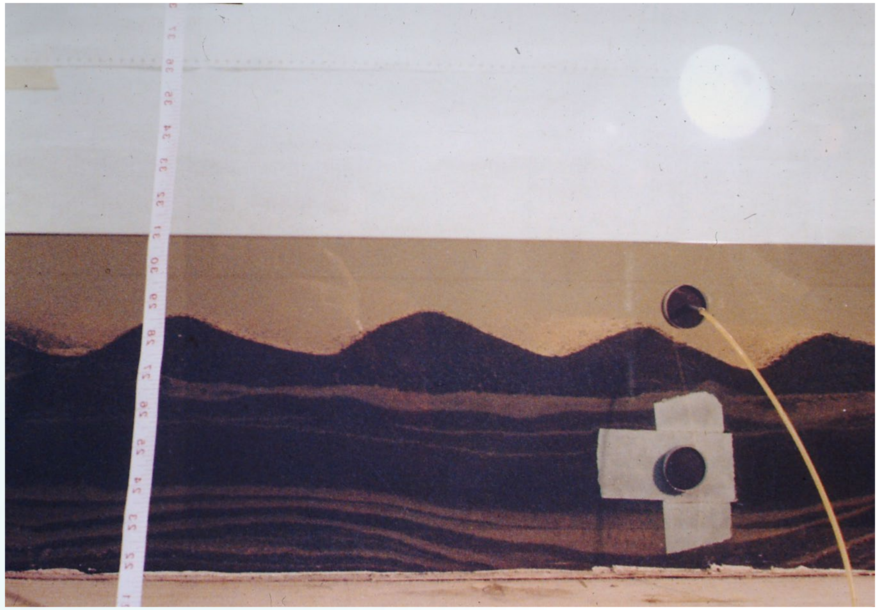
(modified from Sleath, 1970)



(from Clukey, 1983)

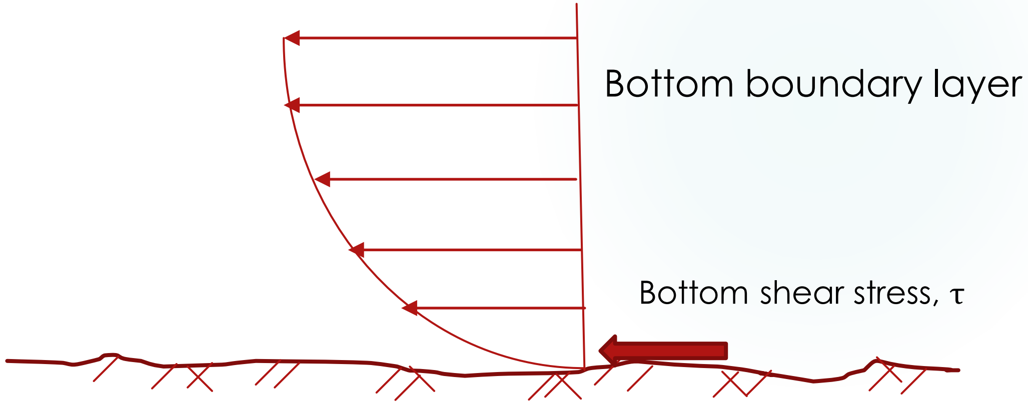
Sand test observation –sand ripples

Observation



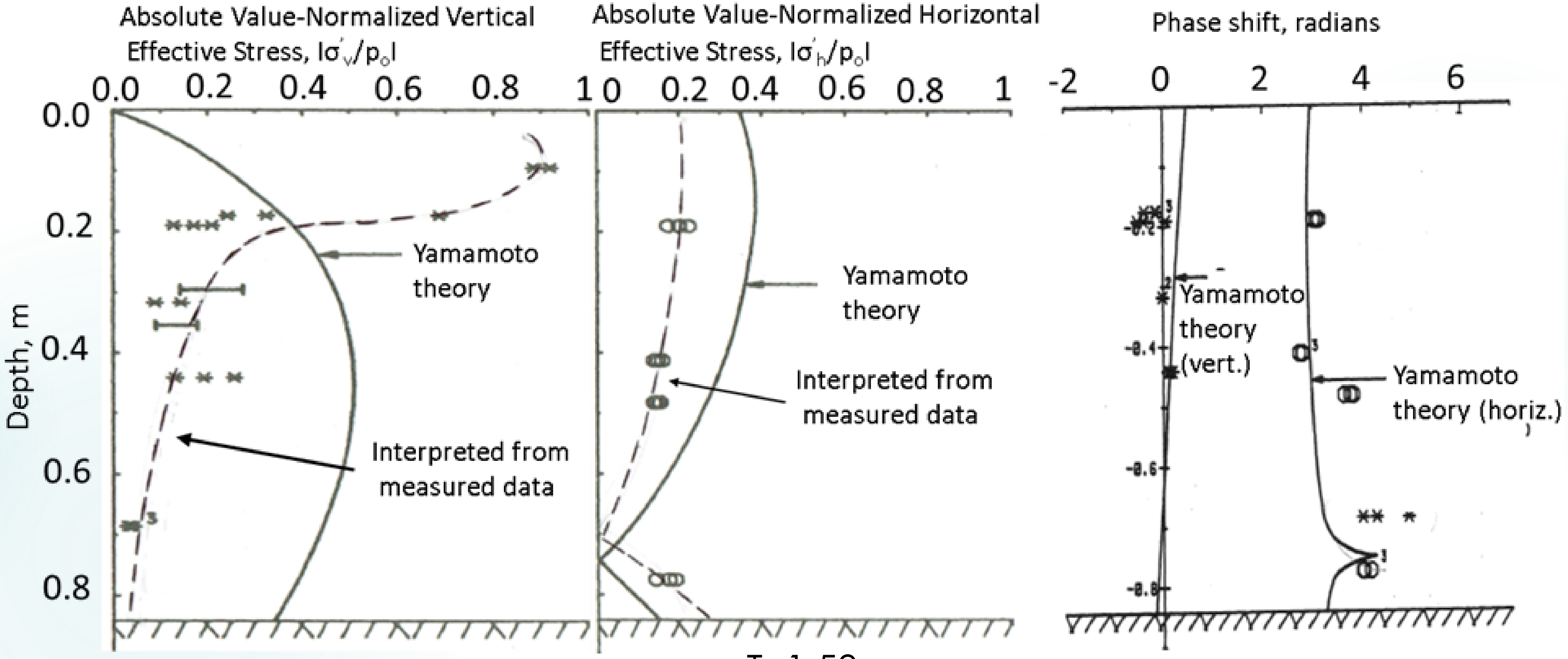
(from Clukey, 1983)

Traditional sediment transport




HD

Measured effective stresses

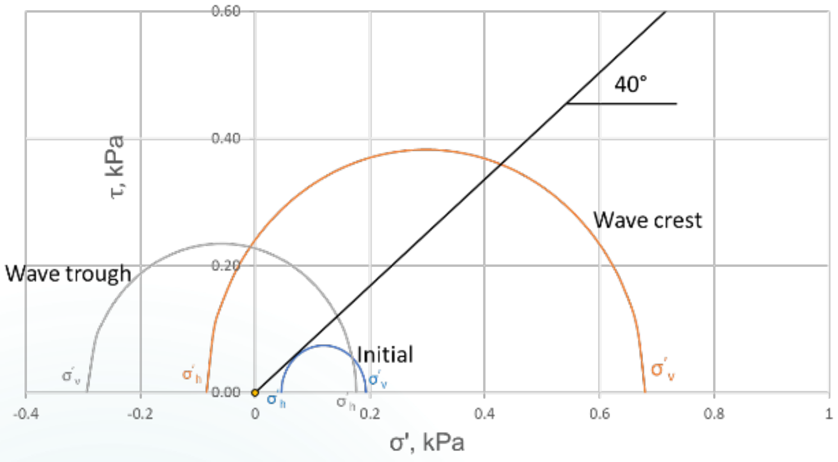


T=1.58 sec

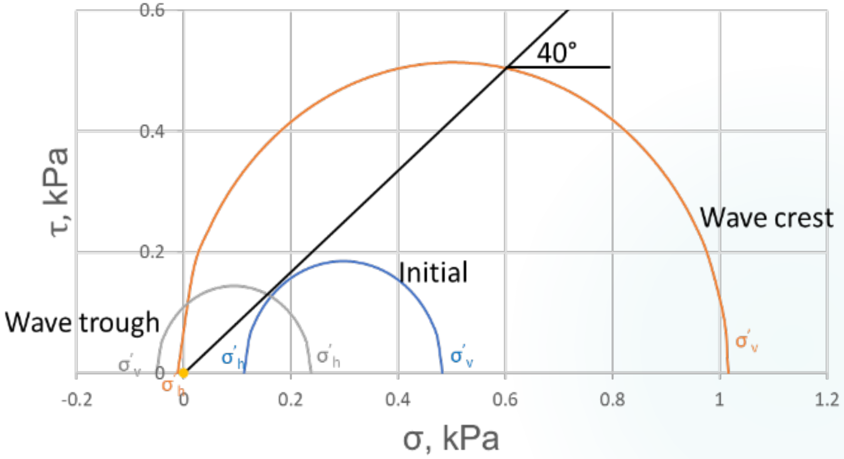
(from Clukey, 1983)

Stress circle analysis

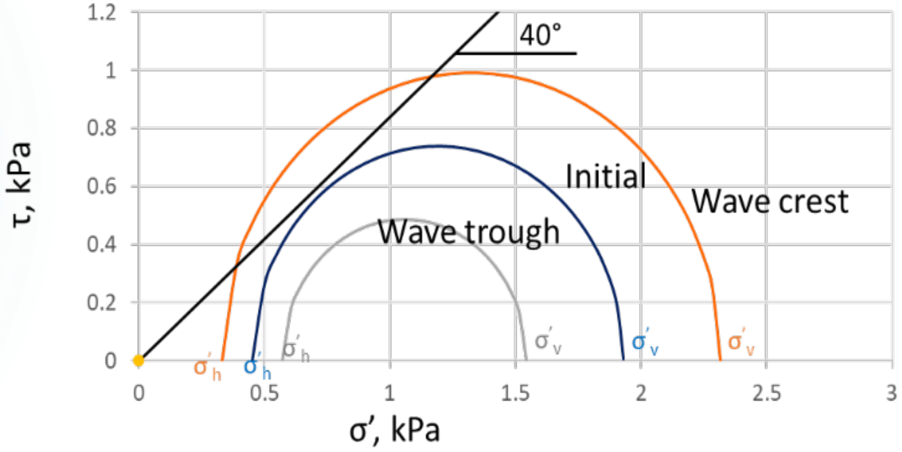
2 cm below top of sand



5 cm below top of sand



20 cm below top of sand



T =1.58 sec.

'Normal' waves can cause liquefaction & bed failure

Primary takeaways

- Freshly deposited fine grained silts will liquefy (with added loads from waves)
- Seabed mobility for sandy soils goes beneath seafloor – temporary liquefaction
- New advanced numerical techniques (better soil representation) will advance seafloor seabed & instability projections (e.g. Block Island) goes benea

Basics of debris flow modeling

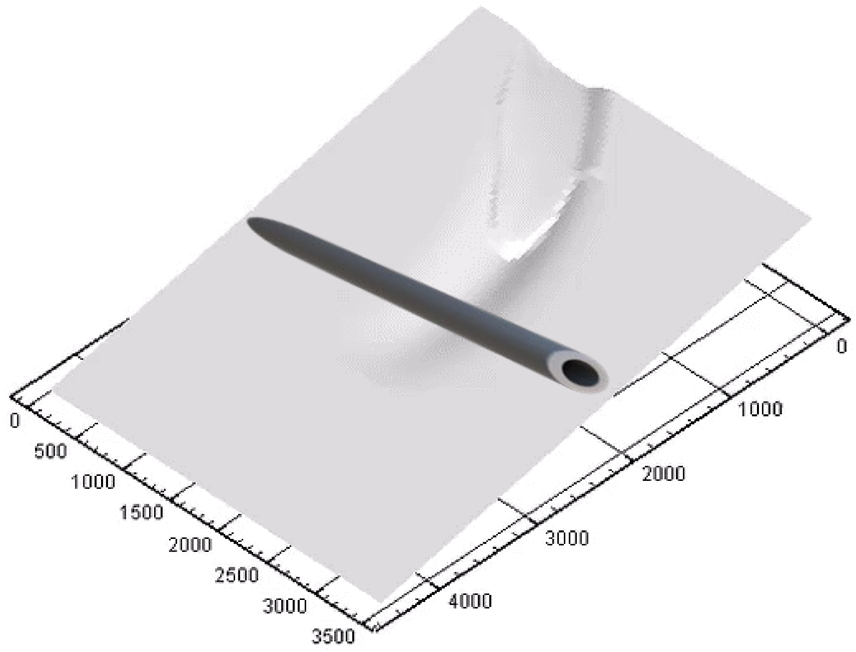
Debris Flow Modeling Analysis

Debris flow - A rapid downslope flow of liquid mud.

Assumption - If the numerical model can adequately simulate an observed debris flow deposit, then it may be used to describe the flow characteristics and to predict behavior of other similar events.

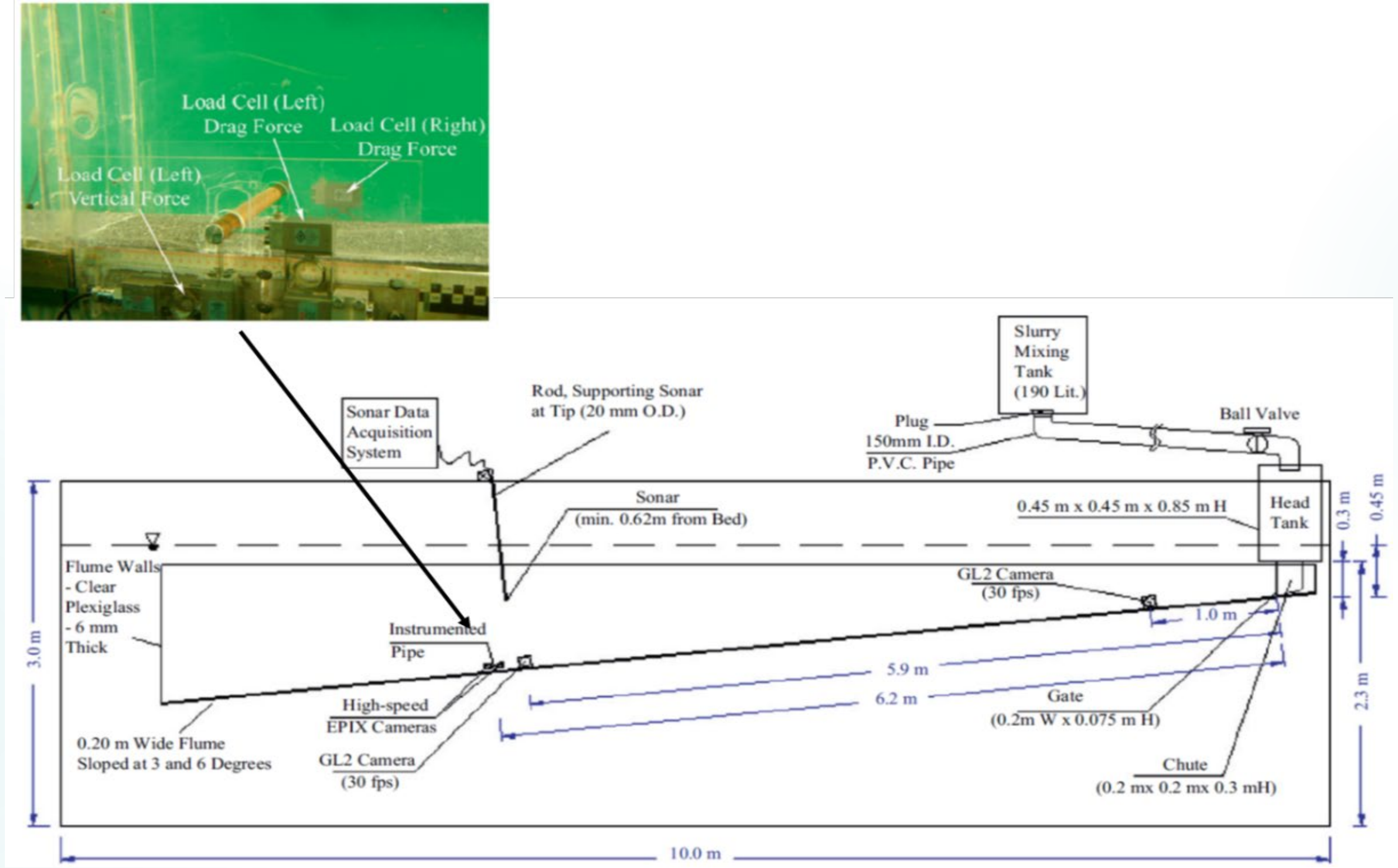
Capabilities -

1. Runout distance
2. Velocity
3. Fluid density
4. What's missing !



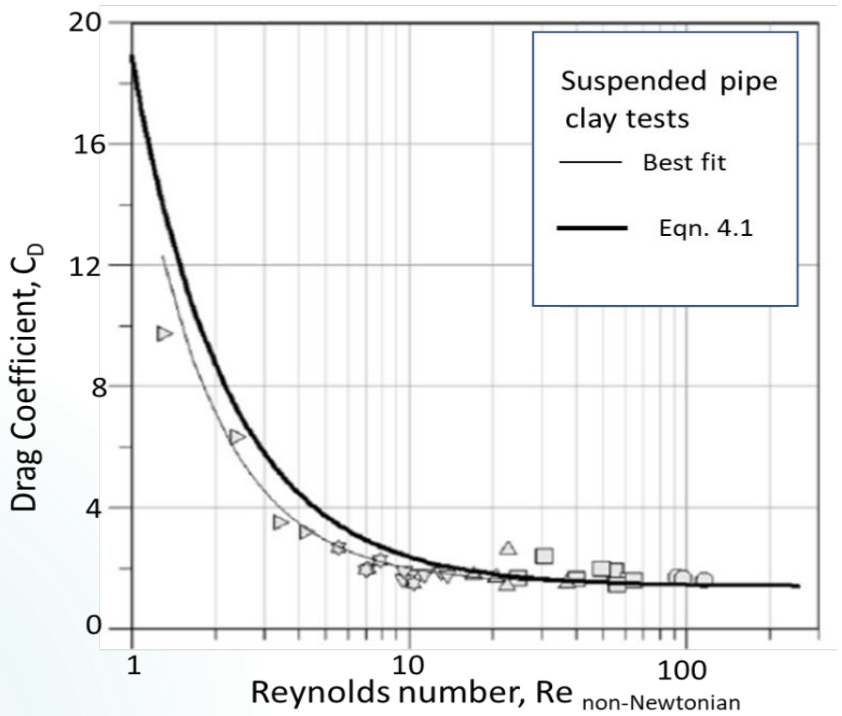
Slide courtesy of Alan Neideroda

Debris flow forces –experimental tests



(from Zakeri, 2008)

Debris flow force results



(from Zakeri, 2009)

$$C_D = 1.6 + \frac{12.8}{Re_{non-Newtonian}^{1.45}}$$

Drag

$$F_n = C_d\left(\frac{1}{2}\rho v_n^2\right)D + N_p S_{u,nom} D$$

Drag + BC

- Debris flow impact forces are now determined in design of offshore pipelines

Primary takeaways

- Well designed small flume tests provided key data to infer mass flow loads on pipelines
- Agreement has been reached on appropriate Reynolds number for fluid drag vs. drag plus bearing failure approaches

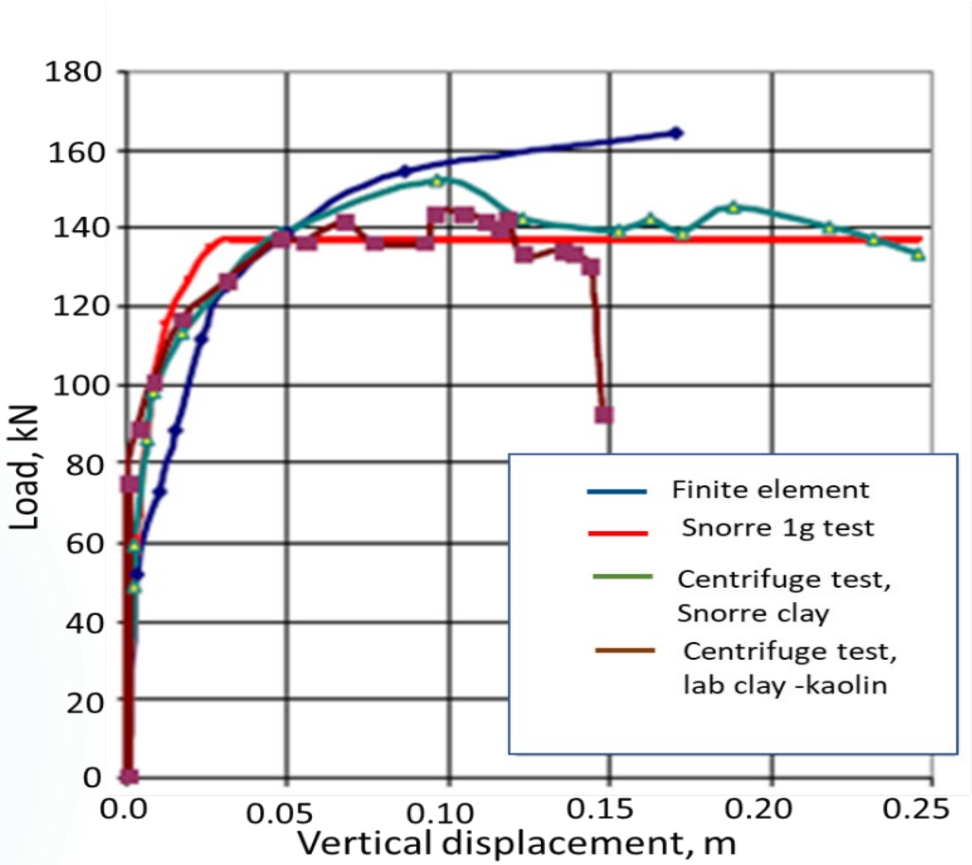
Suction caissons, North Sea - early testing

Slide courtesy of Knut Andersen

Snorre TLP foundations

1-g model tests (~12 to 1 scaling)

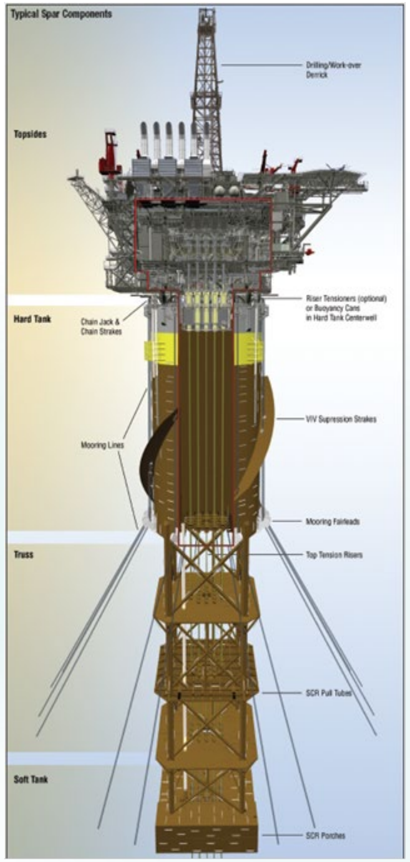
Comparison of 1-g and centrifuge tests



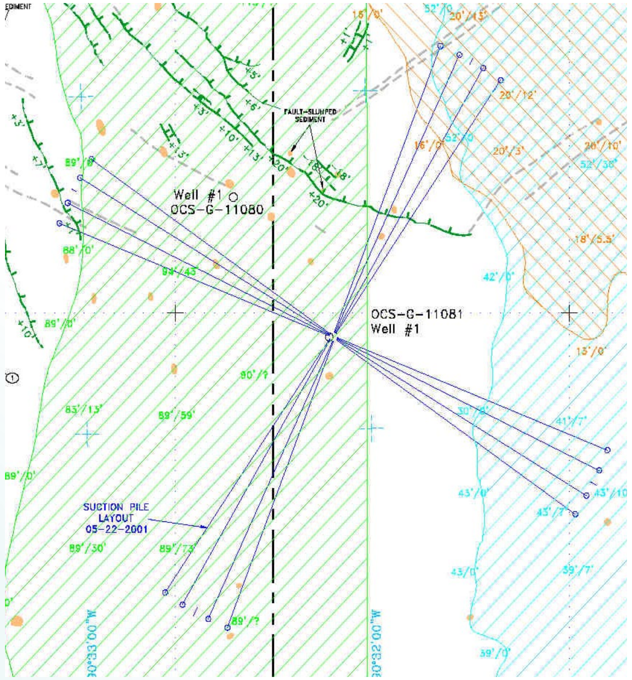
(from Morrison et al., 1994)

Suction caissons - GoM

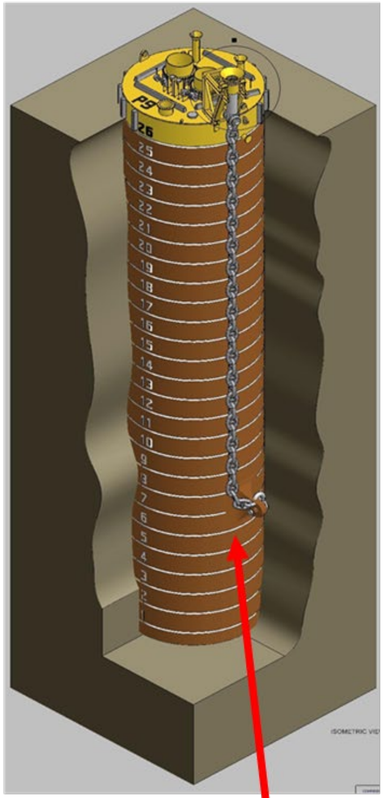
Spar



Mooring system



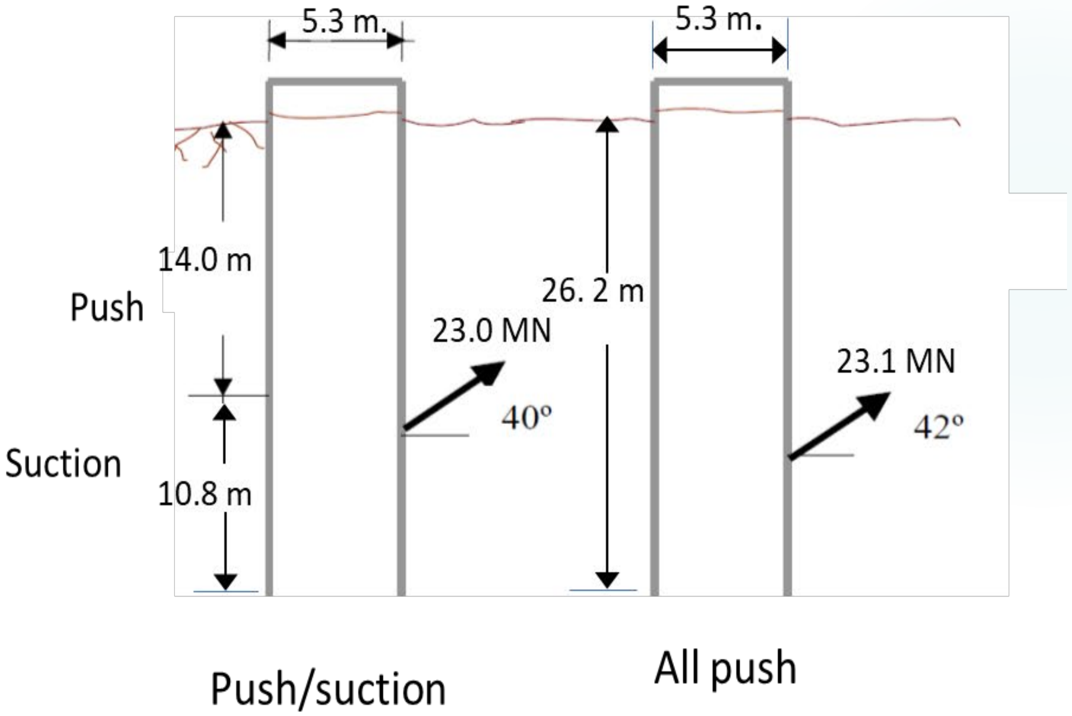
Deepwater suction caissons



Lowered attachment point

Early testing for catenary to taut mooring systems

C- CORE centrifuge

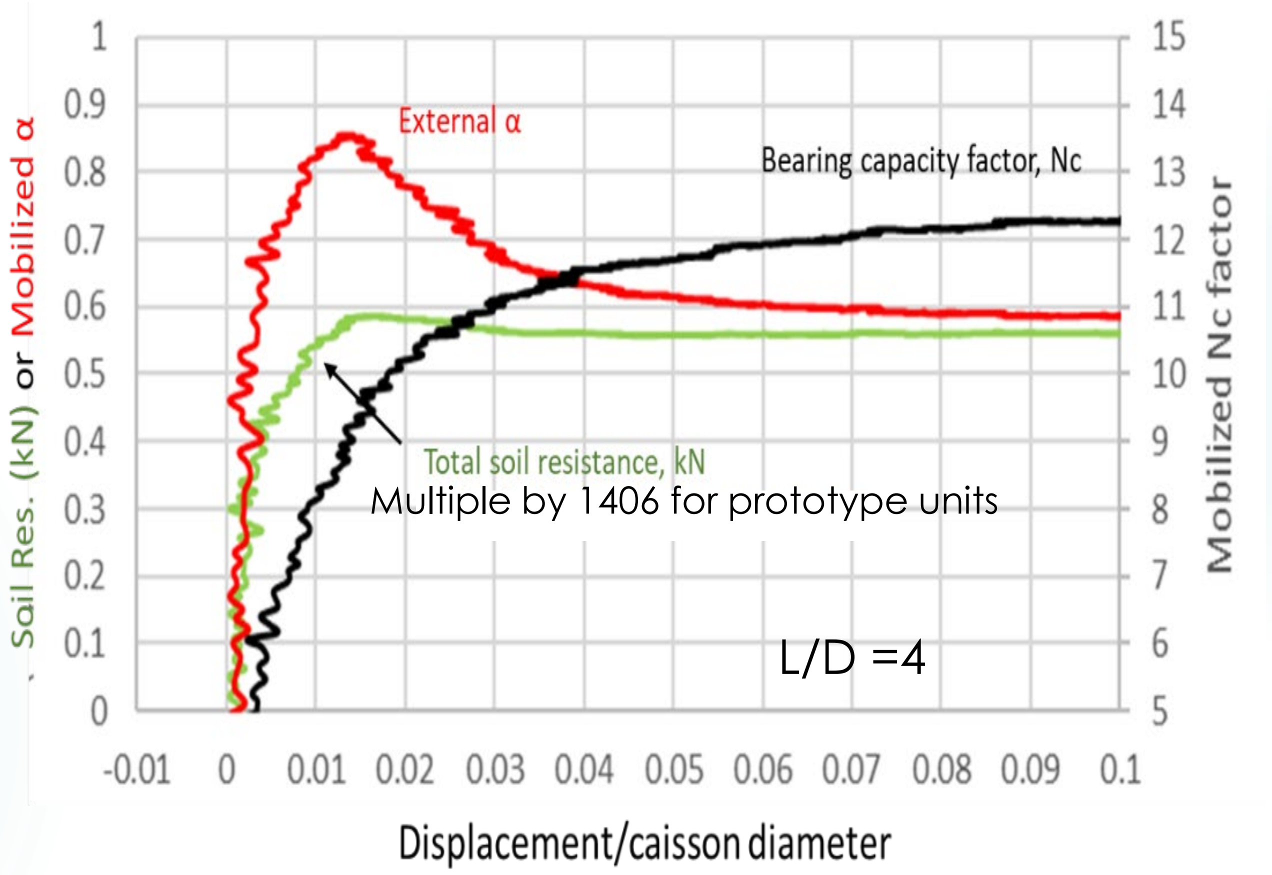


(from Clukey and Phillips, 2006)

More advanced tests

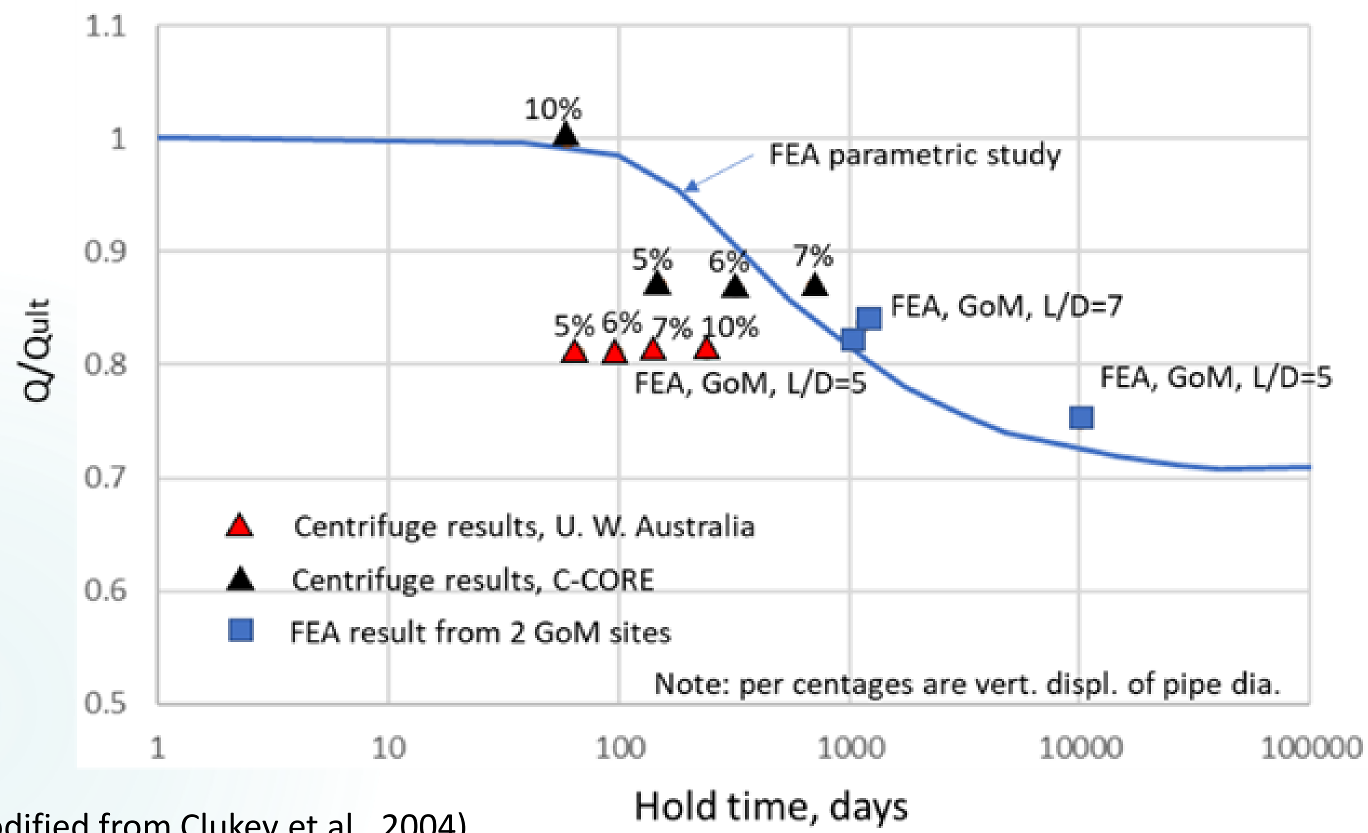
Combined:
BP(C-CORE), UT, UWA
Tests

a (external)	0.85
Nc (tip)	12.4
Nc (B/4)	12.0
Nc (pk load)	9.0



(modified from Jeanjean, 2006)

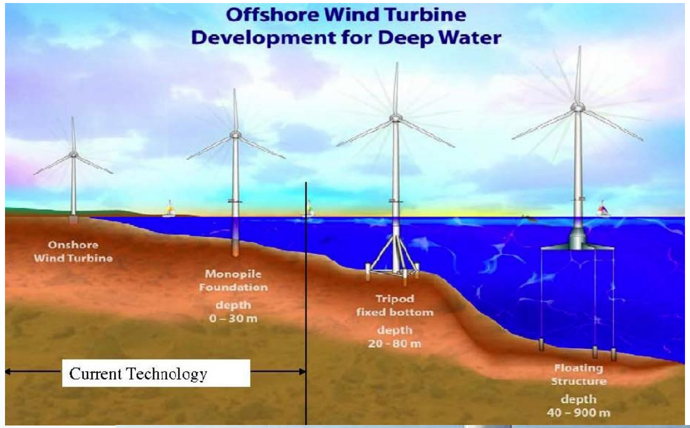
Sustained loading – loop currents

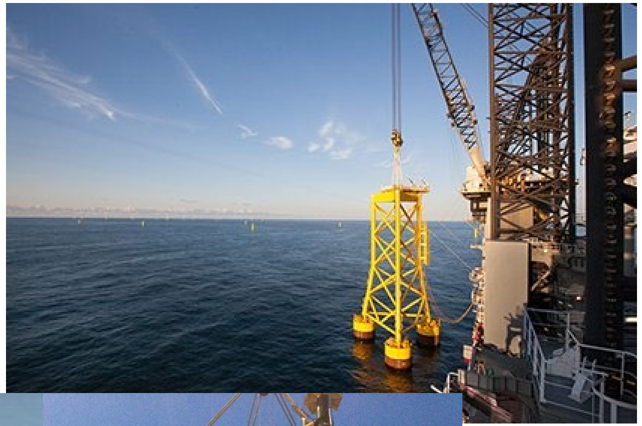


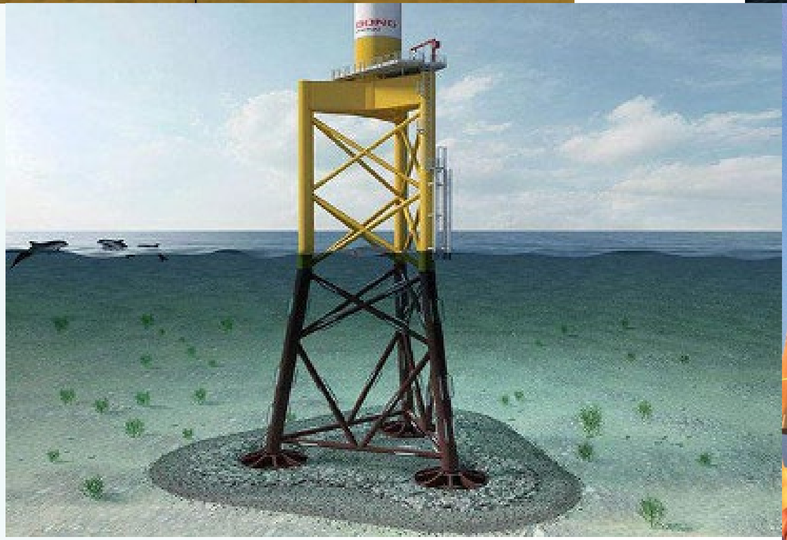
(modified from Clukey et al., 2004)

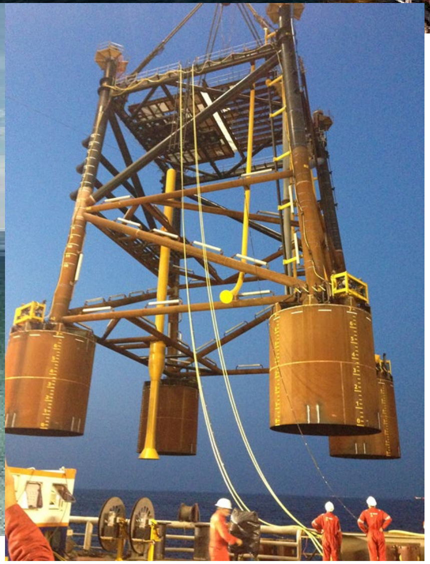
- Model test results now integrated into suction caisson design codes

Suction caissons – offshore wind



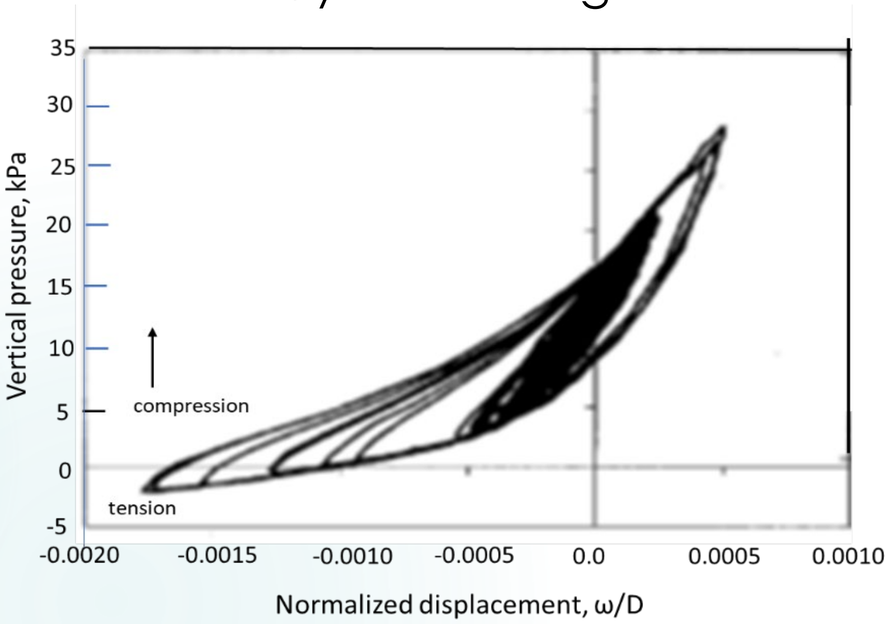




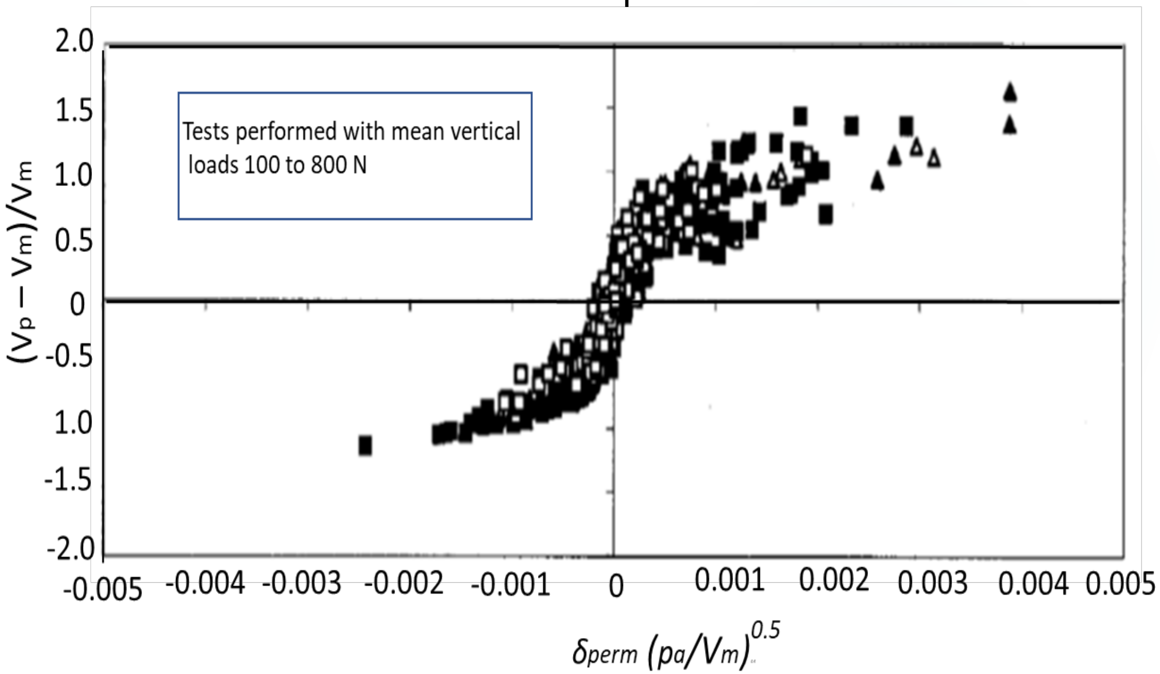


1-g test results

Cyclic loading



Permanent displacements

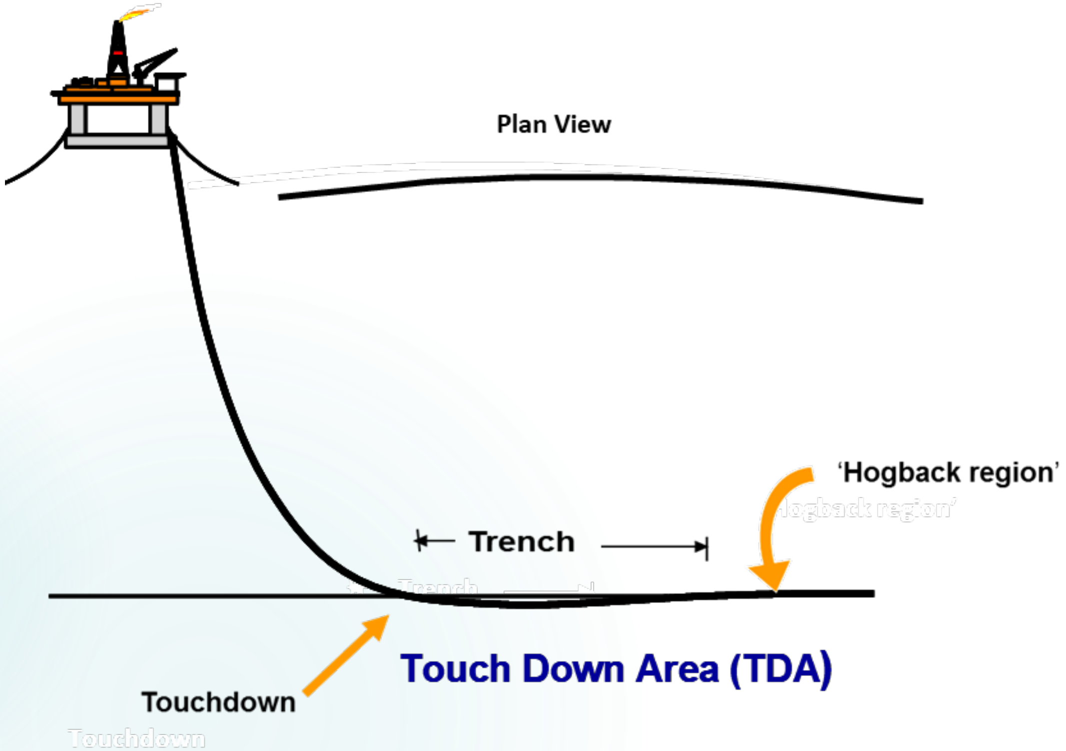


(from Byrne and Houlsby, 2002)

Primary takeaways

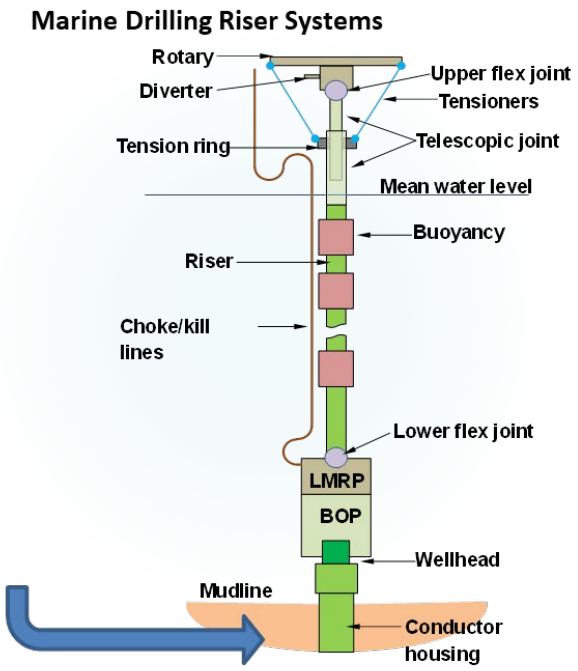
- Model testing (both 1g and centrifuge) provided key information for developing suction caisson technology in clays for deepwater applications – capacity, displacements, long term effects

Fatigue issues conductors & SCRs



Steel Catenary Risers, SCRs

Threaded connection



From: Zakeri at al., 2015

Conductors

SCR fatigue

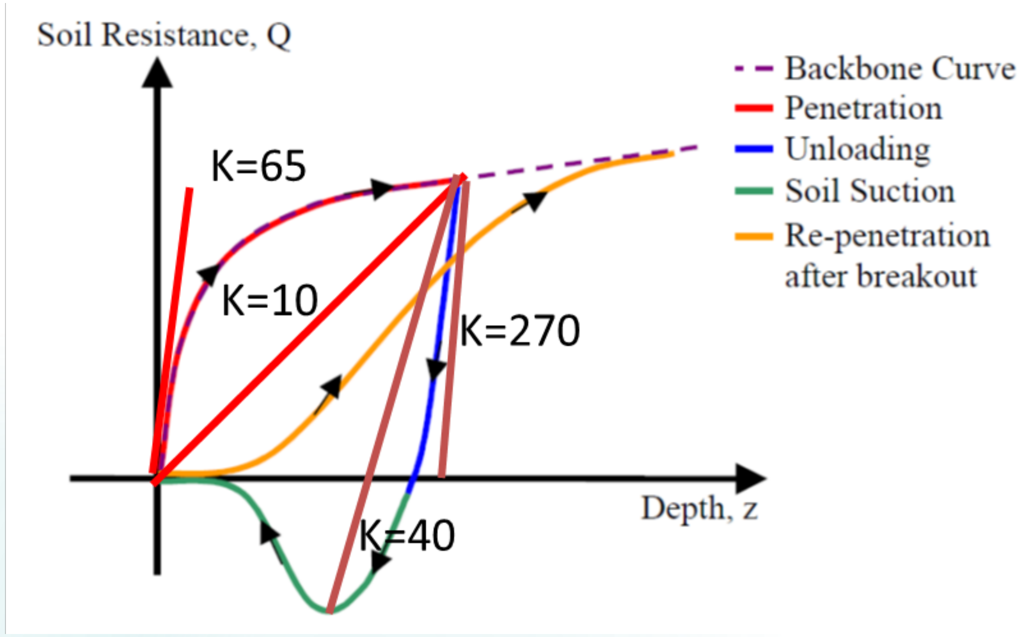
Lab segment tests

Watchett Harbor

Lake Oreille, Oregon

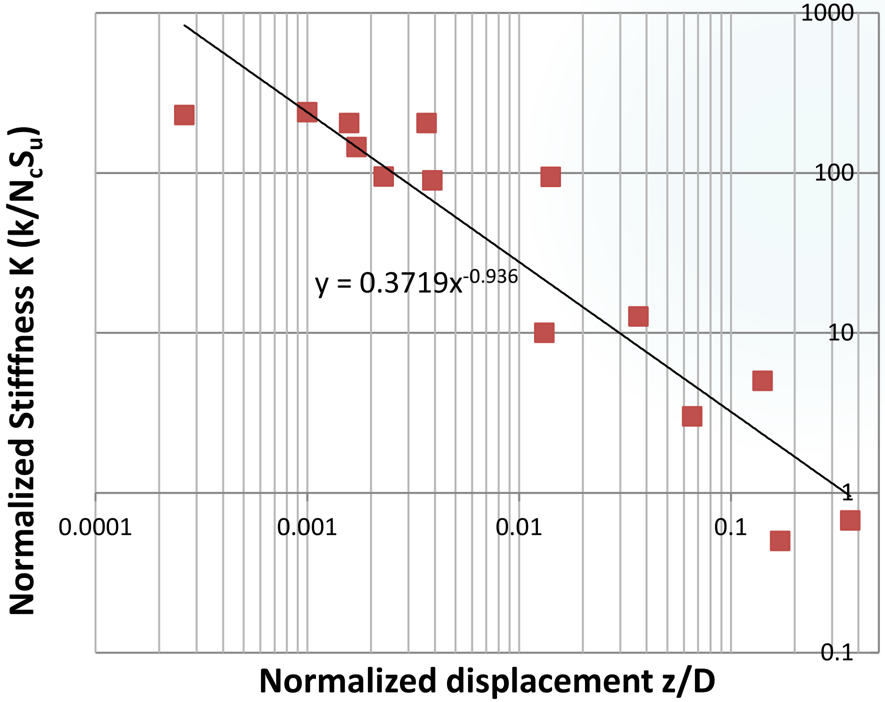
(from Grant et al., 1999)

SCR fatigue –cyclic loading



Re-penetration pipe-soil interaction

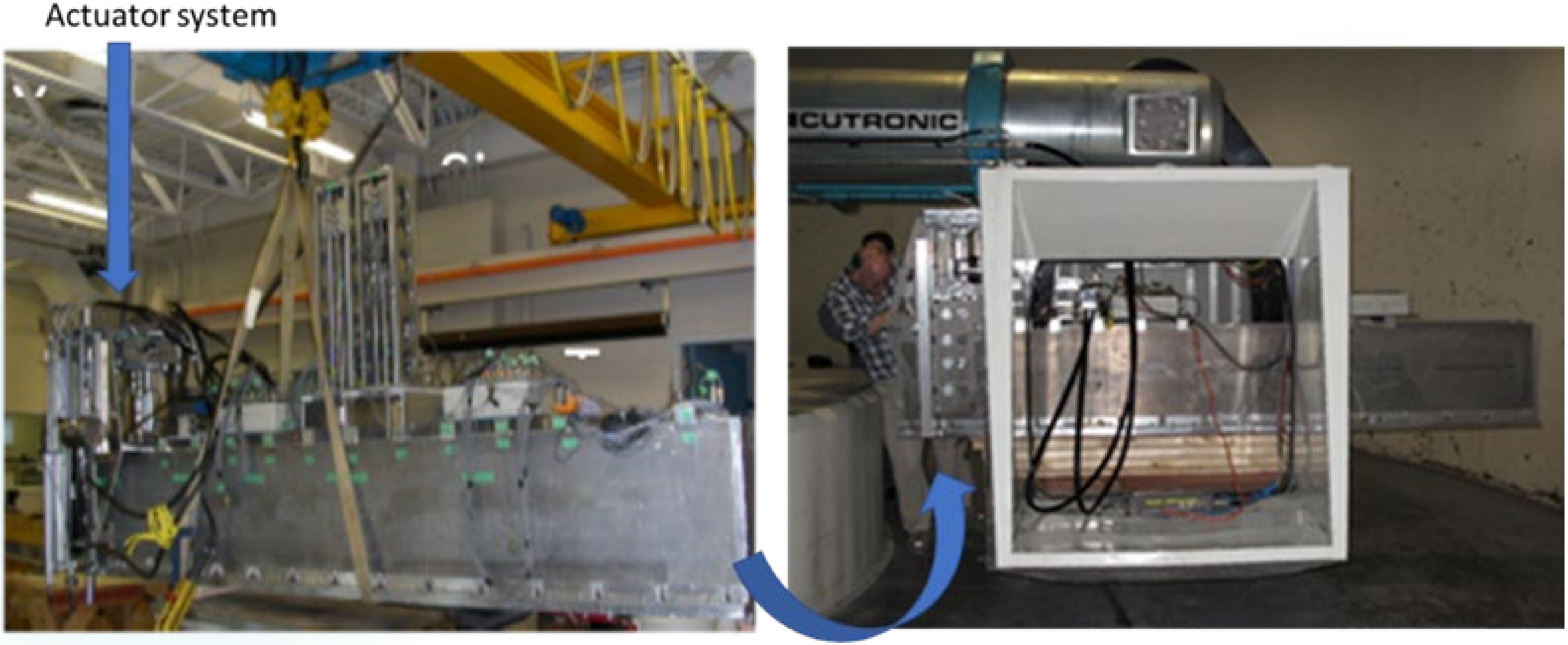
Segment test data



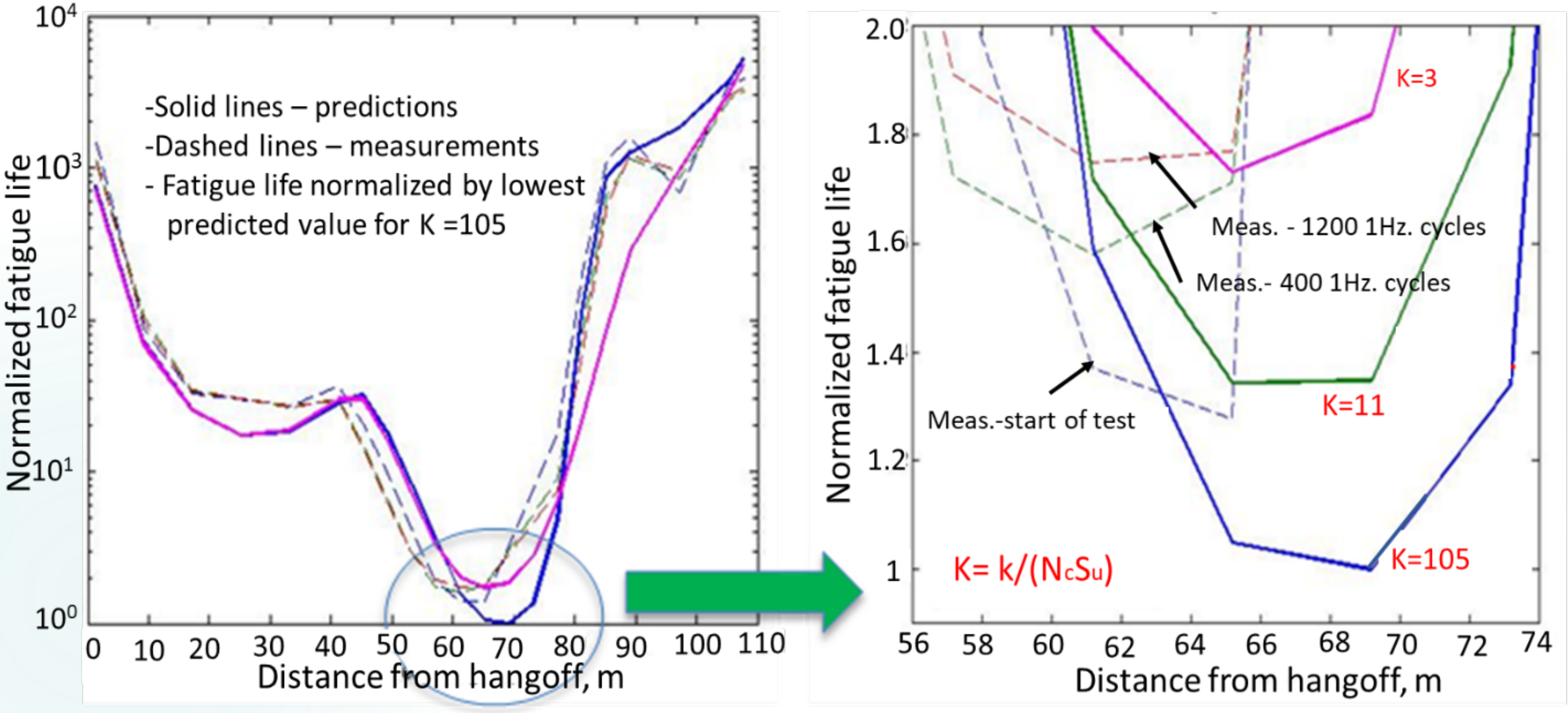
Normalized soil stiffness

$K=k/(N_cS_u)$

SCR fatigue-centrifuge tests

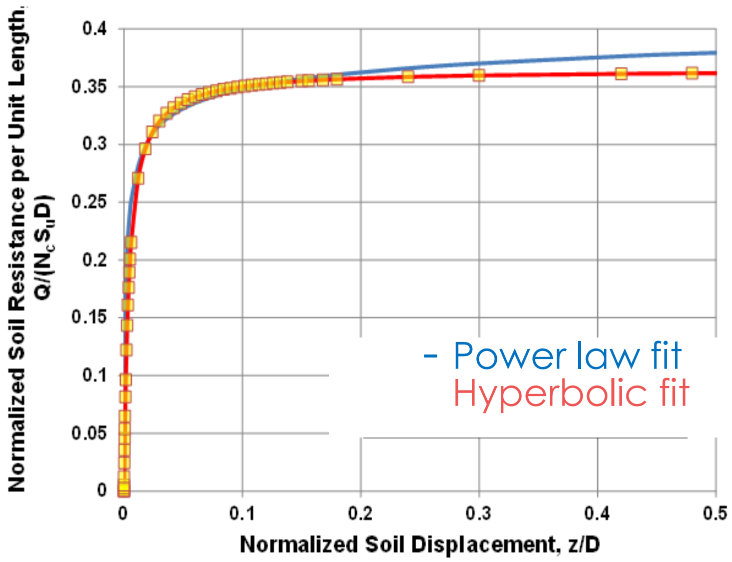


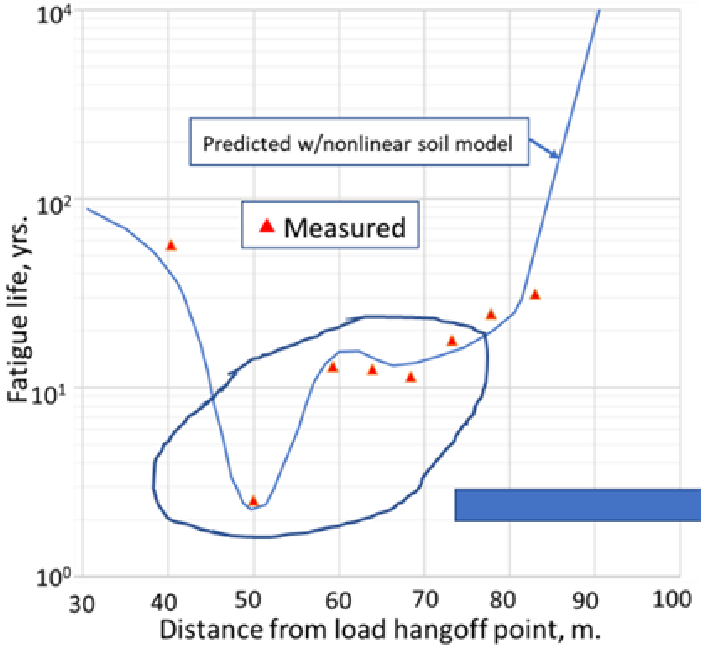
SCR fatigue –GoM results

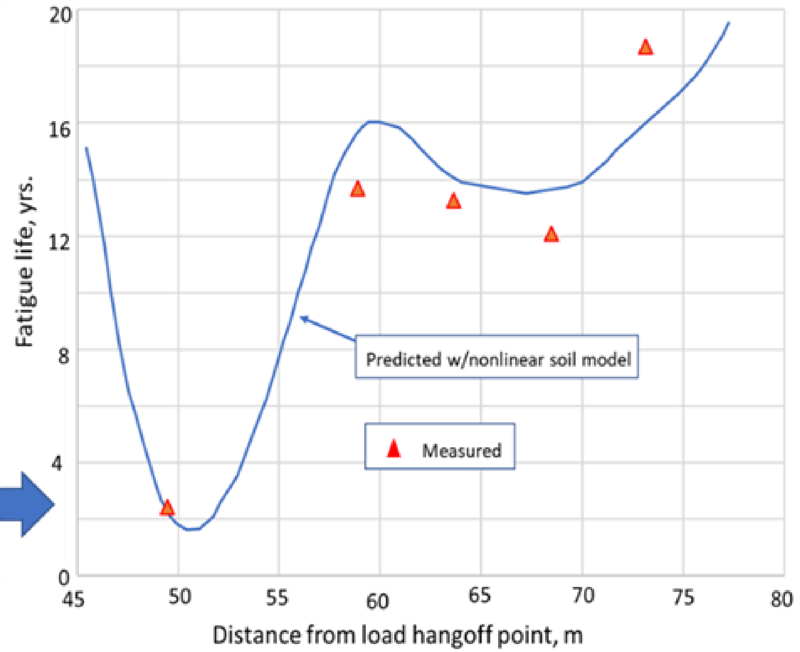


(modified from Clukey et al., 2011)

SCR fatigue-West Africa results



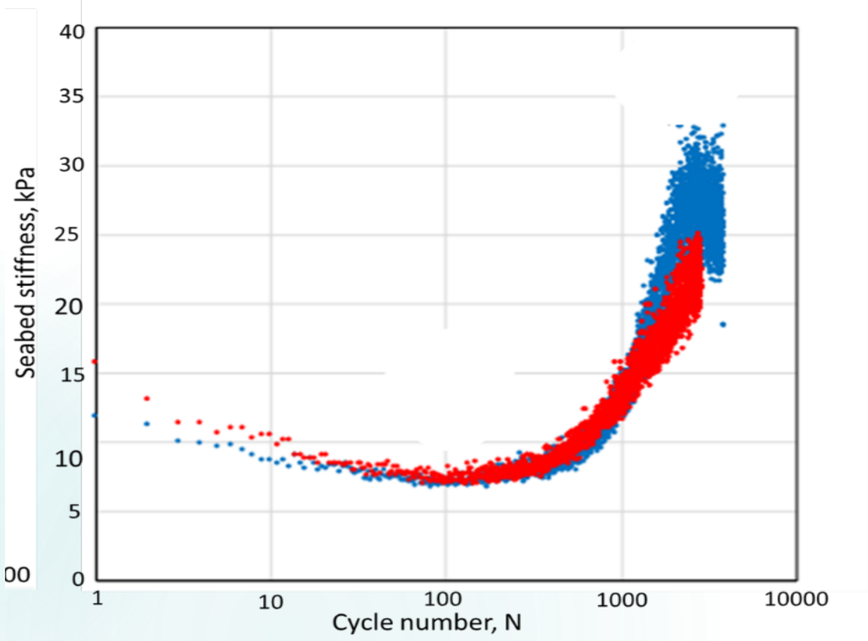




(from Clukey and Zakeri, 2017)

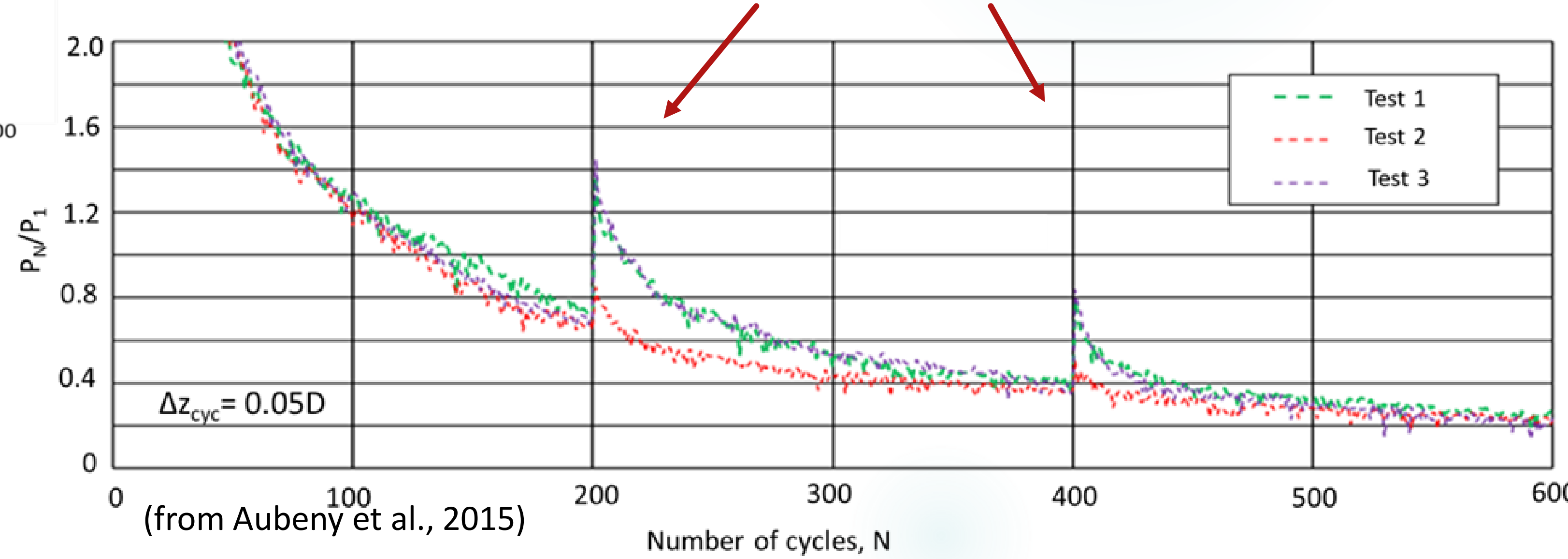
- Secant stiffness based nonlinear curves basis for SCR fatigue in design

SCR fatigue- consolidation issue



(from Yuan et al., 2016)

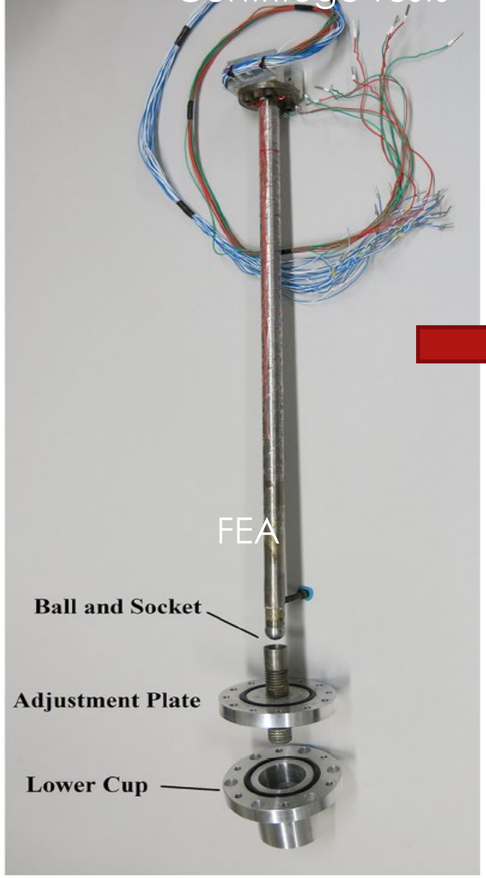
0.2 to 17 day wait periods

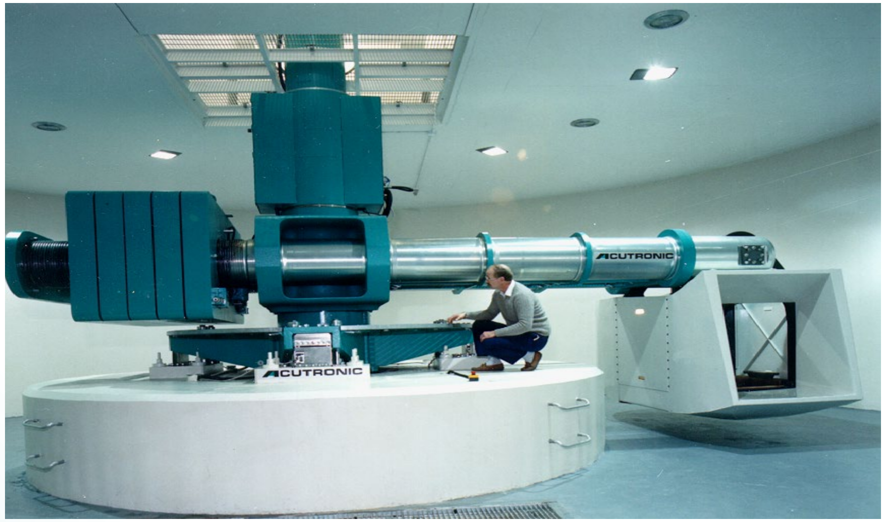


(from Aubeny et al., 2015)

Approach-conductors

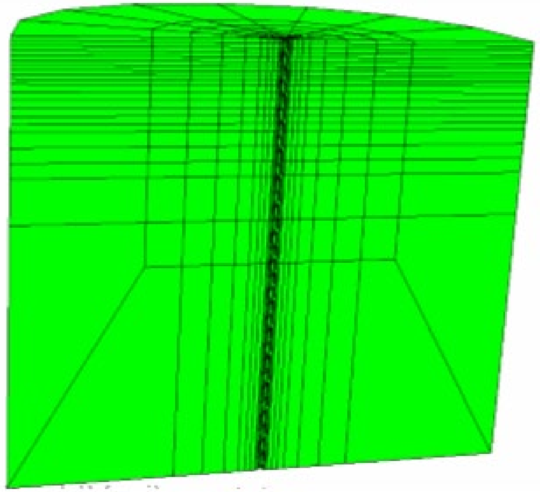
Centrifuge Tests

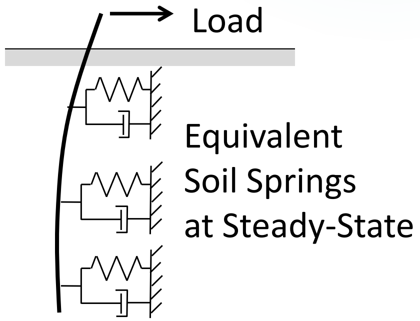




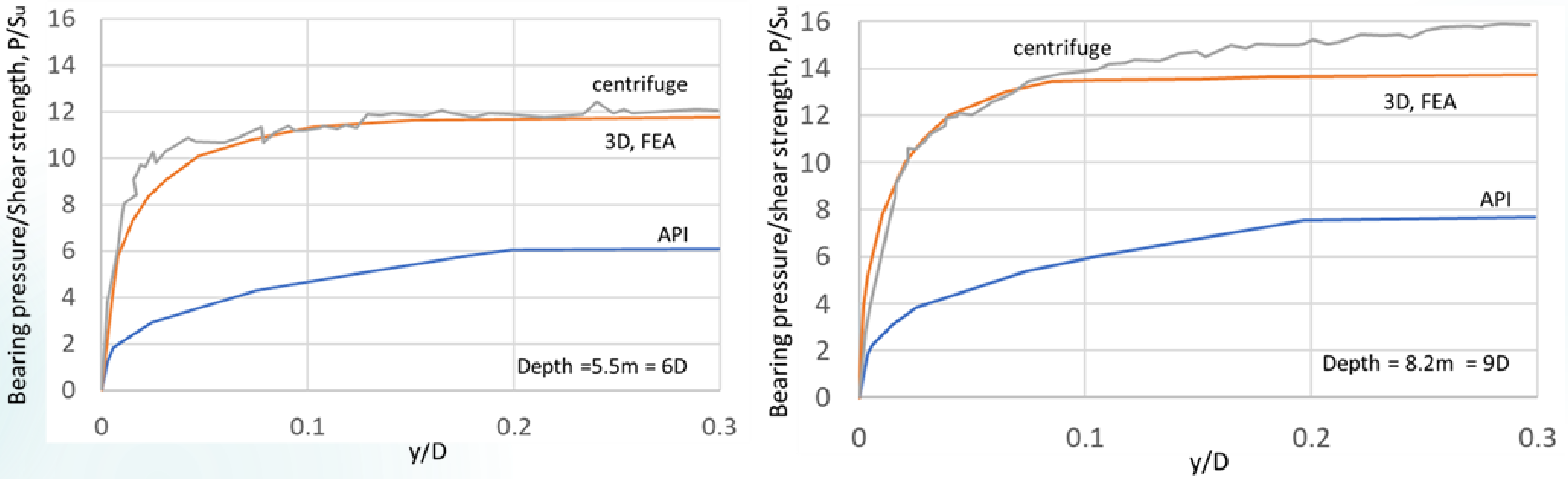
C-CORE centrifuge

FEA



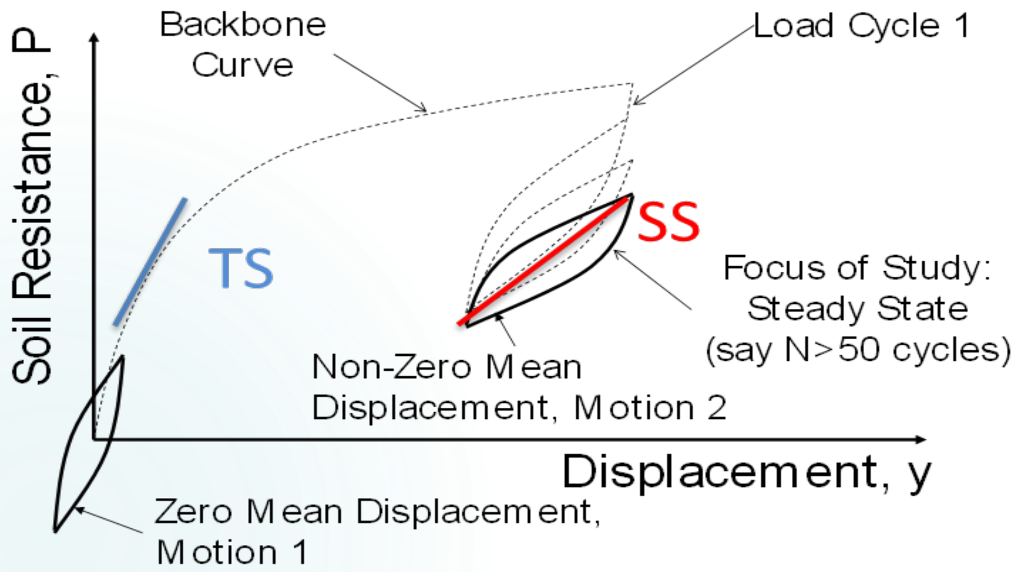


Conductors – p-y curves



(modified from Jeanjean, 2009)

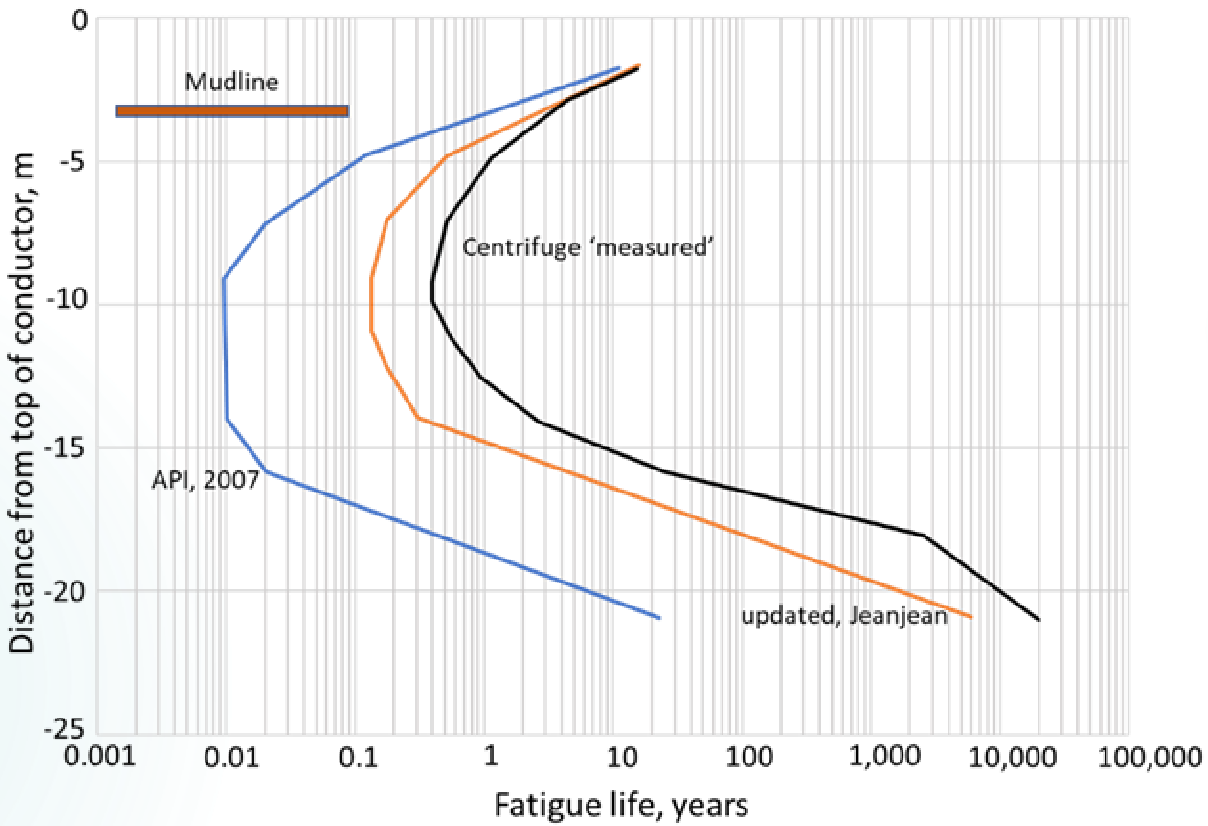
Compensating errors



Modified from: Jeanjean, 2009

- API backbone curves too soft
- Existing codes use tangent stiffness (TS) along backbone curve
- Fully degraded steady state secant stiffness (SS) appropriate
- SS >TS

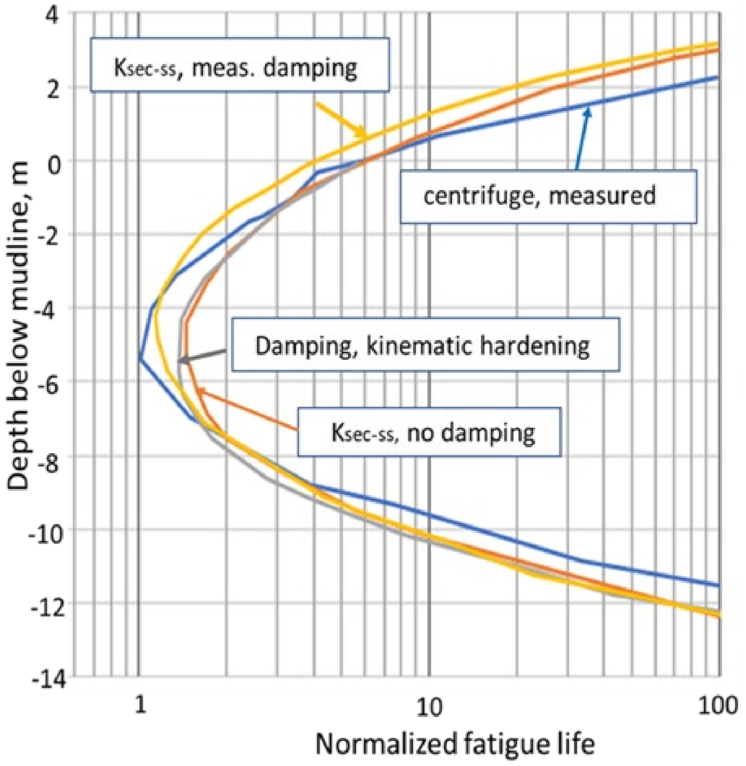
Initial fatigue -conductors



(from Zakeri et al., 2015)

Revised approach -conductors

Harmonic motions



(from Zakeri et al., 2015)

- These results are basis for API design code updates for piles & conductors

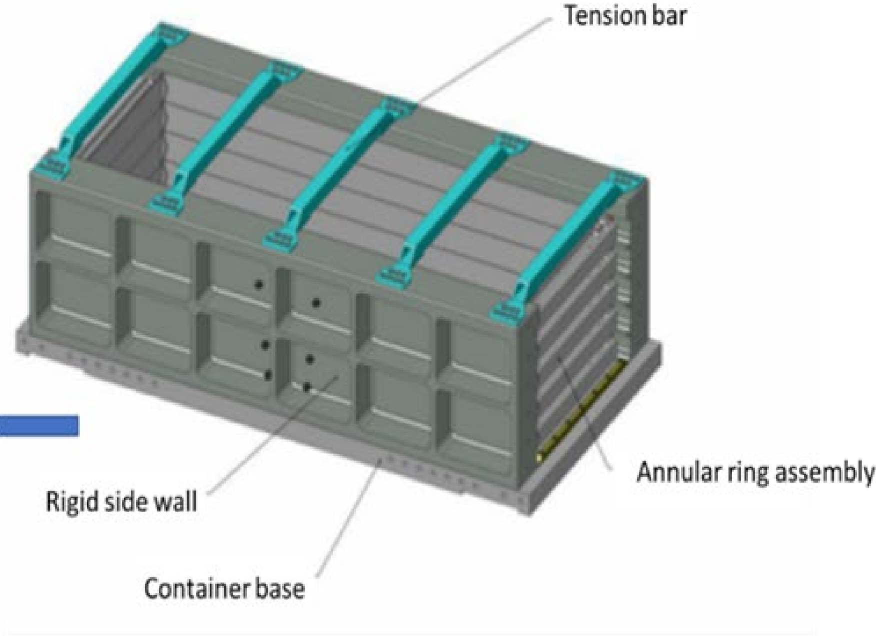
Primary takeaways

- Fatigue problems need to focus on small strain behavior
- SCR fatigue very complicated due to remolding (pipe seperation) & consolidation processes – sectional tests provide better representation of problem and mitigate load vs displacement control effects
- API p-y curves in NC clays significantly too soft and have been adjusted for piles & conductors

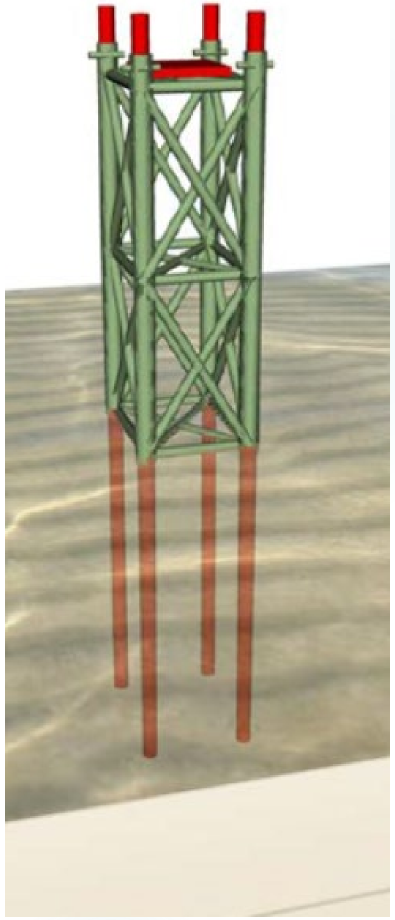
Earthquakes –steel jackets & manifolds

UC Davis centrifuge & shake table

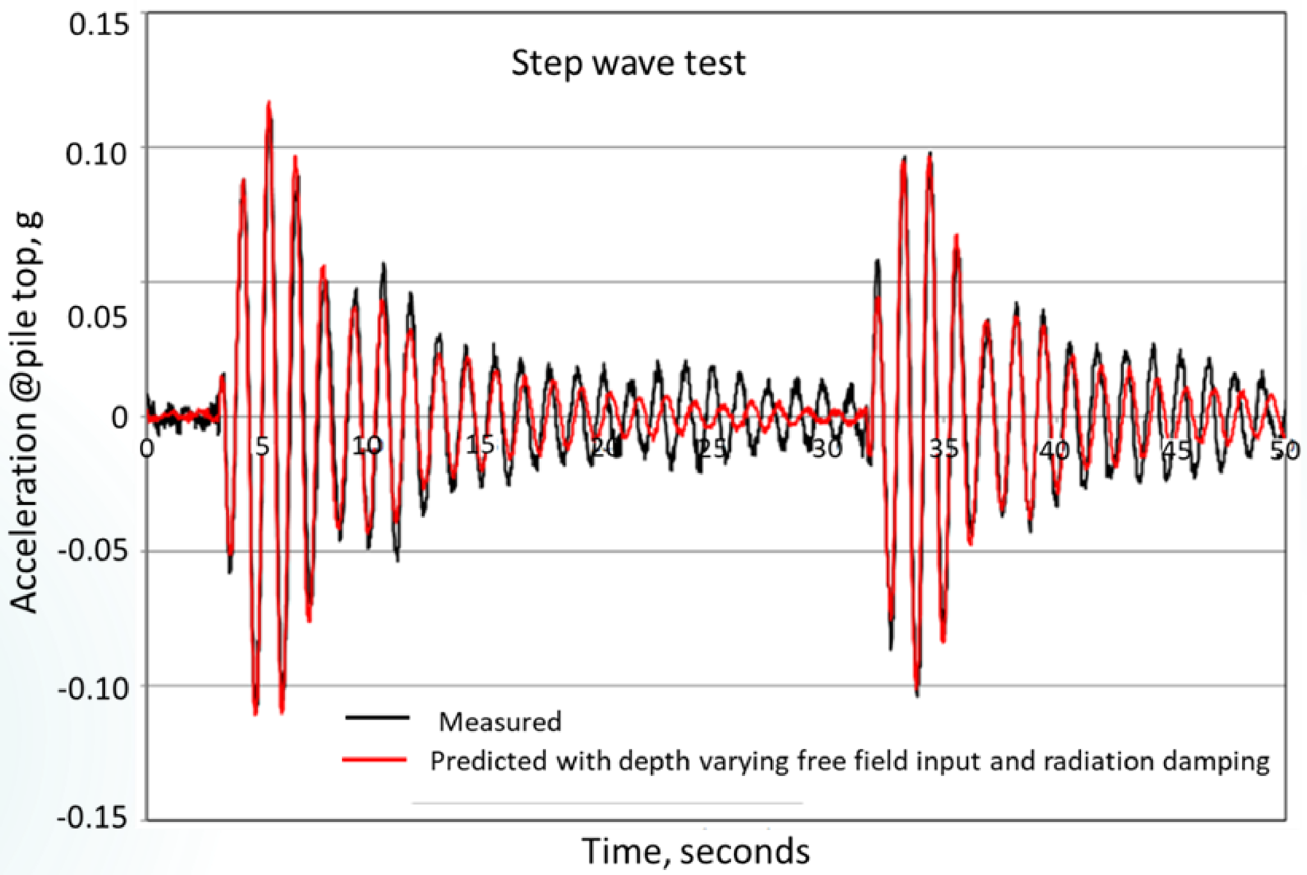
Laminated shear box



(modified from Litton et al., 2014)

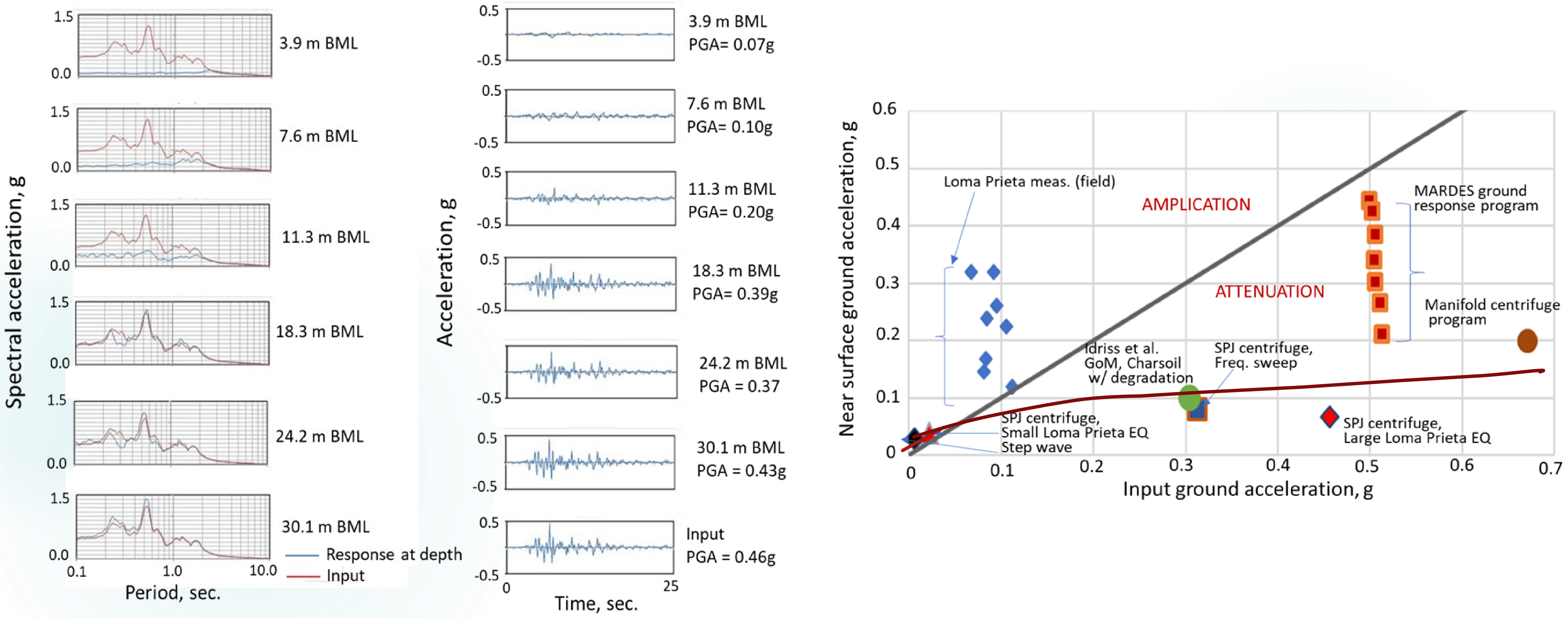


Earthquakes –step wave-free vibration test



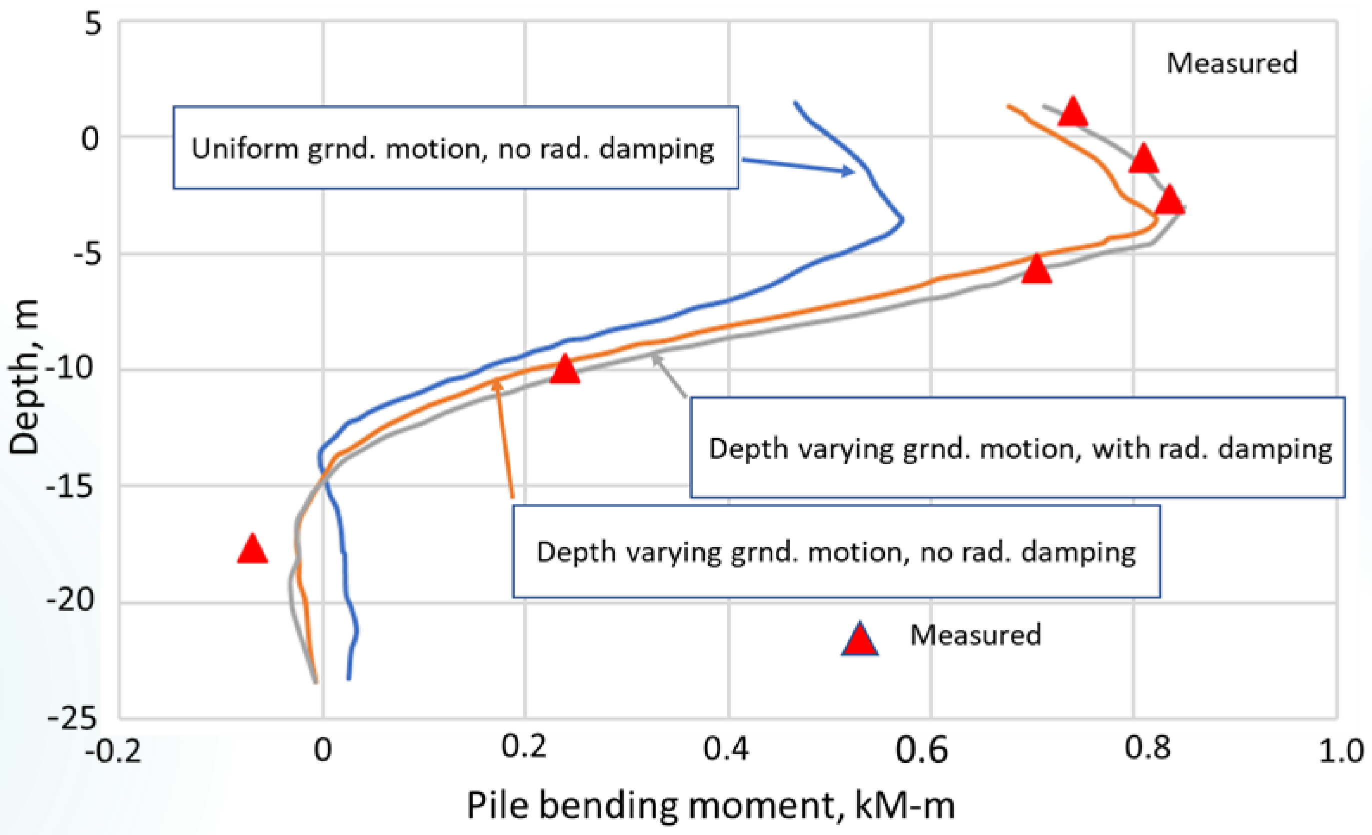
(modified from Litton et al., 2014)

Earthquakes – free field acceleration



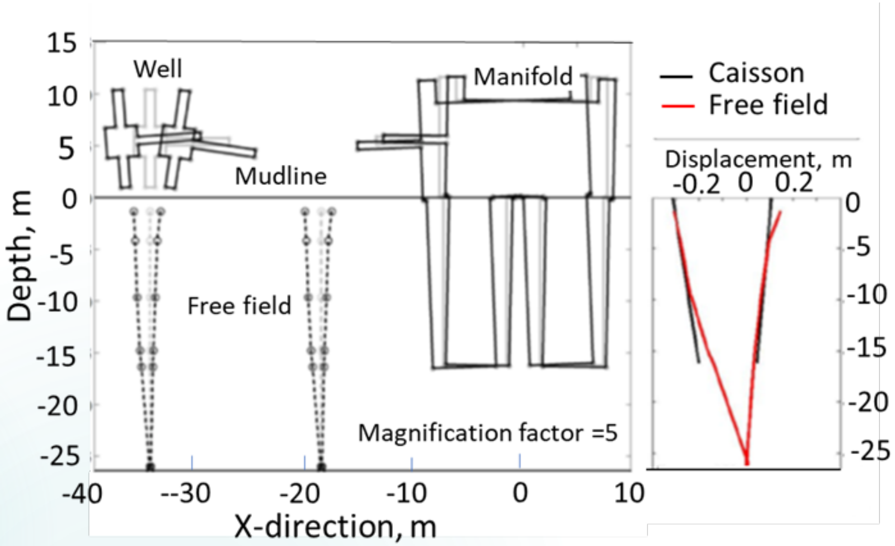
(modified from Litton et al., 2014)

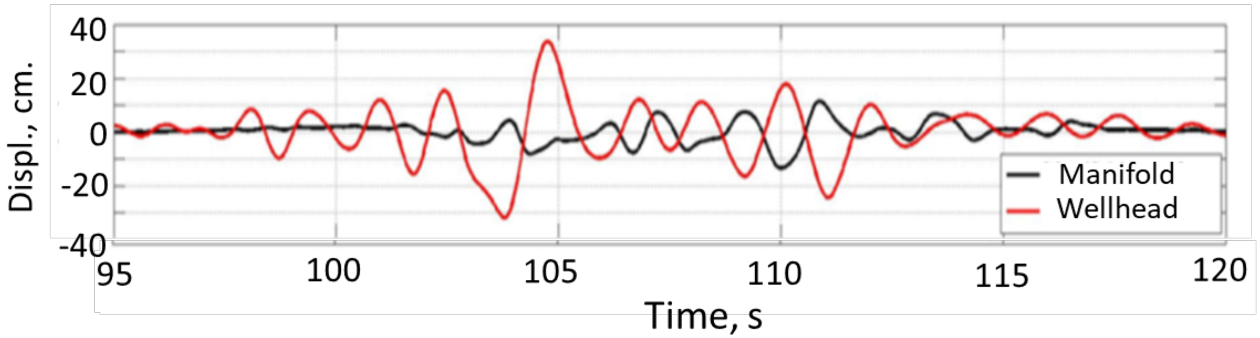
Earthquakes –bending moments



modified from Litton et al., 2014)

Earthquakes –steel jackets & manifolds





(modified from Zheng et al. 2015)

Primary takeaways

- Free vibration tests again showed the need for revised p-y curves to properly predict natural period of pile
- Depth dependent accelerations and radiation damping also required for accurate predictions.
- Much larger attenuation observed in ductility level earthquake with thick NC clay layer
- Centrifuge provided capability to model structure and foundation.

Final thoughts

- Remember your model is a proxy for field conditions
- Don’t work in silos - remember importance of numerical work
- Know what you’re modeling, right & wrong – dimensional approach
- Remember interaction with the structure
- Have fun - take chances

Remember, ‘You cannot swim for new horizons until you have the courage to lose sight of the shore’

William Faulkner

Acknowledgements

University

WPI

Professor Armand Silva

Cornell

Professor Fred Kulhawy

Professor Phil L-F Liu

Industry

USGS

Dr. Dave Cacchione

Dr. Monty Hampton

McClelland Engr.

Mr. Alan Young

EPRCo

Dr. Don Murff

Dr. Jack Templeton III

BP

Dr. Philippe Jeanjean

Dr. Arash Zakeri

Acknowledgements

The Spinners

LCPC

Dr. Jacques Garnier

C-CORE

Dr. Ryan Phillips

UC Davis

Professor Bruce Kutter

Dr. Dan Wilson

UWA

Professor Mark Randolph

Dr. Christophe Gaudin

Univ. Colorado

Professor H. Y. Ko

Personal

Sean & Kevin Clukey

Ms. Maryellen Dufresne

Ms. Jan Sanford

Manuscript prep.

Ms. Jill Revette