Full-scale Testing and Numerical Modeling of Axial and Lateral Soil Pipe Interaction in Deepwater

Civil and Environmental Engineering Department

H41F-0900

Mohammad Sarraf J.[1], Aram M. Raheem[2] , C. Vipulanandan[3]

AGU Fall Meeting, San Francisco, December 2014

Abstract

A thorough understanding of the behavior of deep sea pipes is crucial for off-shore oil & gas industry. During the service life, network of oil and gas pipelines that connect the floating platforms to the subsea wells in deepwater undergo significant changes in temperature and pressure resulting in high shears, strains and movement. These pipelines laid on the very soft seabed become susceptible to large movement and lateral buckling resulting in global instability of the entire system. Hence, it is of paramount importance to address the aforementioned issues through combined numerical modeling and experimental study of various conditions in the field. Modeling this behavior needs to take into account the complex interactions between pipe, water, and soil (which, in this case, will be a saturated porous media). Physical experiments can be challenging as the undrained shear strength is very low of the order of 0.01 kPa. In this research, we have performed large-scale experiments as well as numerical modeling. Several full-scale models have been designed and constructed to investigate the behavior of various types of pipes (steel, plastic) on the simulated clayey sea bed (undrained shear strength ranged from 0.01 kPa to 0.11 kPa). On the numerical modeling front, the pipe-soil behavior is simulated using the Coupled Eulerian Lagrangian (CEL) and Arbitrary-Lagrangian-Eulerian (ALE) formulations.

Pipe Soil Interaction Solutions

➢ Plasticity Solutions

Classical Plasticity theory was utilized to establish lower and upper bound solutions .

strain-rate dependence of undrained shear strength and soil remoulding (gradual loss of strength) could be considered via Upper-Bound-Based Strain Path Method (UBSPM) which merges conventional strain path method and classical upper-bound solutions

➢ Numerical Solutions(LDFE and Material Non Linear Analysis)
- Lagrangian Formulation
- Coupled Eulerian Lagrangian (CEL) Formulation
- Arbitrary Lagrangian Eulerian (ALE) Formulation
- Remeshing and Interpolation Technique with Small Strain (RITSS)

➢ Experimental Model Tests
- Centrifuge Tests
- Model Tests

Research Objective

(1) Propose a clear methodology to establish a CIGMAT Reflective Gridding System to capture soil displacement field and quantitatively tracing ensuing berms formation at vicinity of pipe during series of authentic full-scale tests.

(2) Perform parametric study on the axial pipe soil interaction considering the effect of pipeline material, rate of loading, initial embedment, boundary length and soil shear strength.

(3) Determine axial force displacement responses using different large displacement finite element model.

CIGMAT Reflective Gridding System (CRGS)

Reflective Gridding System (RGS®) is comprised of a projector and series of transparent grids that are reflected on the surface of model test. Set of three cameras are placed along axis of x, y and z to capture soil displacement at desired area at any time. In order to make the soil displacement traceable for camera, specific color chips were placed on top layer of soil. RGS help cameras better synchronize pipe movement and soil deformation at any time increment (Figure).

Fig.. Major components of the systems model for diked wetlands

CRGS Implementation Steps

1) Designing and assembling RGS pattern sheets by copying the gridlines from a parent model outside the soil tank to transparent sheets. These transparent sheets are then fixed on the projector and reflected on the soil model. The angle and distance of projector should be considered in a way that gridlines are straight and perpendicular on the whole surface of soil model.

2) Calibrating and correlating the change in shape and angles of reflected grids to the new topography of soil in every square. Imagine "pattern 1" is reflected on the soil model and due to pipe movement one or some of the gridline squares turn into "shape A" as shown in Figure 3.11. By a quick guess, it is obvious that this new gridline represent a decrease in the elevation of soil in that area or a puddle but the main challenge here is to quantitatively associate any change in the angle or configuration of gridline to the new topology of model. To address this challenge different topography of soil with different slops were built up in CIGMAT laboratory and new gridline patterns meticulously photographed and recorded to make a data base.

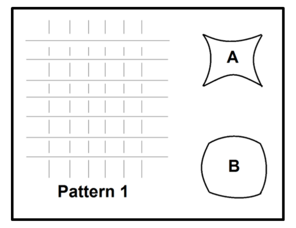


Figure Interpretation of Deformed Gridline from Plan View.

3) Placing light-weighted color chips on the surface of soil model before start of the test. During the test this very small chips will move with particles of soil (soft soil with undrained shear strength of 0.01 to 0.11 kPa) and due to their distinct color they are easier to be tracked. This step is highly recommended if displacement fields in the soil surface are wanted. For berm formation studies during the pipe movement this step could be escaped.

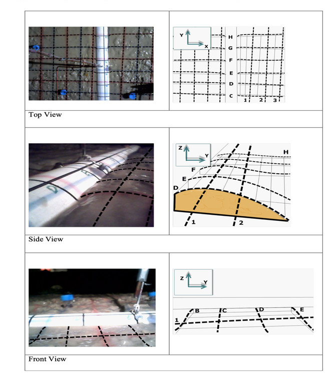


Figure CRGS Simulation for Axial Full Scale Testing.

4) Running the test and recording pipe and soil movements from three cameras in x, y and z axes simultaneously.

5) For any time increment, the photos should be analyzed and nodes (grids intersection) in each photo should be assigned to mathematical coordinates using computer programs. Some commercial photographic software are capable to automatically delineate points of different exposure (in here bright gridlines from the rest of photo). Berms and heaves geometry is exactly determined by merging nodes' coordinates from X, Y, Z cameras.

Laboratory Experiments

Large scale model test was used to simulate the pipe interaction with the soft clay soil representing the seabed. The large scale test facility was 2.44m (8ft) in length, 2.44 m (8ft) width and 1.83 m (6 ft) height and was designed with proper drainage and loading frame at CIGMAT (Center for Innovative Grouting Materials and Technology). The machine used to test the sliding pipe for both axial and lateral was displacement controlled and the pipe was attached to the loading machine using a pulley system with string. During the axial test, the machine pulled the pipe at varying rates. The experimental setup is shown in the following Figure for axial loading. The sliding resistance of pipe on the soft soil was measured using a load cell. The load cell was calibrated and was accurate to 0.01 lb. The pipe displacement in vertical and horizontal directions was monitored using two sets of linear variable differential transducers (LVDT). Excess pore water pressure during axial and lateral cyclic test was monitored by pore pressure transducer installed beneath the pipe invert.

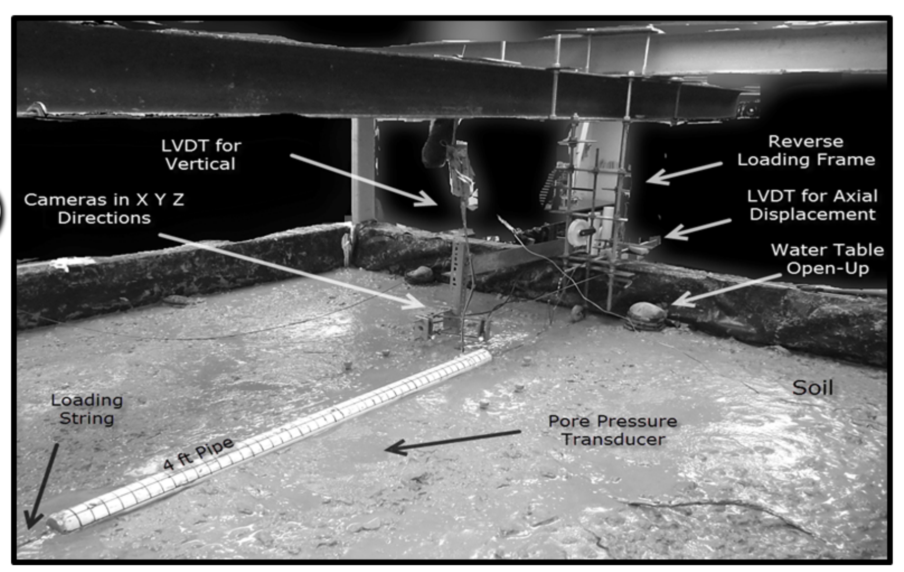


Figure Axial Pipe Soil Interaction Testing Facility at CIGMAT (Center for Innovative Grouting Materials and Technology)

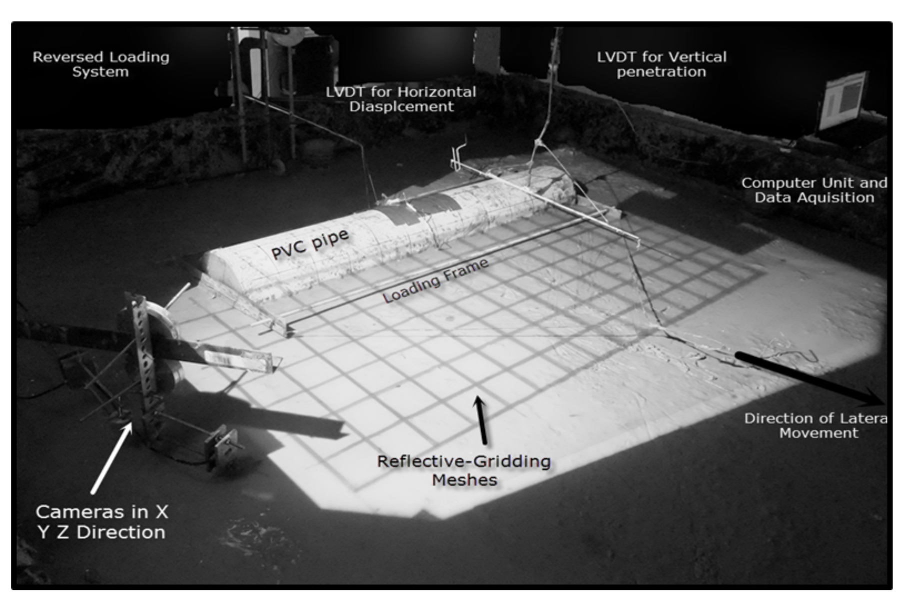
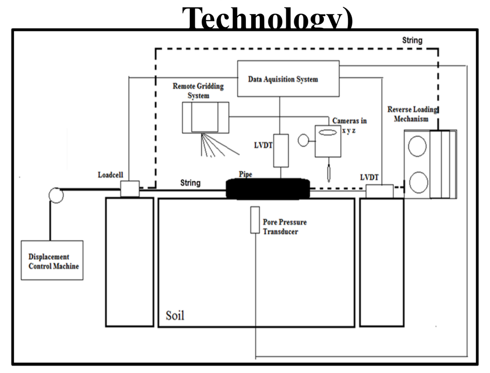


Figure Visualization of CRGS during Full Scale Testing at CIGMAT (Center for Innovative Grouting Materials and Technology)



Numerical Modeling

Sixty-six numerical FEM models were developed in python syntax and user-defined subroutines including SIGINI (to define initial stress field), UMAT (to define constitutive modeling) was used. Finally the python, which is the built-in scripting language of ABAQUS software and FORTRAN subroutines combined and executed in Abaqus/CAE.

The analyses were executed by applying undrained total stress approach. Therefore, the Mohr-Coulomb soil model with no hardening cap was defined with zero friction angle and dilation angle (similar to Tresca model). The elastic part of soil model was defined with Poisson's ratio of 0.49 (almost no volume change) and with young's modulus of 430Su. To obtain optimal E=430Su several models with different E ranged from E=100Su to E=600Su was established and run in ABAQUS. Then the axial force displacement response compared to the experimental test. The E=430Su showed minimum discrepancy. On imperfection of ABAQUS is that linear variation of undrained shear strength with depth cannot be defined as an input . **The undrained shear strength at any point and time increment is a non-linear function of strain rate, and Depth**:

$$S_u(x,t) = f\left(S_{u0}\,, S_t\,, \Delta\epsilon_{p1}, \Delta\epsilon_{p2}\,, \kappa\,, z\,, V_p, \Delta\epsilon_1, \Delta\epsilon_3\,, \dot{\gamma}_{max}, \mu\right)$$

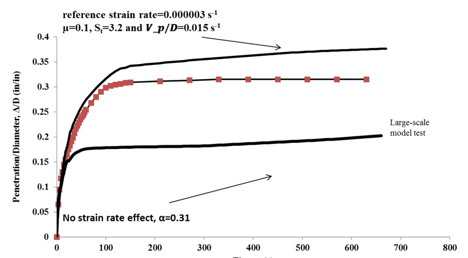
The effect of soil strength non-homogeneity ($Su=Suo+\kappa Z$) and buoyancy on the vertical resistance of pipelines was evaluated. And the effect of strain rate on shear strength was considered as following after each time increment

$$S_u = \left[1 + \mu \log\left(\frac{max(\dot{\gamma}_{max}, \dot{\gamma}_{ref})}{\dot{\gamma}_{ref}}\right)\right] S_{u0}$$

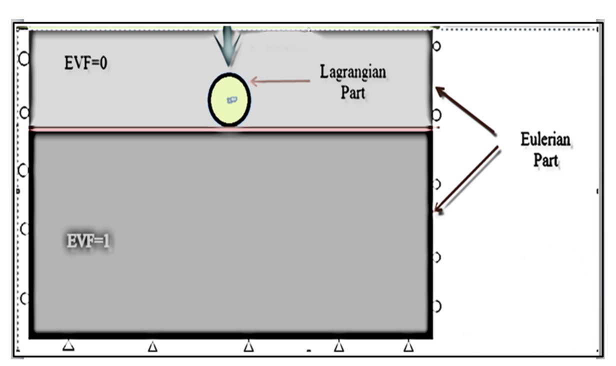
Where:

$$\dot{\gamma}_{max} = \frac{(\Delta\epsilon_1 - \Delta\epsilon_3)}{\frac{\delta}{D}} * \frac{V_p}{D} \quad ; \quad \dot{\gamma}_{ref} = 1 * 10^{-6}\, s^{-1}$$

$\Delta\epsilon_1, \Delta\epsilon_3$ = Major and Minor Principal strain
V_p = Vertical velocity of pipe
δ = Displacement increment
$\dot{\gamma}_{max}$ = Max shear Streain rate at a given location
μ = Rate of strain increase per decade strain rate
κ = Shear strain gradient
$z = Depth$

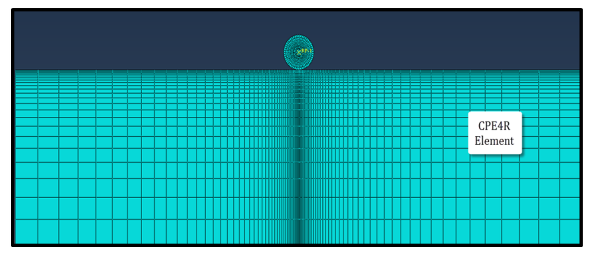


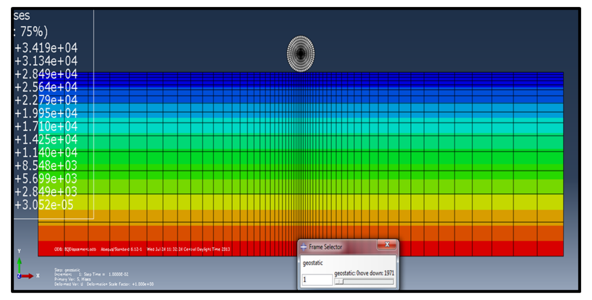
➢ Coupled Eulerian Lagrangian (CEL):



The EVF (Eulerian Volume Fraction) in ABAQUS determines the presence of material inside the element such that EVF=0 means void and EVF=1 means 100% presence of material and any number between 0 and 1 suggests an uncertainty in the presence of material.

➢ Adaptive Lagrangian Eulerian (ALE):





Material	Su(kPa(psi))	D (in)	W (lb-force)	δinitial (in)	Vp (in/min)	λ(in)
Plastic	0.01 (0.0015)	1.35,2.4	0.73, 2.36	No-over-penetration	0.10	96
Plastic	0.03 (0.0044)	2.4,8.5	0.73, 2.36, 7.5	No-over-penetration	0.1,1.05,5	96
Plastic, Metal	0.06 (0.0087)	1.35,2.4,8.6	0.73, 2.36	No-over-penetration,0.25,0.35,0.45	1.05	96
Plastic	0.08 (0.012)	1.35	2.40	No-over-penetration	1.05	10,96,24
Plastic	0.1 (0.0145)	2.40	2.40	No-over-penetration	0.10	96
Plastic , Metal	1 (0.145)	2.4, 8.5	2.40	No-over-penetration,0.55	0.10	96

The concept of the build-in-ALE in ABAQUS consists of five stages. The simulation is performed as usual 10 increments. In most cases the frequency of adaptive meshing is the parameter that most affects the mesh quality and the computational efficiency of adaptive meshing. In an adaptive meshing increment, a new, smoother mesh is created by sweeping iteratively over the adaptive mesh domain. During each mesh sweep, nodes in the domain are relocated—based on the current positions of neighboring nodes and elements—to reduce element distortion

➢ The domain is rediscertized to form a new mesh.

➢ An "advection" process is carried out to convey the variables from the old mesh to the new mesh. ABAQUS uses a Petrov-Galerkin weighting of the free boundary constraint to suppress any oscillations on the boundary regions.

➢ The simulation is continued and this process is repeated.

Results

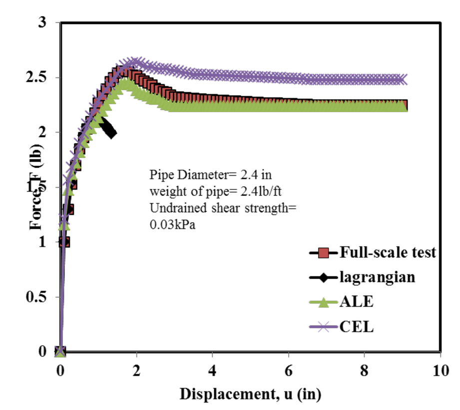


Figure Axial Force Displacement Responses for Pipe Sliding on Soil with Undrained Shear Strength of 0.11 kPa.

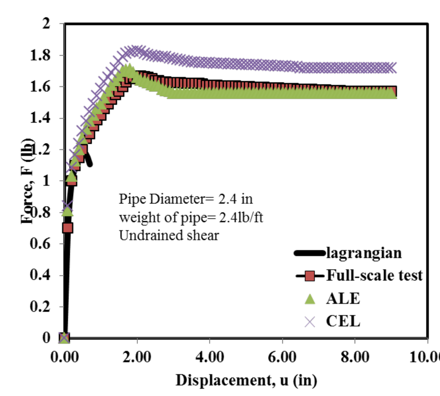
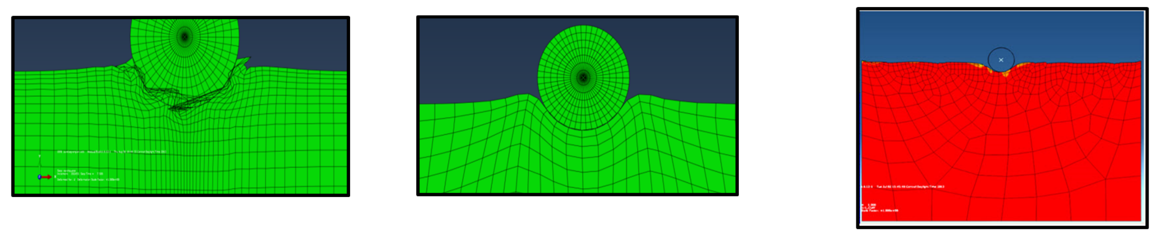


Figure Axial Force Displacement Responses for Pipe Sliding on Soil with Undrained Shear Strength of 0.03 kPa.



(A) (B) (C)

Figure Numerical Analysis: (A) Pure Lagrangian, (B)ALE, and (C) CEL

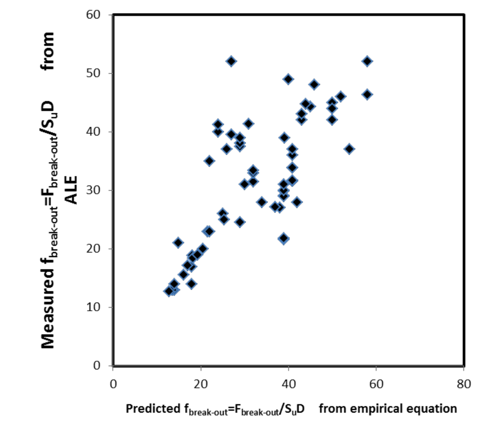


Figure Comparison of the Breakout Resistance Calculated from Empirical Equation and from ALE Finite Element Analyses

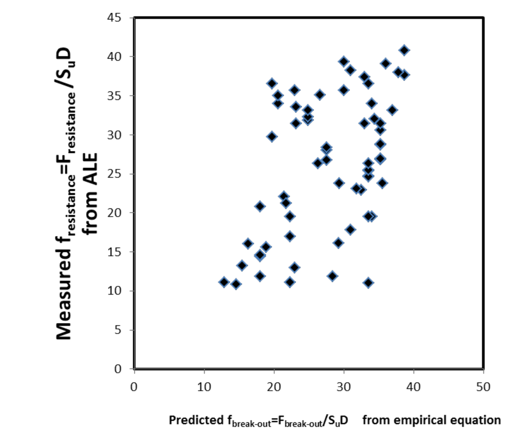


Figure Comparison of the Residual Resistance Calculated from Empirical Equation and from ALE Finite Element Analyses

Conclusions

➢ Large-scale model test was successfully instrumented and simulated the real behavior of plastic and metal pipe on very soft soil.

➢ Series of close photogrammetry approaches were employed in Remote Gridding System (RGS) to capture soil surface displacement field and also berm formation at vicinity of pipe.

➢ Coupled Eulerian Lagrangian (CEL) and Arbitrary Lagrangian Eulerian (ALE) was extensively used to determine axial force displacement responses of subsea pipe on rate-dependent, depth dependent very soft soil.

Authors

[1] MSc., Department of Civil and Environmental Engineering, University of Houston, Houston, TX, m.sarraf.j@gmail.com

[2] Ph.D. Student, Department of Civil and Environmental Engineering, University of Houston, Houston, TX, amraheem@uh.edu

[3] Professor, Department of Civil and Environmental Engineering, University of Houston, Houston, TX, cvipulanandan@uh.edu

References

Sarraf, M. J, Vipulanandan, C. "Axial And Lateral Sliding Of Pipe On Simulated Seabed Soft Soil" Houston: Center for Innovative Grouting Material and Technologies (CIGMAT), 2013.

Sarraf, M. J., Vipulanandan, C. "Numerical Simulation of Subsea Pipeline Response during Installation and Earthquake" Houston: Texas Hurricane Center for Innovative technology, 2013.