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

Hiking in hill country, Texas

Hiking in upper Yosemite

Inside Holstein SC with Jean Audibert

Thunder Horse suction caisson Installation (aboard Balder)
Sightseeing during Japanese centrifuge facility tour

Inspecting Japanese centrifuge facility

Visiting Italy

w Alan Young and friends in Angel Fire New Mexico

w/ Ms. Sanford @ Versailles
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
Ed – the geotechnical profession is in your debt
The Role of Physical Modeling in Offshore Geotechnical Engineering

5th McClelland Lecture

by:

Ed Clukey

Austin, TX
August, 2022
Father of offshore geotechnical engineering

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

Correct stress gradients

Correct body forces

Appropriate failure mechanisms

Professor Ron Scott

Professor Andrew Schofield

Dr. Don Murff
Centrifuge scaling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>( L_mN = L_p )</td>
</tr>
<tr>
<td>Stress</td>
<td>( \sigma_m = \sigma_p )</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho_m = \rho_p )</td>
</tr>
<tr>
<td>Time-consolidation</td>
<td>( T_mN^2 = T_p )</td>
</tr>
<tr>
<td>Time acceleration</td>
<td>( T_mN = T_p )</td>
</tr>
<tr>
<td>Acceleration</td>
<td>( a_m/N = a_p )</td>
</tr>
<tr>
<td>Force</td>
<td>( F_mN^2 = F_p )</td>
</tr>
<tr>
<td>Strain</td>
<td>( \epsilon_m = \epsilon_p )</td>
</tr>
<tr>
<td>Mass</td>
<td>( m_mN^3 = m_p )</td>
</tr>
</tbody>
</table>

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

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

\( \lambda = \) 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

\[ \frac{P}{P_0} = \cosh \lambda \left( \frac{k_x}{k_z} \right) \frac{1}{\sqrt{z+d}} \]

- Top of bed
- Bottom of bed

Kx/Kz = 1.4

(modified from Sleath, 1970)

(from Clukey, 1983)
Sand test observation – sand ripples

Observation

Traditional sediment transport

(from Clukey, 1983)
1. Wave Height: 24 m
2. Water depth: 70 m
3. Wave length: 324 m
4. Liquefaction depth: 2.0 to 2.5 m

- Φ ≥ 90 degrees
- Tensile stresses
Measured effective stresses

(from Clukey, 1983)
Stress circle analysis

'Normal' waves can cause liquefaction & bed failure

$T = 1.58$ sec.
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)
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

\[ C_D = 1.6 + \frac{12.8}{Re^{1.45}_{non-Newtonian}} \]

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

Drag + BC

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

(from Zakeri, 2009)
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

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

(from Clukey and Phillips, 2006)
More advanced tests

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

α (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

\[ \frac{Q}{Q_{out}} \]

Hold time, days

\[ \text{Note: per centages are vert. displ. of pipe dia.} \]

Centrifuge results, U. W. Australia
Centrifuge results, C-CORE
FEA, GoM, L/D=7
FEA, GoM, L/D=5
FEA result from 2 GoM sites

(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

Touch Down Area (TDA)

Threaded connection

Conductors

From: Zakeri at al., 2015
SCR fatigue

Lab segment tests
Watchett Harbor
Lake Oreille, Oregon
(from Grant et al., 1999)
SCR fatigue – cyclic loading

**Normalized soil stiffness**

\[ K = k / (N_c S_u) \]

**Graph:**
- **Axes:** Depth, z (repenetration) and Normalized soil stiffness versus Normalized displacement z/D.
- **Lines:** Various curves for different stiffness values (K=65, K=10, K=270, K=40).
- **Data Points:** Segment test data shown as a scatter plot.
- **Equation:** The plot shows a linear relationship with the equation \( y = 0.3719x^{0.992} \).

**Legend:**
- Backbone Curve
- Penetration
- Unloading
- Soil Suction
- Re-penetration after breakout
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

From: Templeton, 2009

C-CORE centrifuge
Conductors – p-y curves

(modified from Jeanjean, 2009)
Compensating errors

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

$SS > TS$

Modified from: Jeanjean, 2009
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 separation) & 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

(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
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