Torpedo Piles Joint Industry Project -
Model Torpedo Pile Tests in Kaolinite Test Beds

by

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EXECUTIVE SUMMARY

Torpedo piles are steel, torpedo-shaped objects that are installed as projectiles penetrating the sea floor under velocity. They are a potentially viable alternative for anchoring both mobile drilling units as well as permanent facilities. However, they have not yet been used in the Gulf of Mexico. The goal of this project was to improve understanding about how torpedo piles behave during installation and pull-out by conducting 1:30 scale model tests in normally consolidated beds of kaolinite. The model torpedo piles consisted of a straight shaft with a conical tip and a load attachment at the heel (or top).

The following conclusions are drawn from this work:

1. The embedment depth of a torpedo pile increases as the drop height and the weight of the pile increase, and it can be predicted accurately using a simple model for the soil resistance based on its undrained shear strength.
2. The axial pull-out capacity under undrained loading after set-up increases with the embedment depth, the undrained shear strength of the soil, and the weight of the torpedo pile. The soil immediately adjacent to the shaft may be reconstituted at a higher moisture content during penetration; the predicted capacity in our model tests matches the measured capacity when an empirical side shear transfer factor, α, value of 0.5 is used in the prediction model. This zone of reconstituted soil is localized, and may not affect the mobilized side shear on the fins for a torpedo pile with fins.
3. The lateral pull-out capacity under undrained loading after set-up is predicted well by a simple model that assumes the pile rotates as a rigid body in undisturbed soil.

The model test results indicate that torpedo piles do have the potential to provide a practical alternative for offshore anchors. Recommendations for further work include performing additional model tests in the laboratory and full-scale tests in the field.

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INTRODUCTION

Torpedo piles are steel, torpedo-shaped objects that are installed as projectiles penetrating the sea floor under velocity. They are a potentially viable alternative for anchoring both mobile drilling units as well as permanent facilities. However, they have not yet been used in the Gulf of Mexico. The goal of this project was to improve understanding about how torpedo piles behave during installation and pull-out by conducting 1:30 scale model tests in normally consolidated beds of kaolinite.

BACKGROUND

Torpedo-shaped projectiles penetrating soil have been considered and studied for a variety of applications (Table 1). The earliest work was to use projectiles as disposable devices for characterizing soil. The torpedo would be dropped and its position versus time tracked using acoustic telemetry. The measured profile of deceleration through the soil could be used to estimate the shear strength of the soil. Examples of studies related to using torpedoes for site characterization include McNeill (1979), Young (1981), Chari et al. (1981), Beard et al. (1985), and Levacher (1985). In the 1980's, torpedo-shaped containers were considered for use in disposing of nuclear waste. Several large-scale field tests were performed for this application, as reported by Freeman et al. (1984), Freeman and Burdett (1986), Freeman et al. (1988), and Hickerson (1988).

Recently, torpedoes have been used as piles to anchor oil and gas facilities offshore Brazil. Medeiros (2002) reports on Petrobras's successful use of more than 90 torpedo piles to anchor flexible risers. These 30-in.-OD, finless torpedo piles have also been used to anchor ships and mono-buoys. The author also describes field tests in the Campos Basinwith torpedo piles with outside diameters (OD) of 30 and 42 inches. The 30-in.-OD torpedo piles used to anchor risers were fitted with fins and weighted up to 400 kN, while the 42-in.-OD piles had an air weight of 620 kN. Penetrations ranged from 13.5 to 29 meters after a 30-m free fall. Pull-out capacities immediately after deployment were roughly 1.5 times the air weight of the torpedo pile, while pull-out capacities after ten days of set-up time were 3 to 4 times the air weight of the torpedo pile. Unfortunately, no information about the soil conditions has been published for these tests. These tests were intended to support the use of torpedo piles to anchor mobile offshore drilling units (MODUs) and Floating Production Storage and Offloading (FPSOs) facilities (Fig. 1). The larger torpedo piles were incorporated into the Petrobras P-50 FPSO renovation (Bonfim dos Santos et al. 2004). Centrifuge model tests of the Petrobras torpedo anchor designs were performed in kaolin beds at the Center for Offshore Foundation Systems (COFS) of the University of Western Australia (O'Loughlin, 2004). These 75-mm long models were scaled for mass, length and surface area of the flukes to represent a typical average torpedo pile used by Petrobras. The model impact velocities were 10 to 30 m/s and vertical pull-out capacities normalized for frontal area compared well with the results of the full scale tests described by Medeiros (2002).

Figure 1. Typical torpedo pile geometries (after Bonfim dos Santos et al 2004)

Table 1. Summary of published data for torpedo-shaped projectiles penetrating soil

Testing Program	Diameter (in)	L/D	Air Weight (lb)	Velocity at Impact (ft/s)	Theater	Reference
SEASWAB	3	20	100	80	Marine	McNeill, 1979
	9	11	1100	900		
Wendover, Utah	3 to 8.75	12 to 26	12 to 300	72 to 300	Onshore	Young, 1981
Laboratory	0.8	NA	NA	7.5	Laboratory	Chari et al., 1981
	3	NA	NA	7.5		
Station G141	3	48	76	NA	Marine	
Summary of many sites	3.5	22.5	315	82 to 88	Marine	Beard, 1985
DOMP I RRS *Discovery*, GME	12.8	10	3970	164	Marine	Freeman et al., 1984
Laboratory	2	3.8	5	10 to 30	Laboratory - Model	Levacher, 1985
DOMP II MV *Tyro*, NAP	9.1	25	3970	171	Marine	Freeman and Burdett, 1986
	12.8	11.1	3970	180		
	12.8	10	5200	203		
	15.7	10.2	3970	148		
	19.7	4	3970	157		
	12.8	14.4	5830	180		
	12.8	14.4	4750	164		
Tyro 86 MV *Tyro*, GME	14	10	4120 to 6930	141 to 223	Marine	Freeman. et al., 1988
	15	6.7	3970			
	14	10	3020	NA		
				98		
Hocus *Castor 02* Antibes, Mediterranean	10.7	13.9	3250	148	Marine	Hickerson, 1988 Freeman et al., 1988
	14.1	10	4160	105		
	12.8	10	3970	161		
	12.6	9.4	3420	98		
	15	7.5	3970	121		
Flexible Risers MODU anchor	30	15.7	53,900	33 to 72	Marine	Medeiros, 2002
	30	15.7	89,900	NA		
	42	11.2	139,000	NA		
Laboratory	0.24	12.5	0.028 to 0.037	33 to 98	Laboratory (Centrifuge)	O'Loughlin et al., 2004

OBJECTIVES

The goal of this study was to provide a fundamental understanding of how torpedo piles behave in normally consolidated clay during installation and pull-out under rapid loading conditions (representing a storm load). Specific objectives were:

1. Measure how the final penetration depth of a torpedo pile varies with the velocity at the mudline, the weight and geometry of the torpedo pile, and the undrained shear strength of the clay;
2. Measure how the pull-out capacity for rapid loading varies with the penetration depth, the set-up time between installation and pull-out, the angle of loading, and the undrained shear strength of the soil; and
3. Compare measured behavior with predictive models of behavior.

APPROACH

The objectives were achieved by conducting tests in large tanks of normally consolidated kaolinite using torpedo piles with a scale that is approximately 1:30 field scale. Kaolinite was used because (1) it drains quickly compared to other clay soils, meaning that preparation and set-up could be accomplished quickly and (2) it has been the subject of numerous model tests for offshore foundations both here and elsewhere (e.g., El-Sherbiny et al. 2005 and O'Loughlin et al. 2004). The model torpedo piles had a diameter of 1 inch and a length of 12 inches. They were designed to be as simple as possible with a straight shaft, a conical tip and no fins. The intent in using a simplified geometry for the pile was to provide fundamental information that could be compared with and possibly extrapolated to a variety of different torpedo pile shapes.

EXPERIMENTAL EQUIPMENT

A schematic of the test equipment is shown on Figure 2. The soil tanks holding the test beds of kaolinite soil (Fig. 3) have been utilized for many similar testing programs in the past with suction caissons: Luke (2002), Coffman (2003) and El-Sherbiny (2005). The tanks were made by bolting together two steel, 4- foot by 8-foot tanks, each 3 feet tall (Pedersen 2001 and Luke 2002). The tanks have a drainage layer in the bottom to accelerate consolidation of the kaolinite during test bed preparation. A drainage valve was added in this study so that the bottom drainage layer could be vented to the atmosphere to speed consolidation. An aluminum frame rests on top of the tanks and provides a framework to mount the required panels and pulleys for model torpedo pile deployment and recovery, as well as T-bar tests to measure the undrained shear strength of the kaolinite.

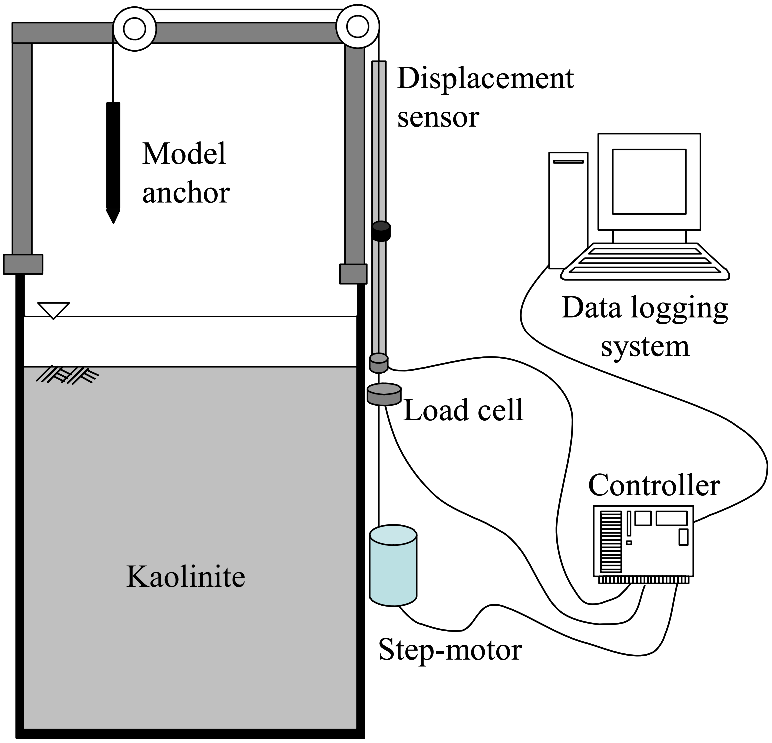


Figure 2. Schematic of test equipment (from Audibert et al. 2006)

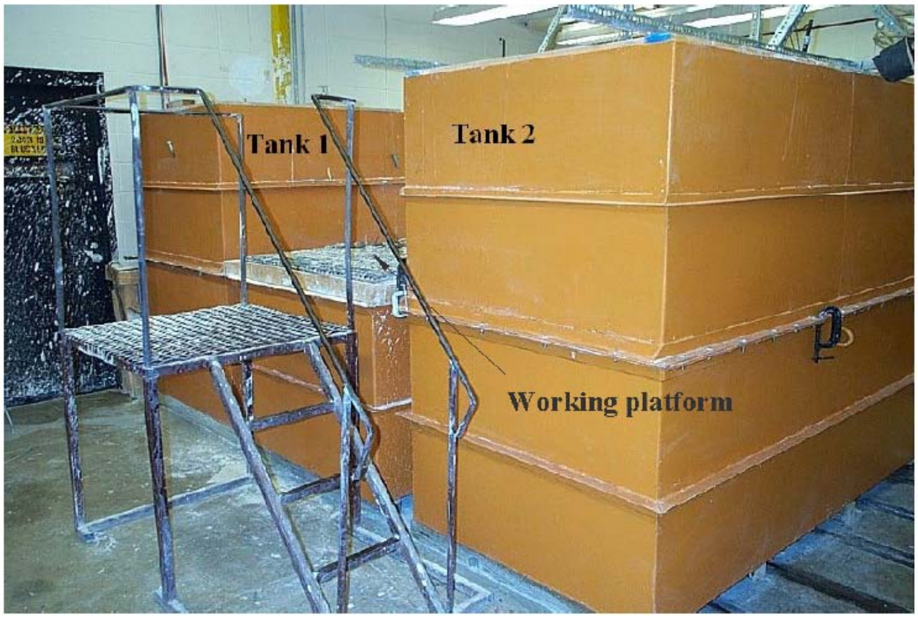


Figure3. Soil tanks (from Vanka, 2004)

The test beds were prepared from kaolinite consolidated from slurry under self-weight. The kaolinite had a mean particle size of 0.7 µm and a specific gravity of 2.58. The liquid limit of the clay ranged between 54% and 58% and the plasticity index ranged between 20 and 26. Two test beds from previous testing on suction caissons (El-Sherbiny 2005) were used for preliminary tests; these beds are designated Test Beds 3 and 4. A new test bed was then prepared and consolidated as described by Morvant (2008). This test bed, designated Test Bed 5, was used for the main testing program. Several inches of water were maintained above the surface of the soil (the mudline) during the torpedo pile testing.

The undrained shear strength of the kaolinite beds was measured using a T-bar penetration test. These tests were performed by attaching the 1-inch diameter by 4-inch long acrylic bar (Fig. 4) to the end of a 54-inch long, 0.375-inch-diameter brass rod, which was attached to a universal joint at the top. Just below the universal joint is an acrylic plate that clamps onto the brass rod. Weights can be stacked onto this acrylic plate to provide the driving force for penetration. A 25-pound capacity load cell is attached above the universal joint and provides the resistance measurement. A cable is attached to the top of the load cell and also the vertical actuator. The T-bar is lowered into the test bed at the desired penetration rate using the vertical actuator. In addition, moisture content samples were obtained from the kaolinite beds using a miniature piston sampler built by Pedersen (2001).

Figure 4. Acrylic tip for the T-bar (from Vanka, 2004)

Displacement measurements of the model torpedo pile during deployment were made using an MTS® Tempsonics® 2-meter travel displacement sensor. A portion of a steel measuring tape was secured adjacent to the sensor and provided redundant information on the total displacement of the model during deployment in case there was a problem with the data acquisition system. The model torpedo pile was pulled out from the kaolinite bed using the vertical component of a bilinear actuator or step motor. Forces were measured using an Interface SML-25 load cell with a twenty-five pound maximum capacity. The transducer was calibrated in tension by attaching the top of the load cell to a rigid frame and attaching a hanger to the bottom of the load cell. The same data acquisition system built by Mecham (200) and used by El-Sherbiny (2005) for suction caisson tests was used for this study. The data acquisition system includes the power supplies for the transducers, a data acquisition card and a computer with a National Instruments Labview® software package.

MODEL TORPEDO PILE

The model torpedo pile used for this study (Fig. 5) was machined from aluminum. It is 12 inches long and one inch in diameter. It was designed and machined so that it could be taken apart and ballasted to test piles with different weights. With no ballast, the aluminum model weighs 0.7 pounds in air. When it is ballasted with tungsten and lead, it weighs 1.3 pounds. The model has a 60^{o} conical nose cone at the tip, and has female threads at the heel in order to receive the mail threads of a connector with the cable attachment. The connector is attached to one end of a one-millimeter diameter cable. The cable is a seven-strand stainless steel cable purchased from SAVA Cable and is rated for 250 pounds.

Figure 5. Model torpedo pile

TEST PROCEDURE

The torpedo pile model tests were performed in four stages: preparation, deployment, set-up, and recovery.

Preparation

The first stage is the preparation stage. The aluminum framework that provides the overhead support is positioned across the short axis of the tank, providing the appropriate spacing in the long direction. Once the framework is secured to the top of the tank, the motor that will be used for the recovery of the torpedo pile is mounted and secured to the framework. The pulley that will be positioned above the torpedo pile is then moved to its appropriate location along the framework, providing the required spacing in the short direction of the tank. The 1-mm-diameter cable is then attached on one end to the displacement sensor slide and on the other end to the ballasted and sealed model torpedo pile. Clamps are placed on the displacement sensor's slide rail to prevent the accidental deployment of the torpedo pile while the correct distance above the mud line is being set. Once the tip of the nose of the model torpedo pile is at the desired drop height above the mudline, a nylon cord is attached from an anchor point to the displacement sensor slide. This cord is pull taught so that when the clamps are removed the torpedo pile's elevation does not change. A torpedo pile at the completion of the preparation stage and ready for deployment is shown on Figure 6.

Figure 6. Torpedo pile model prior to deployment

Deployment

The deployment sequence begins by removing the clamps and ensuring that the elevation of the torpedo pile is as desired. The deployment is then triggered by cutting the nylon cord with a pair of sharp shears, allowing the torpedo pile to free fall, impact the mudline and embed itself in the 4-foot thick bed of normally consolidated kaolinite inside the tank. Position data are collected by the displacement sensor and also obtained manually for redundancy by using the slide as a reference point on the scale mounted adjacent to the sensor. The disturbed surface of the kaolinite soil bed is shown in Figure 7 immediately after deployment.

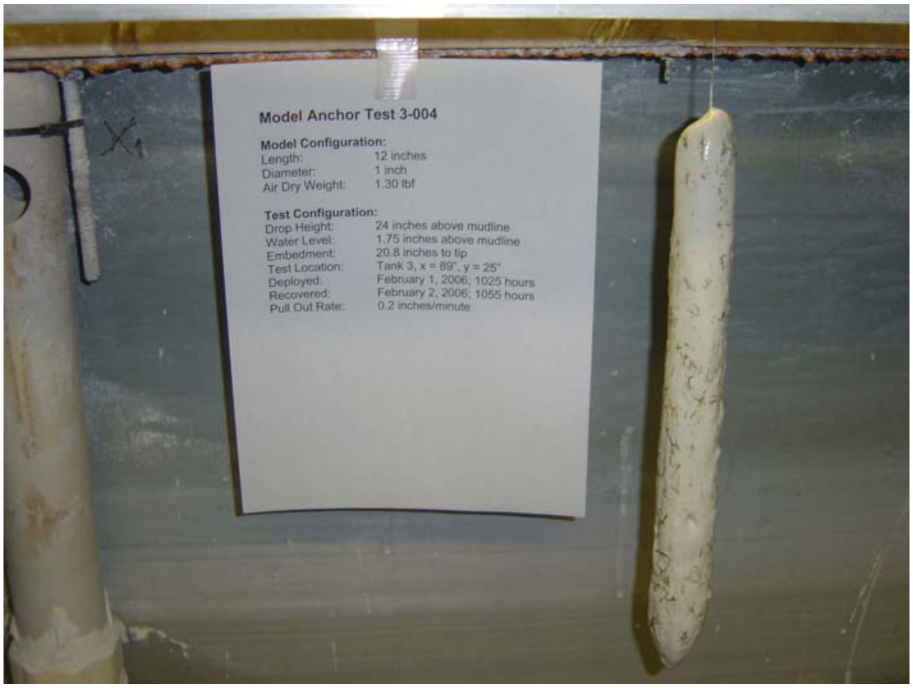
Set-up

The set-up stage begins after the torpedo pile comes to rest in the kaolinite bed a few seconds after it is deployed. The pile is allowed to sit in the soil and set-up for a selected period of time, ranging from hours to days (Appendix A).

Figure 7. Slight disturbance in soil surface after deployment

Recovery

Once the selected set-up time has been reached, a load cell is mounted to the motor for the last stage, the recovery or pull-out test. Data from the load cell are initially recorded to determine the no load or zero reading of the load cell. A nylon cord is then attached from the displacement sensor slide to a loop connection on the load cell. This cord is not pulled taught, but allowed to lay with some slack, so that no force is inadvertently applied to the model. The data acquisition is then started and the motor set in motion at a displacement rate of 0.2 inches per minute. This displacement rate was selected to provide for undrained loading conditions. With this rate, the peak pull-out capacity is reached in about 10 minutes, which is comparable to the times to reach peak deviator stress in laboratory tests for undrained shear strength (ASTM D 2850). The displacement is continued past the peak resistance force until the limit of the motor is reached. The torpedo pile model is then completely withdrawn from the kaolinite bed and the soil adhered to the model is collected for moisture content determination. A torpedo pile that has been recovered and is covered in soil is shown on Figure 8.



Model Anchor Test 3-004

Model Configuration:
Length: 12 inches
Diameter: 1 inch
Air Dry Weight: 1.30 lbf

Test Configuration:
Drop Height: 24 inches above mudline
Water Level: 1.75 inches above mudline
Embedment: 20.8 inches to tip
Test Location: Tank 3, x = 89", y = 25"
Deployed: February 1, 2006; 1025 hours
Recovered: February 2, 2006; 1055 hours
Pull Out Rate: 0.2 inches/minute

Figure 8. Torpedo pile covered with kaolinite after recovery

TEST PROGRAM

The test program consisted of three rounds of testing.

Round 1

The first round of testing was conducted to evaluate the effect of set-up time on the pull-out capacity. These tests were performed in Test Bed 3, which had been used previously for testing model suction caissons (El-Sherbiny 2005). Most of the tests were located in areas that were not previously disturbed by testing of suction caissons so that undrained shear strength data that were available for the undisturbed soil could be used. The test layout is summarized in Table 2 and shown on Figure 9.

Table 2. Summary of model torpedo pile tests performed in Test Bed 3

Test Identification	X Coord (in.)	Y Coord (in.)	Test Type	Date Test Initiated
3-001	89	7	T	January 20, 2006
3-002	89	13	T	January 27, 2006
3-003	89	19	T	January 31, 2006
3-004	89	25	T	February 1, 2006
3-005	89	31	T	February 3, 2006
3-006	83	31	T	February 6, 2006
3-007	83	25	T	February 8, 2006
3-008	83	19	T	February 8, 2006
3-009	83	7	T	February 8, 2006
3-010	79	12	T	February 9, 2006
3-011	72	12	T	February 9, 2006
3-012	60	12	T	February 9, 2006
3-013	66	12	T	February 12, 2006

Key:	T	Model torpedo pile test - deployed with free-fall

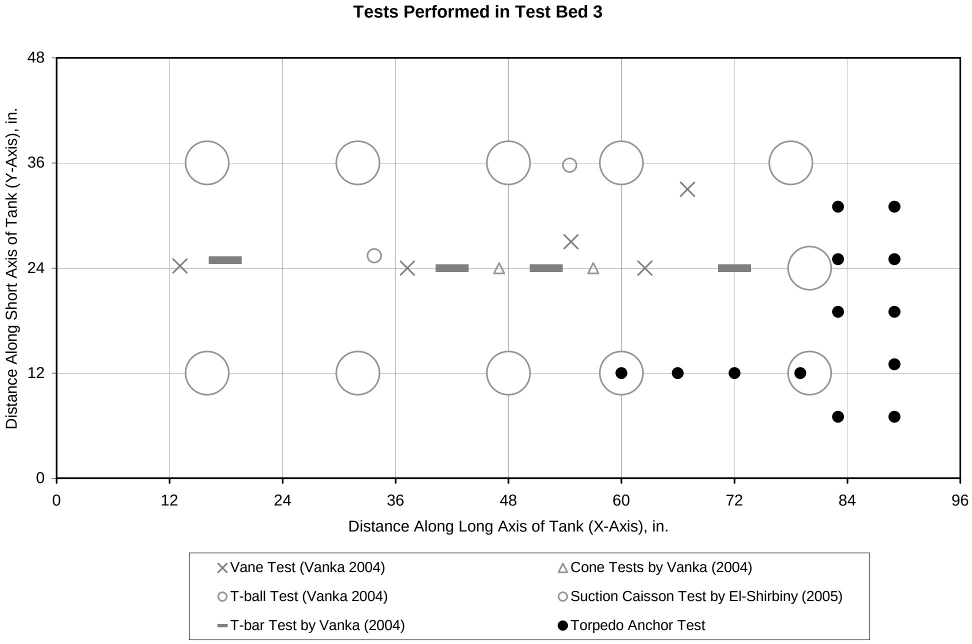


Figure 9. Tests performed in Test Bed 3

Round 2

The second round of tests was conducted to evaluate penetration of the torpedo pile. In these tests, the drop height and weight of the model were varied. In addition, undrained shear strength tests were performed in the vicinity of the torpedo pile tests in order to characterize the soil. The test layout is summarized in Table 3 and shown on Figure 10.

Table 3. Summary of tests performed in Test Bed 4

Test Identification	X Coord (in.)	Y Coord (in.)	Test Type	Date Test Initiated
4-001	37	40	T	February 12, 2006
4-002	37	32	T	February 15, 2006
4-003	37	24	T	February 17, 2006
4-004	37	16	T	February 20, 2006
4-005	29	32	T	February 22, 2006
4-006	29	40	T	February 24, 2006
4-007	29	16	T	February 27, 2006
4-008	17	40	T	March 7, 2006
4-009	17	14	T	March 21, 2006
4-010	17	30	T	March 28, 2006
4-011	17	6	T	April 3, 2006
4-012	16.5	35	T-bar	April 11, 2006
4-013	9	33	T-ball	May 9, 2006
4-014	42	8	T-bar	June 10, 2006
4-015	45	19	T-bar	June 11, 2006
4-016	45	29	T-bar	June 11, 2006
4-017	45	41	T-bar	June 11, 2006

Key:		
	T	Model torpedo pile test - deployed with free-fall
	T-bar	T-bar test
	T-ball	T-ball test

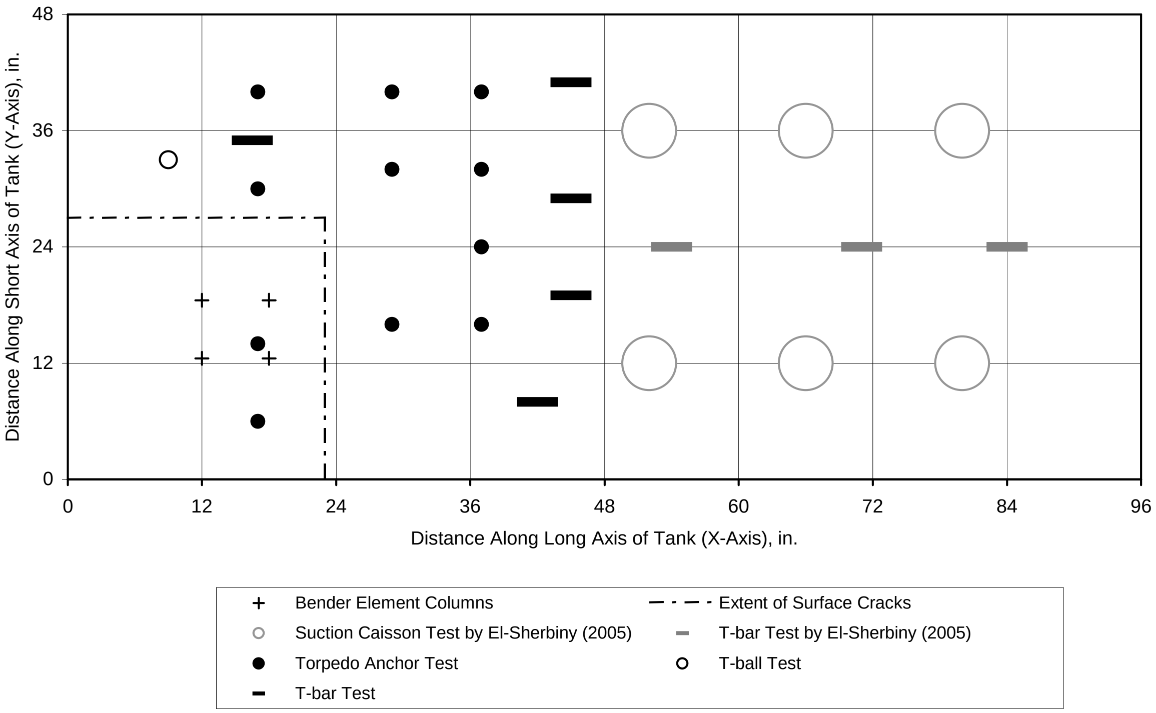


Figure 10. Tests performed in Test Bed 4

Round 3
Pull-out capacity was the focus for the third round of tests. The penetration depth, angle of loading and shear strength of the soil (undisturbed versus remolded) were varied. In addition, the undrained shear strength and moisture content of the soil were measured. The test layout is summarized in Table 4 and shown on Figure 11.

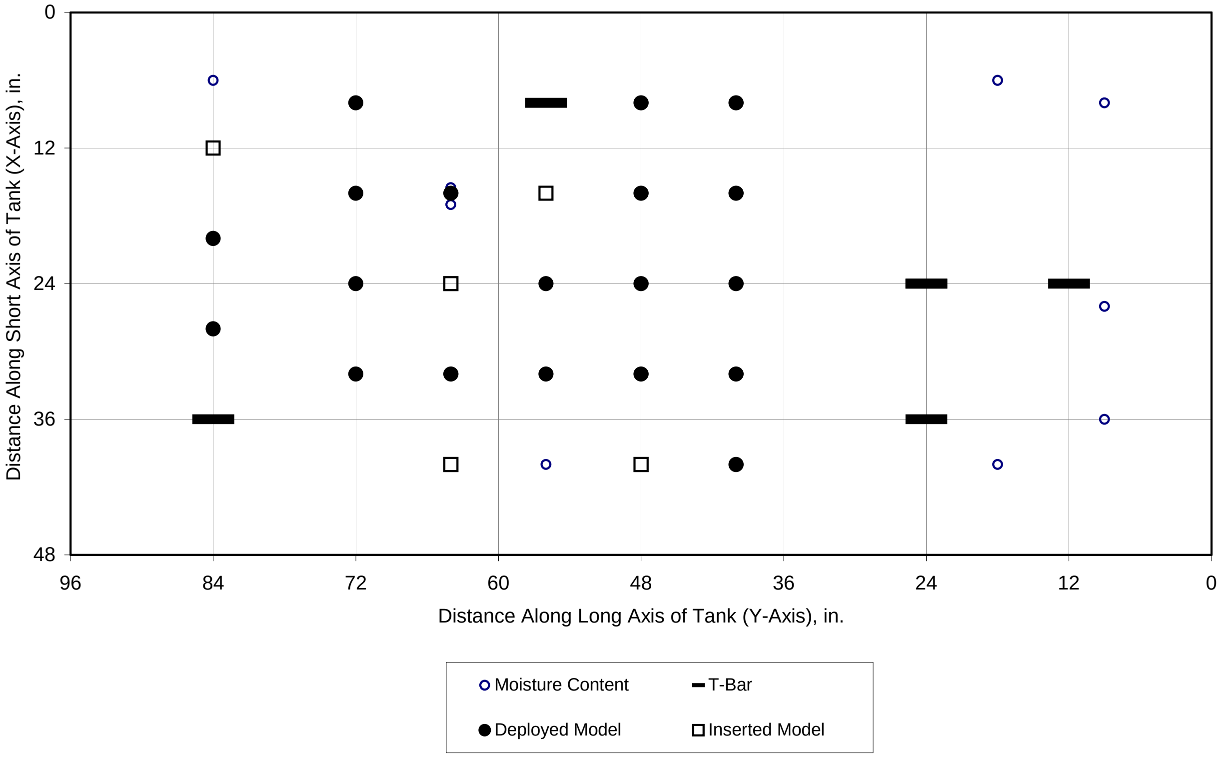


Figure 11. Tests performed in Test Bed 5

Table 4. Summary of tests performed in Test Bed 5

Test Identification	X Coord (in.)	Y Coord (in.)	Test Type	Date Test Initiated
5-001	36	9	M	December 11, 2006
5-002	26	9	M	January 5, 2007
5-003	24	12	T-bar	January 13, 2007
5-004	40	18	M	January 22, 2007
5-005	6	18	M	February 20, 2007
5-006	24	24	T-bar	February 20, 2007
5-007	24	24	T-bar	February 28, 2007
5-008	36	24	T-bar	February 28, 2007
5-009	8	9	M	March 1, 2007
5-010	40	40	T	March 5, 2007
5-011	32	40	T	March 8, 2007
5-012	24	40	T	March 10, 2007
5-013	16	40	T	March 12, 2007
5-014	8	40	T	March 14, 2007
5-015	8	48	T	March 16, 2007
5-016	16	48	T	March 18, 2007
5-017	32	48	T	March 22, 2007
5-018	24	48	T	March 24, 2007
5-019	32	56	T	March 29, 2007
5-020	24	56	T	April 2, 2007
5-021	16	56	Ti	April 4, 2007
5-022	8	56	T-bar	April 7, 2007
5-023	40	56	M	April 7, 2007
5-024	24	64	Ti	April 7, 2007
5-025	40	64	Ti	April 10, 2007
5-026	16	64	T	April 12, 2007
5-027	15.5	64	M	April 23, 2007
5-028	17	64	M	April 23, 2007
5-029	40	72	Tr	April 23, 2007
5-030	16	72	T	April 25, 2007
5-031	24	72	T	April 27, 2007
5-032	32	72	T	April 30, 2007
5-033	8	72	T	May 2, 2007
5-034	40	48	Ti	May 3, 2007
5-035	20	84	T	May 4, 2007
5-036	36	84	T-bar	May 5, 2007
5-037	28	84	T	May 5, 2007
5-038	32	64	T	May 6, 2007
5-039	12	84	Ti	May 7, 2007
5-040	6	84	M	May 7, 2007

Key:	M	Moisture content profile
	T-bar	T-bar test
	T	Model torpedo pile test - deployed with free-fall
	Ti	Model torpedo pile test - inserted into test bed
	Tr	Model torpedo pile test - deployed in remolded soil column

TEST RESULTS

The test results are presented, analyzed and discussed in this section. The results for each individual model test are summarized in Appendix A. Details for all test results are provided in detail in Morvant (2008).

Soil Bed Properties

Profiles for the total unit weight and undisturbed, undrained shear strength versus depth are presented in Figures 12 and 13. These profiles represent average properties based on all of the test results in each test bed, and they represent the properties at the time the torpedo pile model tests were conducted. Test Bed 5 had the lowest unit weight and the smallest undisturbed, undrained shear strength. The variability in undrained shear strength between test beds provides useful information in comparing predicted and measured behavior. The sensitivity of the soil, defined as the ratio of the undisturbed to the remolded undrained shear strength, was approximately two for all of the test beds: 2.0 for Test Bed 3, 1.9 for Test Bed 4 and 2.1 for Test Bed 5.

The undrained shear strengths in Figure 13 correspond to a T-bar penetration rate of 0.2 cm/s, which is comparable to the “conventional” undrained shear strength that is used in pile design and measured in laboratory tests (Vanka 2004 and El-Sherbiny 2005). This rate of shear is also approximately the same as the rate at which the undrained pull-out tests were conducted on the torpedo piles. However, since the soil is sheared at faster rates during torpedo pile penetration, a series of tests were conducted to measure the effect of shear rate on the undrained shear strength (Fig. 15). These tests indicate that the undrained shear strength increases at approximately 21 percent for each log-cycle increase in shear rate, which is consistent with results obtained by El-Sherbiny (2005) in other test beds of normally consolidated kaolinite.

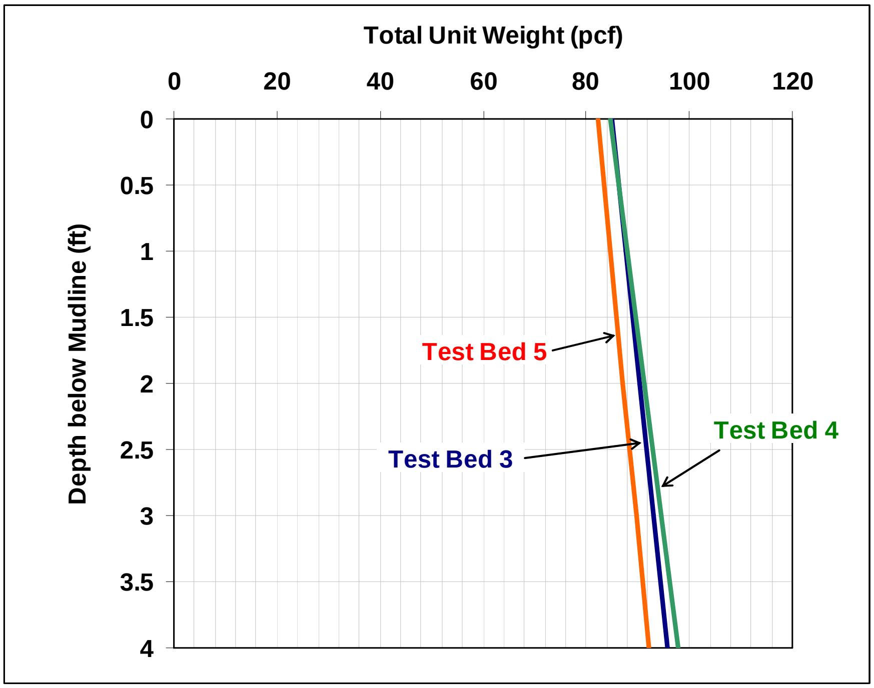


Figure 12. Profiles of total unit weight for test bed soils

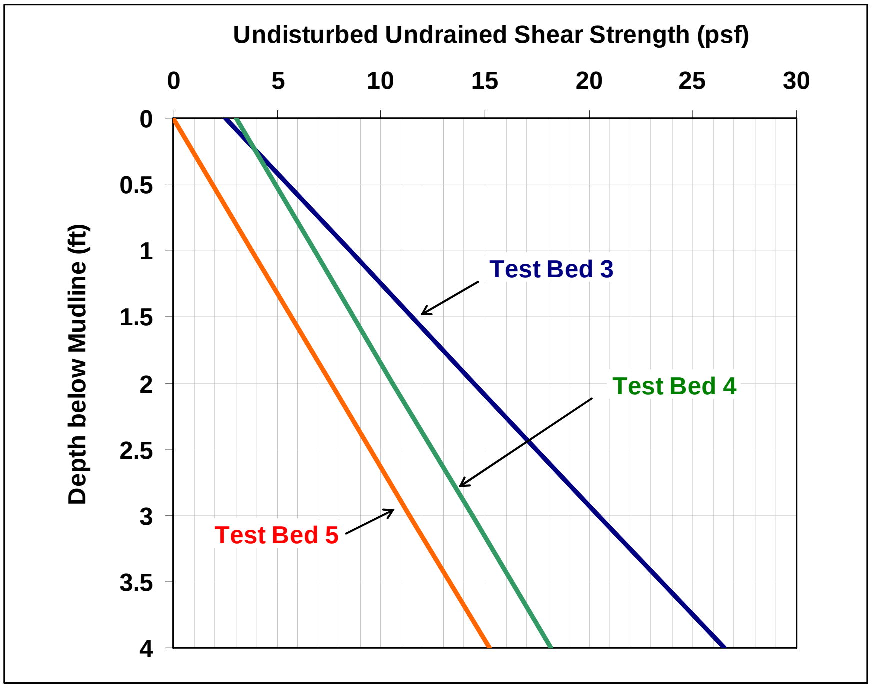


Figure 13. Profiles of undisturbed, undrained shear strength for test bed soils

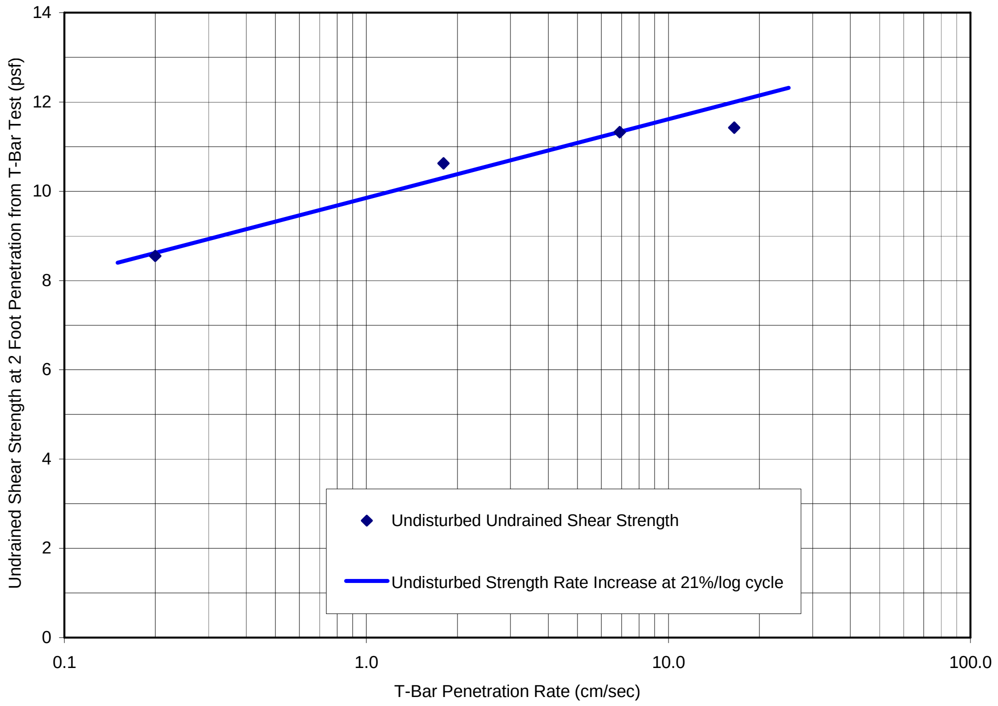


Figure 14. Undrained shear strength versus T-bar penetration rate

Additional data are available from the consolidation of Test Bed 5, which was prepared specifically for the torpedo pile model testing. This bed was created beginning on November 28, 2006 when kaolinite slurry was pumped into the empty tank. The tank was filled to within about a foot of the upper lip and the distance from the tank lip to the mudline was recorded over time. A plot of the height change of the test bed versus time during self-weight consolidation is provided in Figure 15. After 84 days of self-weight consolidation the test bed had consolidated 10 inches, from an initial thickness of five feet to a thickness of four feet, two inches. The drainage valve that had been installed in the tank before the slurry was placed was then opened to apply a hydraulic gradient across the test bed to consolidate the test bed to a higher density and shear strength. This seepage gradient provided an additional one inch of consolidation over a period of a week. Undrained shear strength (Fig. 15) and moisture content profiles (Fig. 16) were also measured periodically during consolidation.

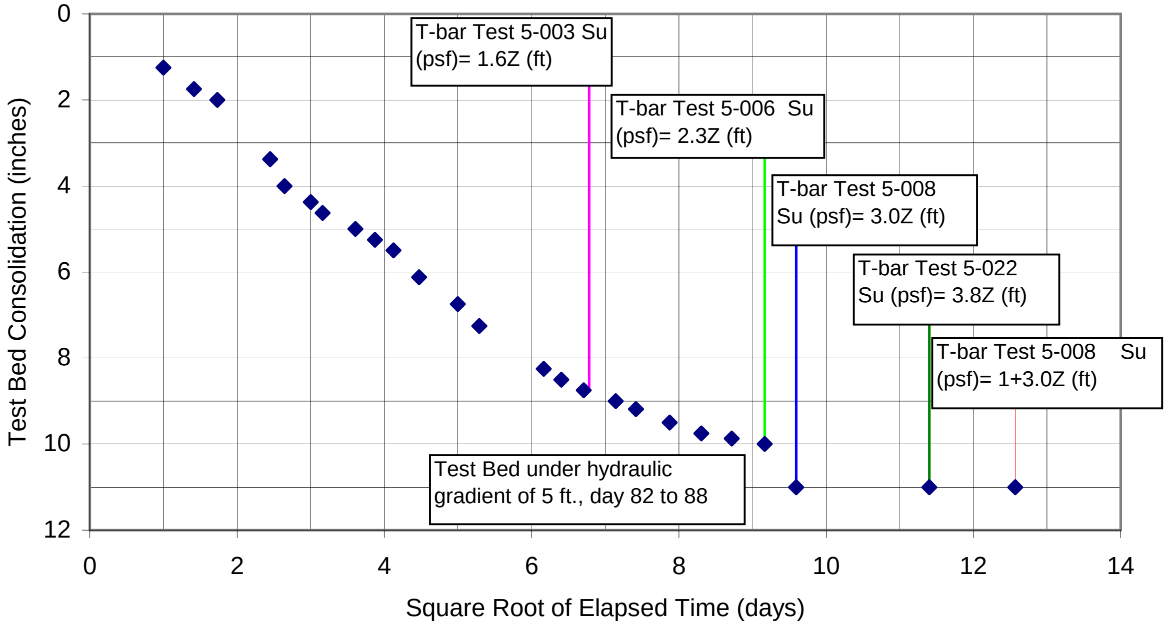
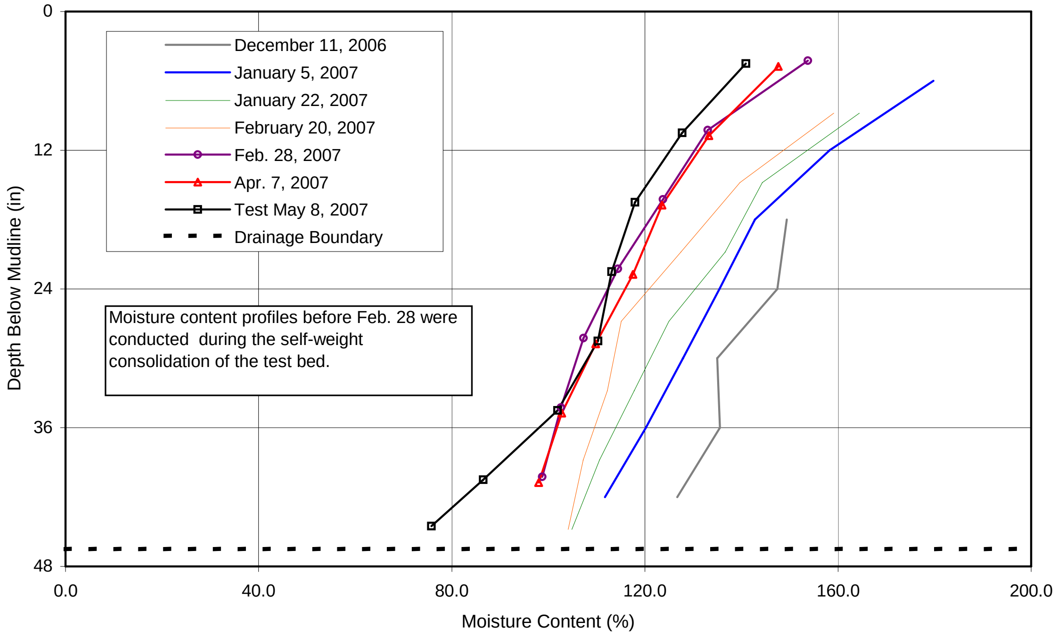


Figure 15. Self-weight consolidation results for Test Bed 5



Moisture Content vs Depth Below Mudline
Test Bed 5

Figure 16. Moisture content results during consolidation of Test Bed 5

Penetration Resistance

The results of penetration tests are summarized in Table 5 and an example profile of velocity versus penetration is shown on Figure 17. As expected, the embedment depth increases as the drop height and the weight of the pile increase.

For comparison, a model of penetration was developed and used to predict the final penetration or embedment for each model test. The embedment model is adapted from a differential equation proposed by True (1976) for the undrained vertical penetration of projectiles into the ocean floor:

$$m'\underline{(dv/dz)(dz/dt)} = W' - F_{resistance}$$

where m' is the submerged mass of the torpedo, v is the velocity of the projectile, t is time, z is depth, W' is the submerged unit weight of the torpedo pile, and $F_{resistance}$ is the upward force resisting movement of the torpedo pile through the air, water or soil. The submerged weight and mass are calculated at a given time based on the length of the pile that is in air, water or soil. When the tip of the torpedo pile is in a fluid, air or water, the resisting force is calculated using Morrison's (Morrsion et al. 1950) equation:

$$F_{resistance} = F_{drag} = ½\, v\, |v|\, A_{end}\, C_d\, \rho_{fluid}$$

where A_{end} is the projected area of the end of the torpedo pile, C_d is the drag coefficient, and ρ_{fluid} is the mass density of the fluid that the tip is in at any given time. A value of 0.15 is used for C_d based on field tests with torpedoes (Visintini 1982). When the torpedo pile enters the soil, the resisting force is calculated using the API (2003) design method for driven piles:

$$F_{resistance} = F_{end} + F_{side} = N_c\, s_{u(v),undisturbed}\, A_{end} + \alpha\, s_{u(v),remolded}\, A_{side}$$

where F_{end} is the bearing capacity at the tip of the pile, F_{side} is the side shear along the shaft of the pile, N_c is an empirical bearing capacity factor, α is an empirical side shear factor, $s_{u(v)}$ is the undrained shear strength of the soil as a function of the penetration velocity, and A_{side} is the area of the shaft that is in the soil. A value of 17 is assumed for N_c, which is consistent with experience with cone penetration tests (Audibert et al. 2006), and a value of 1.0 is assumed for α, which is consistent with a normally consolidated soil. The undrained shear strength, $s_{u(v)}$, is varied with velocity by increasing or decreasing the undrained shear strength in Figure 13 by 21 percent for every log-cycle difference in the penetration rate compared to a base rate of 0.2 cm/s. Since $F_{resistance}$ is a function of the velocity and the penetration depth into water or soil at any given time, the differential equation for the velocity at any given depth or time is solved numerically using a finite difference approach. The predicted embedment corresponds to the depth where the velocity of the torpedo pile goes to zero.

A comparison of measured and predicted embedment depths is presented in Table 5 and Figure 18. The predictive model works very well, with the majority of the predicted values falling within +/- 10 percent of the measured test results (Fig. 18). Most of those points that fall outside of the +/- 10 percent boundaries are for tests where the model was deployed from the mudline, which is not a condition the predictive model was expressly designed to handle as it would be unusual to deploy a torpedo pile without some free-fall before impact. Deploying at the mudline also represents an unusual initial condition for the embedment model as the tip of the model torpedo pile is in water while the shaft is in air.

Table 5. Test results for penetration during deployment

Test Identification	X Coord (in.)	Y Coord (in.)	Air Dry Weight (lb)	Bouyant Weight in Soil (lb)	Drop Height Above Mud Line (in.)	Water Level Above Mud Line (in.)	Embedment Mud Line to Tip (in.)	Predicted Penetration (in)	Prediction Performance Over = Pos. Under = Neg
3-001	89	7	0.69	0.22	12	1.0	12.0	12.2	1.8
3-002	89	13	1.30	0.82	24	1.8	22.6	23.8	5.3
3-003	89	19	1.30	0.82	24	1.8	21.4	23.8	11.2
3-004	89	25	1.30	0.82	24	1.8	20.8	23.8	14.4
3-005	89	31	1.30	0.82	24	1.8	23.0	23.8	3.4
3-006	83	31	1.30	0.81	24	2.3	24.8	23.8	-3.9
3-008	83	19	1.30	0.82	24	2.0	21.0	23.8	13.3
3-009	83	7	1.30	0.82	24	2.0	22.2	23.8	7.2
3-011	72	12	1.30	0.82	24	1.5	21.8	23.8	9.4
3-013	66	12	1.30	0.82	24	2.0	21.4	23.8	11.3
4-001	37	40	1.30	0.80	24	0.5	29.0	30.2	4.1
4-002	37	32	1.30	0.81	0	0.5	22.0	15.9	-27.9
4-003	37	24	1.30	0.81	12	0.5	25.2	24.4	-3.1
4-004	37	16	1.30	0.81	6	0.2	24.0	20.7	-13.7
4-005	29	32	1.30	0.80	30	0.3	30.8	32.4	5.5
4-006	29	40	1.30	0.80	36	0.1	32.5	34.8	7.1
4-007	29	16	0.69	0.22	12	0.0	13.1	14.3	9.2
4-008	17	40	0.69	0.21	24	0.0	15.3	18.7	22.9
4-009	17	14	2.76	2.23	6	-1.0	49.8	43.8	-11.9
4-010	17	30	1.01	0.52	36	1.3	24.3	29.0	19.5
4-011	17	6	2.76	2.23	0	1.3	50.6	38.5	-23.8
5-010	40	40	1.01	0.53	18	1.5	33.4	33.7	1.0
5-011	32	40	1.01	0.54	0	1.5	25.4	24.4	-4.2
5-012	24	40	0.70	0.24	0	2.1	16.1	18.4	14.4
5-013	16	40	0.70	0.23	6	2.1	21.4	21.9	2.3
5-014	8	40	0.70	0.23	12	2.3	24.9	24.6	-1.0
5-015	8	48	0.70	0.23	9	2.3	23.3	23.3	0.1
5-016	16	48	0.70	0.24	3	2.3	19.6	20.3	3.4
5-017	32	48	0.70	0.23	15	1.9	22.9	25.8	12.5
5-018	24	48	0.70	0.23	18	2.3	25.1	26.9	7.1
5-019	32	56	1.01	0.54	12	1.6	27.0	31.2	15.4
5-020	24	56	0.70	0.23	12	1.9	24.8	24.6	-0.5
5-026	16	64	1.01	0.54	12	1.6	26.8	31.2	16.4
5-029	40	72	1.01	0.53	9	1.1	30.3	29.7	-1.8
5-030	16	72	0.70	0.23	12	1.3	21.8	24.6	13.2
5-031	24	72	0.70	0.23	12	1.3	21.0	24.6	17.3
5-032	32	72	0.70	0.23	12	1.3	21.6	24.6	13.9
5-033	8	72	0.70	0.23	12	1.3	22.8	24.6	8.3
5-035	20	84	0.70	0.24	12	1.1	20.0	24.6	23.2
5-037	28	84	2.76	2.27	0	1.0	44.2	55.7	26.0
5-038	32	64	0.70	0.23	12	0.9	20.8	24.6	18.4

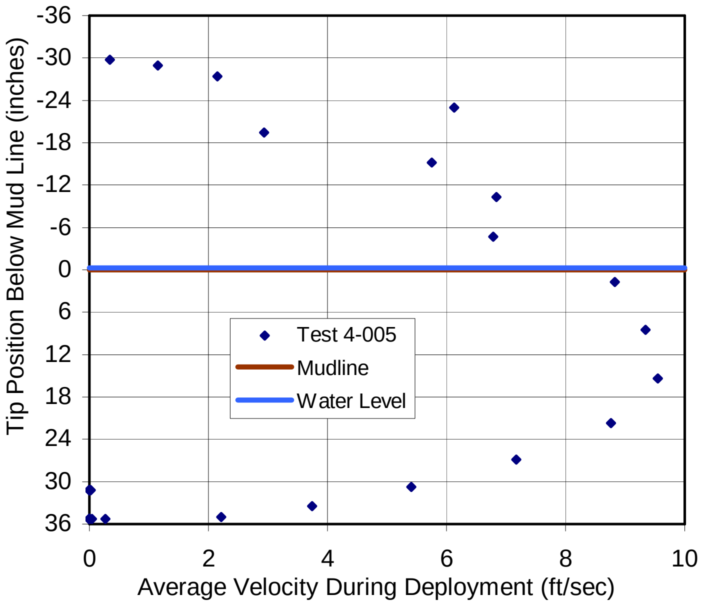


Figure 17. Example profile of velocity versus penetration during installation

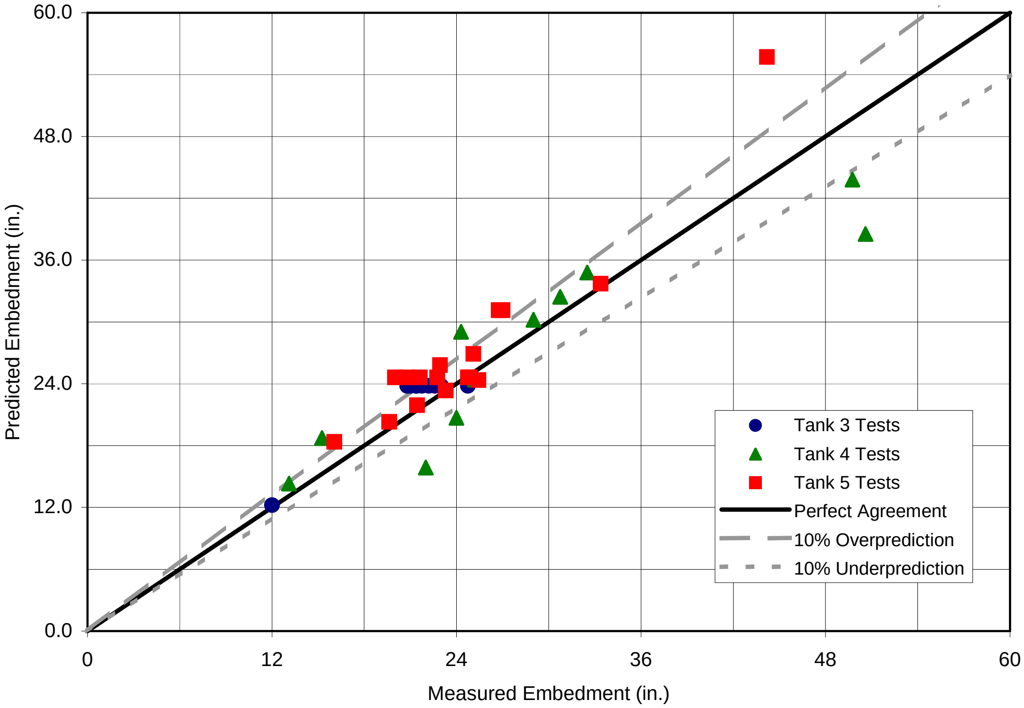


Figure 18. Comparison of predicted versus measured embedment during installation

Pull-out Capacity

The effect of set-up was the first variable studied for pull-out capacity. The test results are summarized in Table 6; all tests here correspond to undrained, axial loading. To account for variations in undrained shear strength, the maximum pull-out capacity is normalized to the capacity at 100 hours of set-up. A plot normalized pull-out capacity versus set-up time is shown in Figure 19. The test data indicate that a set-up time of approximately 45 hours is sufficient to reach a capacity that is apparently no longer dependent on set-up time (at least for set-up times of up to 250 hours). This conclusion is consistent with results for suction caisson model tests in the same soil (El-Sherbiny 2005). Note that two tests are included in Table 6 and Figure 19 for a torpedo pile that is pushed (inserted) into place rather than penetrated under velocity (deployed). In these tests, the pull-out capacity at a 48-hour set-up time is assumed to be equal to that at a 100-hour set-up time.

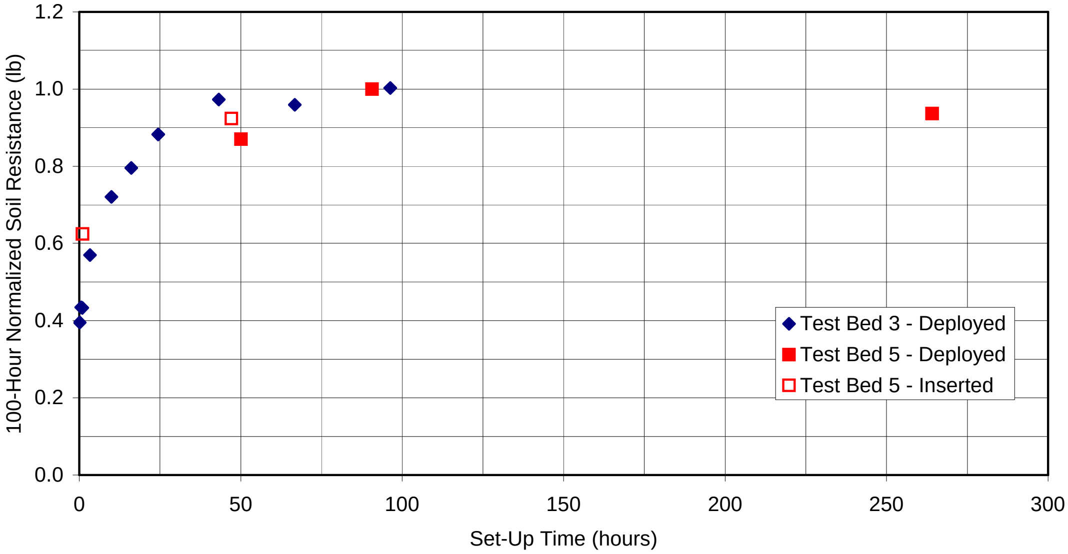


Figure 19. Pull-out capacity for undrained, axial loading versus set-up time

Table 6. Summary of test results for pull-out capacity under undrained, axial loading versus set-up time

	Test Details						Model Performance			Resistance to Pull Out from Soil (lb)	100 Hour Soil Resistance (lb)	100-Hour Normalized Soil Resist. (unitless)
Test Identification	X Coord (in.)	Y Coord (in.)	Air Dry Weight (lb)	Bouyant Weight in Soil (lb)	Drop Height Above Mud Line (in.)	Water Level Above Mud Line (in.)	Embedment Mud Line to Tip (in.)	Set-Up Time (hours)	Peak Pull-Out Resistance, P (lb)			
3-002	89	13	1.3	0.82	24	1.75	22.6	96.3	2.42	1.60	1.6	1.00
3-003	89	19	1.3	0.82	24	1.75	21.4	16.1	2.09	1.27		0.80
3-004	89	25	1.3	0.82	24	1.75	20.8	24.5	2.23	1.41		0.88
3-005	89	31	1.3	0.82	24	1.75	23.0	66.8	2.35	1.53		0.96
3-006	83	31	1.3	0.81	24	2.25	24.8	43.3	2.37	1.56		0.97
3-008	83	19	1.3	0.82	24	2.00	21.0	3.3	1.73	0.91		0.57
3-009	83	7	1.3	0.82	24	2.00	22.2	10.0	1.97	1.15		0.72
3-010	79	12	1.3	0.82	24	1.50	23.2	0.6	1.51	0.69		0.43
3-011	72	12	1.3	0.82	24	1.50	21.8	0.2	1.45	0.63		0.40
3-013	66	12	1.3	0.82	24	2.00	21.4	1.0	1.51	0.69		0.43
Test Bed 5 - Deployed Models												
5-010	40	40	1.01	0.53	18	1.50	33.4	50.1	1.50	0.97	1.11	0.87
5-019	32	56	1.01	0.54	12	1.63	27.0	90.7	1.65	1.11		1.00
5-026	16	64	1.01	0.54	12	1.63	26.8	264.1	1.58	1.04		0.94
Test Bed 5 - Inserted Models												
5-025	40	64	2.76	2.27	- -	1.50	38.5	47.1	4.63	2.36	2.55	0.92
5-039	12	84	2.76	2.28	- -	0.75	36.9	1.0	3.87	1.59		0.62

The next variable studied was the pull-out capacity under undrained, axial loading conditions after full set-up, where full set-up is defined by a set-up time of at least 45 hours (approximately). The test results for these conditions are summarized in Table 7. As expected, the axial pull-out capacity increases as the depth of embedment increases and as the weight of the pile increases.

Table 7. Test results for pull-out capacity under undrained, axial loading conditions after set-up

	Test Details						Model Performance		
Test Identification	X Coord (in.)	Y Coord (in.)	Air Dry Weight (lb)	Bouyant Weight in Soil (lb)	Drop Height Above Mud Line (in.)	Water Level Above Mud Line (in.)	Embedment Mud Line to Tip (in.)	Set-Up Time (hours)	Peak Pull-Out Resistance, P (lb)
3-002	89	13	1.3	0.82	24	1.75	24.0	96.3	2.42
3-005	89	31	1.3	0.82	24	1.75	23.0	66.8	2.35
3-006	83	31	1.3	0.81	24	2.25	24.8	43.3	2.37
4-001	37	40	1.3	0.80	24	0.50	29.0	73.8	2.24
4-002	37	32	1.3	0.81	0	0.50	22.0	42.2	1.82
4-003	37	24	1.3	0.81	12	0.50	25.2	67.6	2.01
4-004	37	16	1.3	0.81	6	0.20	24.0	47.6	2.01
4-005	29	32	1.3	0.80	30	0.25	31.5	45.0	2.31
4-006	29	40	1.3	0.80	36	0.10	32.5	66.4	2.30
4-008	17	40	0.69	0.21	24	0.00	15.3	47.4	1.06
4-009	17	14	2.76	2.23	6	-1.00	49.8	48.1	3.89
4-011	17	6	2.76	2.23	0	1.25	50.6	48.3	3.98
5-010	40	40	1.01	0.53	18	1.50	33.4	50.1	1.50
5-011	32	40	1.01	0.54	0	1.50	25.4	49.5	1.28
5-012	24	40	0.7	0.24	0	2.13	16.1	45.0	0.65
5-013	16	40	0.7	0.23	6	2.13	21.4	45.5	0.84
5-014	8	40	0.7	0.23	12	2.33	24.9	46.4	0.96
5-015	8	48	0.7	0.23	9	2.33	23.3	47.4	0.93
5-016	16	48	0.7	0.24	3	2.33	19.6	95.8	0.90
5-017	32	48	0.7	0.23	15	1.88	22.9	45.9	1.03
5-018	24	48	0.7	0.23	18	2.25	25.1	45.7	1.04
5-019	32	56	1.01	0.54	12	1.63	27.0	90.7	1.65
5-020	24	56	0.7	0.23	12	1.88	24.8	46.4	1.10
5-026	16	64	1.01	0.54	12	1.63	26.8	264.1	1.58
5-021	16	56	1.01	0.55	Pushed	1.75	20.3	47.2	1.46
5-024	24	64	0.7	0.24	Pushed	1.50	19.3	45.6	1.34
5-025	40	64	2.76	2.27	Pushed	1.50	38.5	47.1	4.63
5-026	16	64	1.01	0.54	12	1.63	26.8	264.1	1.58
5-029	40	72	1.01	0.53	9	1.13	30.3	56.9	1.52
5-034	40	48	2.76	2.28	Pushed	1.25	37.8	48.5	4.79
5-037	28	84	2.76	2.27	0	1.00	44.2	50.8	4.36

For comparison, a model of axial pull-out capacity was developed based on the API (2003) design method for driven piles:

$$Q = Q_{side} + Q_{end,heel} + W' = \alpha s_{u.avg} A_{side} + 9 s_{u,heel} A_{heel} + W'$$

where Q is the total pull-out capacity, Q_{side} is the capacity provided by side shear along the wall of the shaft, $Q_{end,heel}$ is the capacity provided by end bearing at the heel (top) of the pile, and W' is the submerged (or buoyant) weight of the pile in soil. The side shear capacity, Q_{side}, is calculated using an empirical shear transfer factor, α, the average value for the undisturbed, undrained shear strength along the pile shaft, $s_{u,avg}$, and the area of the shaft, A_{side}. The end bearing capacity is calculated using the undrained shear strength at the heel of the pile, $s_{u.heel}$, and the area of the heel, A_{heel}.

A comparison of the predicted versus measured pull-out capacity is shown on Figure 20, where the predicted capacity is obtained using the conventional (or ideal) value of 1.0 for α in a normally consolidated soil. The predicted capacity is greater than the measured capacity for all of the torpedo piles that were deployed (that is, dropped so that they penetrated the soil under velocity). However, for the torpedo piles pushed into place like a pile or suction caisson, the predicted capacity matches up well with the measured capacity (Fig. 20).

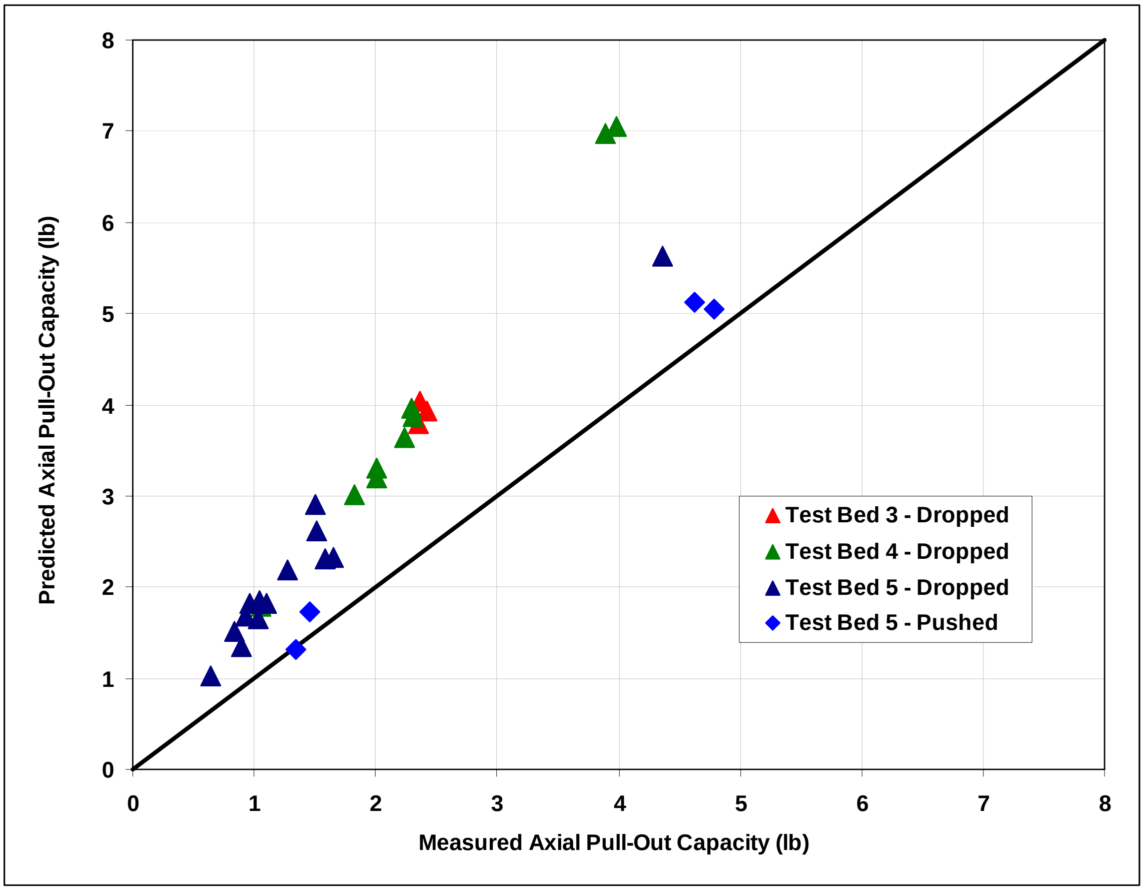


Figure 20. Comparison of predicted (ideal case with α = 1.0) versus measured pull-out capacity for undrained, axial loading after set-up

One hypothesis to explain the results on Figure 20 is that the soil has been reconstituted at a higher water content in the vicinity of pile wall during penetration. There are several indirect pieces of evidence supporting this hypothesis. First, the torpedo piles that were pushed into place provided higher capacity, indicating that the mobilized undrained shear strength and therefore moisture content of the soil is similar before installation (as measured in a T-bar test) and after set-up. Second, Test number 5-029 was conducted after initially remolding/reconstituting the soil by rotating a 2-inch diameter shear vane while pushing it into the soil. This process may have disturbed the soil at a constant water content (remolding) or it may have introduced additional water in the disturbed column (reconstituting). The torpedo pile was then deployed in this disturbed column of soil, and its pull-out capacity was measured after set-up. The measured capacity of Test number 5-029 is similar to that of Test number 5-026, where the soil was not disturbed prior to deployment while the depth of embedment was about the same (Table 7). Hence, deployment of the torpedo pile under velocity apparently affects the soil in a similar fashion as remolding or reconstituting it with a vane.

A more direct piece of evidence about how the soil is affected by penetration of the torpedo pile under velocity is obtained by studying the moisture content data. A comparison of moisture content measurements in the vicinity of the pile before and after deployment is shown on Figure 21. The solid lines depict the average profile of moisture content in the soil before testing. The symbols represent measured data that were obtained in situ by sampling the soil adjacent to the pile just prior to pull-out and after set-up (the circles) and by sampling the soil adhering to the model torpedo pile after recovery (the diamonds). These data show that the moisture contents in immediate vicinity of the torpedo are higher after deployment (Fig. 21). However, the zone of disturbance is apparently localized. The data labeled “Moisture Contents in Disturbed Zone” (the asterisk symbols) were obtained from about 1-inch away from the torpedo. These moisture contents, just one pile diameter away from the shaft, are very similar to the in situ moisture contents before deployment (Fig. 21).

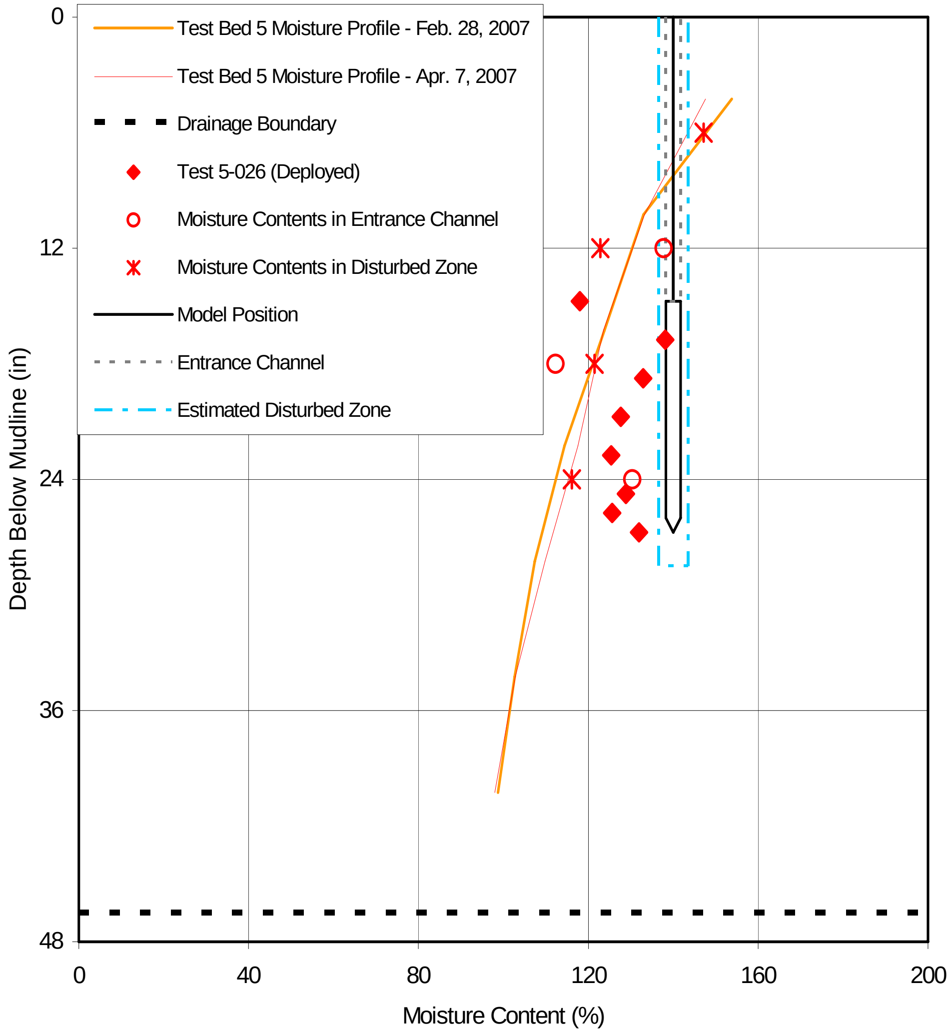


Figure 21. Measured moisture contents for torpedo pile before and after deployment

In order to better predict the pull-out capacity under undrained, axial loading, the value of α in the prediction model was varied until the predicted capacities were comparable to the measured capacities. The best-fit value for α is 0.5 (Fig. 22). This value of α means that the mobilized undrained shear strength in side shear is approximately the same as the remolded undrained shear strength for this soil (the sensitivity is about two).

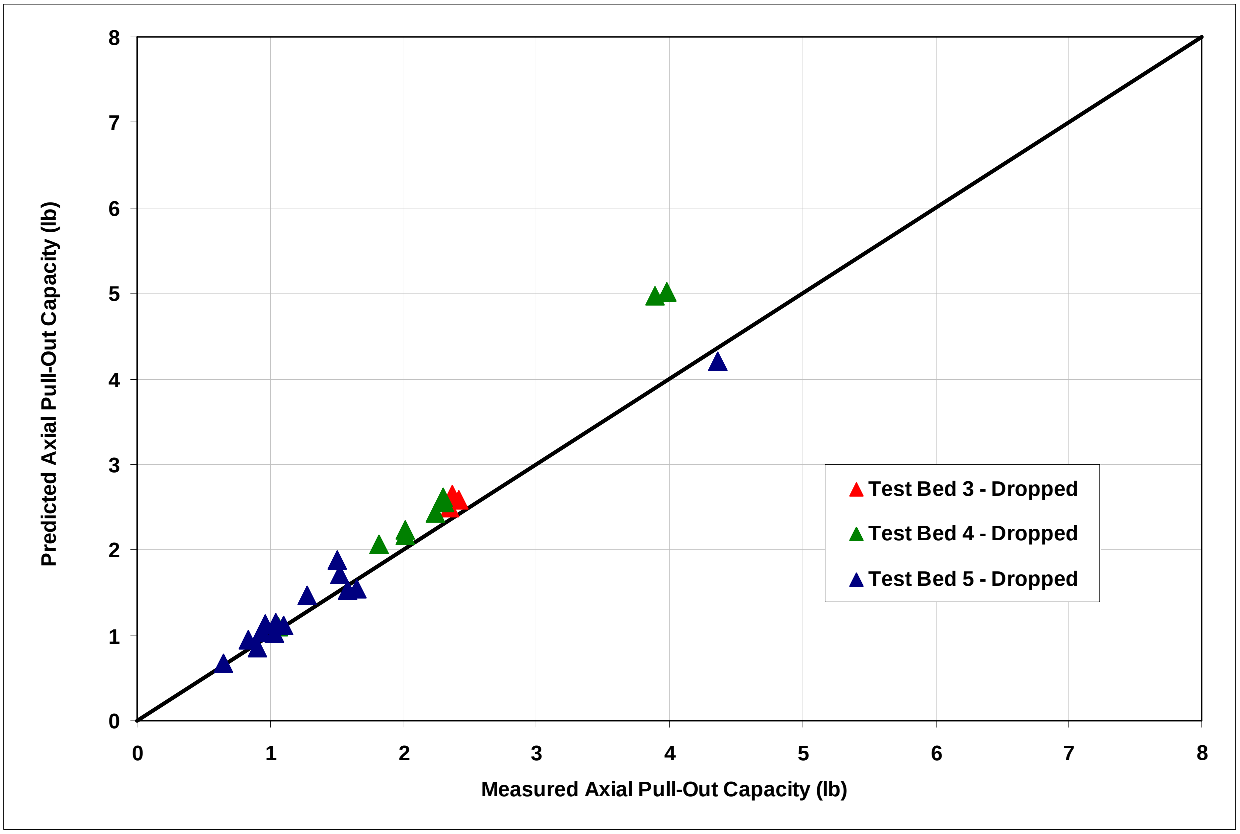


Figure 22. Comparison of predicted (α = 0.5) versus measured pull-out capacity for undrained, axial loading after set-up

The final variable studied for pull-out capacity was the angle of loading. These test results are summarized in Table 8 and plotted on Figure 23. Note that the vertical component of capacity increases when the pile is loaded 15 degrees off from vertical. This result is consistent with the hypothesis that the disturbance of the soil due to penetration under velocity is localized a small zone around the pile. When the pile is pulled off from vertical, the vertical component of capacity may increase since the soil that is sheared is less disturbed than the soil that is adjacent to the pile

Table 8. Test results for pull-out capacity under undrained, inclined loading conditions after set-up

Test Identification	Embedment Mud Line to Tip (in.)	Set-Up Time (hours)	Peak Pull-Out Resistance, P (lb)	Moisture Content of Attached Soil (%)	Inclination to Vertical For Recovery (degrees)	Vertical Component of Capacity (lb)	Horizontal Component of Capacity (lb)
5-014	24.9	46.4	0.96	159	0	0.96	0.00
5-020	24.8	46.4	1.10	152	15	1.06	0.28
5-030	21.8	46.6	1.08	150	30	0.94	0.54
5-031	21.0	59.1	1.06	132	45	0.75	0.75
5-032	21.6	46.6	1.11	131	60	0.56	0.96
5-033	22.8	48.3	1.19	133	75	0.31	1.15
5-038	20.8	50.6	1.29	123	90	0.00	1.29

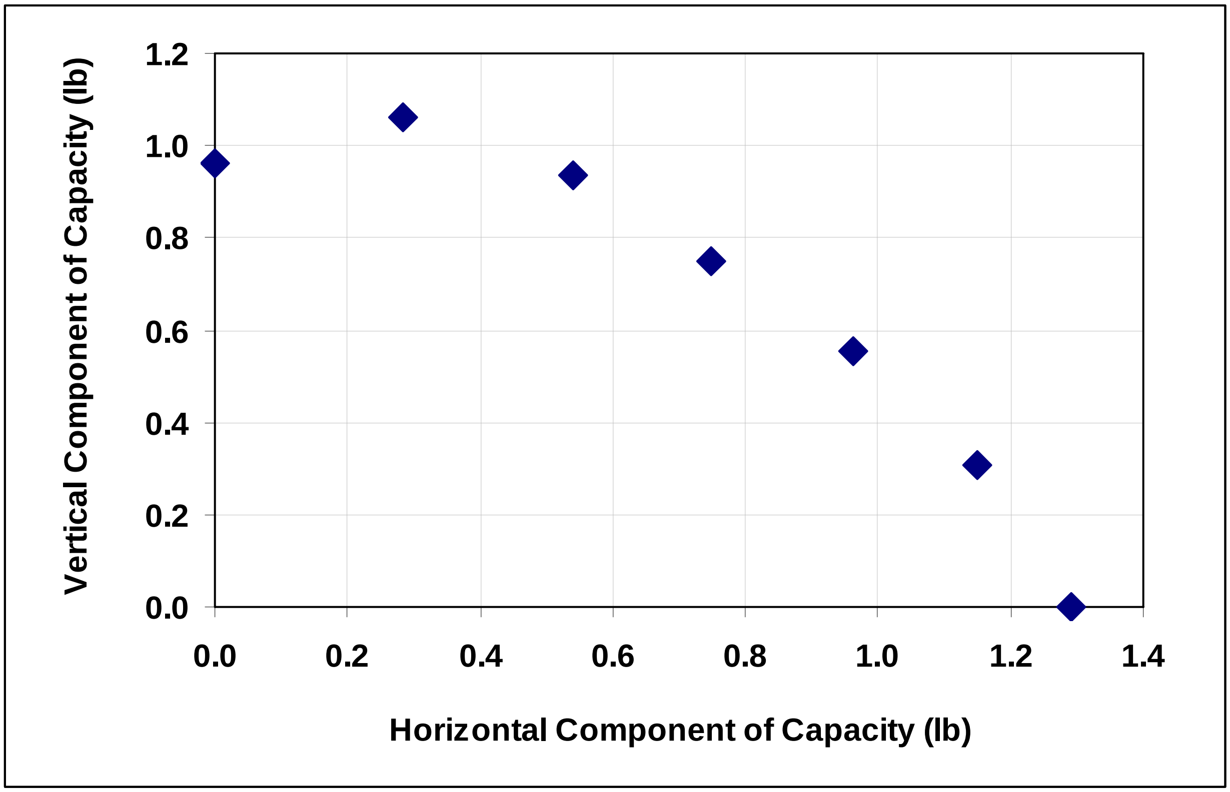


Figure 23. Interaction diagram for measured pull-out capacity under undrained, inclined loading after set-up

For comparison, a model of lateral pull-out capacity was developed based on assuming that the pile rotates as a rigid body and that the lateral bearing capacity is 9 times the undrained shear strength:

$$P = \frac{-0.5L + [(-0.5L)^2 + (1/4)(9s_{u,avg}DL)^2]^{1/2}}{0.5(1/9s_{u,avg}D)}$$

where L is the length of the pile, D is the diameter of the pile, and $s_{u,avg}$ is an average or representative undrained shear strength along the side of the pile (the model assumes that the undrained shear strength is a constant with depth). A practical approximation for the representative undrained shear strength is to use the shear strength at a depth that is 1/3 of the way from the heel of the pile to the tip.

The predicted and measured pull-out capacities are compared on Figure 24. The predicted lateral capacity is essentially equal to the measured lateral capacity (Fig. 24).

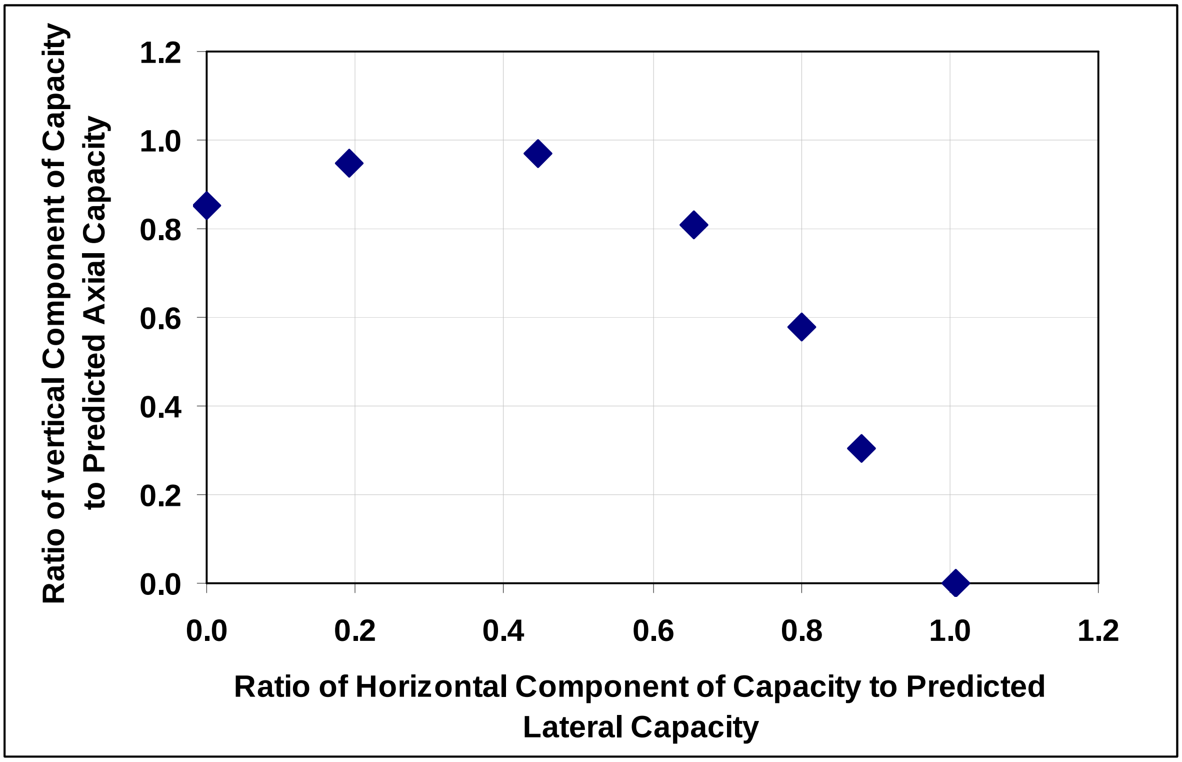


Figure 24. Interaction diagram for measured versus predicted pull-out capacity for undrained loading after set-up

DISCUSSION

The model test results indicate the torpedo piles have the potential to provide a practical alternative for offshore anchors in temporary or permanent mooring systems.

The most important issue with torpedo piles is the ability to predict how far they will embed into the sea floor. These test results indicate that the depth of embedment can be predicted accurately using a simple model that relates the embedment to the geometry and weight of the torpedo pile, the drop height, and the undrained shear strength of the soil. Therefore, the same type of project-specific soil information that is typically obtained and needed to design other anchors, including driven piles, suction caissons, drag embedment anchors and vertically loaded anchors, can be used to design torpedo piles.

The tests results also indicate that the axial and lateral capacity of a torpedo pile under undrained loading conditions can be predicted using a simple model that accounts for side shear and end bearing in the surrounding soil. The measured axial pull-out capacities after set-up in these model tests ranged from two to five times the weight of the torpedo pile, which is consistent with reported field data from Petrobras (Medeiros 2002). The model tests also show that the mobilized side shear along the shaft of the torpedo pile may be less than the ideal case of a pushed (or driven) pile, apparently due to disturbance of the soil that occurs during penetration. Back-calculated values of the empirical side shear transfer factor, α, were about 0.5 and less than the ideal case of 1.0 for a normally consolidated clay. This conclusion has the following practical implications:

- This reduced side shear may affect the axial pull-out capacity, but does not affect the lateral capacity. Since mooring systems will generally pull on an anchor at an angle closer to horizontal than vertical, this effect may not be significant.
- Since field tests and other model tests with torpedo piles generally applied an axial load to measure the capacity, this effect should be considered in interpreting other test results.

- This effect of soil disturbance is apparently localized to the shaft and may not affect the mobilized side shear on fins. For example, if fins make up 50 percent of the total area in side shear, the mobilized value of α may be about 0.75, not 0.5.
- The kaolinite clay used in these model tests is not directly representative of typical marine clay in that it displays little thixotropy (strength increase with time at a constant water content). This effect of soil disturbance may be less pronounced in clays where the strength continues to increase with time at a constant water content, like a typical marine clay from the Gulf of Mexico.
- If the soil disturbance is related to water getting dragged down by the tip of the torpedo pile, this hydrodynamic effect may depend on scale and could be different with a full-scale torpedo pile where the penetration velocity and the diameter are larger.

CONCLUSIONS

The goal of this study was to improve understanding about how torpedo piles behave during installation and pull-out by conducting 1:30 scale model tests in normally consolidated beds of kaolinite. The model torpedo piles consisted of a straight shaft with a conical tip and a load attachment at the heel (or top). The following conclusions are drawn from this work:

4. The embedment depth of a torpedo pile increases as the drop height and the weight of the pile increase. A simple model of soil resistance during penetration that accounts for remolding and rate effects on the undrained shear strength is able to predict the embedment depth accurately (generally within +/- 10 percent of the measured value).
5. The axial pull-out capacity under undrained loading after set-up increases with the embedment depth, the undrained shear strength of the soil, and the weight of the torpedo pile. The soil immediately adjacent to the shaft in our model tests was reconstituted at a higher moisture content during penetration; the predicted capacity matches the measured capacity when an empirical side shear transfer factor, α, value of 0.5 is used in the prediction model. This zone of reconstituted soil is localized, and may not affect the mobilized side shear on the fins of a torpedo pile with fins.

6. The lateral pull-out capacity under undrained loading after set-up is predicted well by a simple model that assumes the pile rotates as a rigid body in undisturbed soil.

The model test results indicate the torpedo piles have the potential to provide a practical alternative for offshore anchors in temporary or permanent mooring systems. Recommendations for further work include performing additional model tests with different pile geometries (such as fins), different pile diameters and lengths, different soil conditions (such as a soil with a different sensitivity or thixotropic behavior) and different loading conditions (such as sustained loads). In addition, field-scale testing of installation and pull-out with a small torpedo pile (perhaps 1/3 to ½ of full scale) would be very valuable.

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APPENDIX A SUMMARY OF TORPEDO PILE MODEL TEST RESULTS

Table A.1. Model test results for Test Bed 3

Test Identification	X Coord (in.)	Y Coord (in.)	Air Dry Weight (lb)	Bouyant Weight in Soil (lb)	Drop Height Above Mud Line (in.)	Water Level Above Mud Line (in.)	Embedment Mud Line to Tip (in.)	Set-Up Time (hours)	Peak Pull-Out Resistance, P (lb)	Moisture Content of Attached Soil (%)	Notes:
Su (psf) =	2.5	+	6.0	Z (ft)		γ_t (pcf) =	84.9	+	2.75	Z (ft)	
3-001	89	7	0.69	0.22	12	1.0	12.0	71.5	0.76	123	(2)
3-002	89	13	1.30	0.82	24	1.8	22.6	96.3	2.42	121	
3-003	89	19	1.30	0.82	24	1.8	21.4	16.1	2.09	126	
3-004	89	25	1.30	0.82	24	1.8	20.8	24.5	2.23	120	
3-005	89	31	1.30	0.82	24	1.8	23.0	66.8	2.35	122	
3-006	83	31	1.30	0.81	24	2.3	24.8	43.3	2.37	118	
3-007	83	25	1.30	0.82	24	2.3	18.8	1.1	1.76	109	(3)
3-008	83	19	1.30	0.82	24	2.0	21.0	3.3	1.73	121	
3-009	83	7	1.30	0.82	24	2.0	22.2	10.0	1.97	120	
3-010	79	12	1.30	0.82	24	1.5	23.2	0.6	1.51	130	(3)
3-011	72	12	1.30	0.82	24	1.5	21.8	0.2	1.45	131	
3-012	60	12	1.30	0.87	24	1.5	-17.7	44.6	2.59	108	(4)
3-013	66	12	1.30	0.82	24	2.0	21.4	1.0	1.51	129	

Notes:

(1) Results are not available due to equipment malfunction.

(2) Pull out was performed at a rate too slow to simulate undrained conditions (0.02 inches/minute). All other tests were recovered at 0.2 inches per minute.

(3) Test was unintentionally performed adjacent to the location of a previous suction caisson test.

(4) Test was intentionally performed in the same location as a 6" diameter suction caisson test performed over a year ago.

Table A.2 Model test results for Test Bed 4

Test Identification	X Coord (in.)	Y Coord (in.)	Air Dry Weight (lb)	Bouyant Weight in Soil (lb)	Drop Height Above Mud Line (in.)	Water Level Above Mud Line (in.)	Embedment Mud Line to Tip (in.)	Set-Up Time (hours)	Peak Pull-Out Resistance, P (lb)	Moisture Content of Attached Soil (%)	Notes:
Su (psf) =	3.0	+	3.8	Z (ft)		γ_t (pcf) =	84.8	+	3.3	Z (ft)	
4-001	37	40	1.30	0.80	24	0.5	29.0	73.8	2.24	132	
4-002	37	32	1.30	0.81	0	0.5	22.0	42.2	1.82	133	
4-003	37	24	1.30	0.81	12	0.5	25.2	67.6	2.01	128	
4-004	37	16	1.30	0.81	6	0.2	24.0	47.6	2.01	134	
4-005	29	32	1.30	0.80	30	0.3	30.8	45.0	2.31	129	
4-006	29	40	1.30	0.80	36	0.1	32.5	66.4	2.30	127	
4-007	29	16	0.69	0.22	12	0	13.1	66.0	(1)	111	(5)
4-008	17	40	0.69	0.21	24	0	15.3	47.4	1.06	85	
4-009	17	14	2.76	2.23	6	-1	49.8	48.1	3.89	92	(6)
4-010	17	30	1.01	0.52	36	1.3	24.3	47.3	(1)	108	
4-011	17	6	2.76	2.23	0	1.3	50.6	48.3	3.98	91	(6)

Notes:

(1)	Results are not available due to equipment malfunction.
(5)	Pull out test was not performed because there was insufficient embedment to simulate field condtions.
(6)	Solid brass model, one inch diameter, 12 inches long.

Table A.3. Model test results for Test Bed 5

Test Identification	X Coord (in.)	Y Coord (in.)	Air Dry Weight (lb)	Bouyant Weight in Soil (lb)	Drop Height Above Mud Line (in.)	Water Level Above Mud Line (in.)	Embedment Mud Line to Tip (in.)	Set-Up Time (hours)	Peak Pull-Out Resistance, P (lb)	Moisture Content of Attached Soil (%)	Notes:
Su (psf) =	0	+	3.8	Z (ft)		γ_t (pcf) =	82.2	+	2.5	Z (ft)	
5-010	40	40	1.01	0.53	18	1.5	33.4	50.1	1.50	131	
5-011	32	40	1.01	0.54	0	1.5	25.4	49.5	1.28	160	
5-012	24	40	0.70	0.24	0	2.1	16.1	45.0	0.65	163	
5-013	16	40	0.70	0.23	6	2.1	21.4	45.5	0.84	159	
5-014	8	40	0.70	0.23	12	2.3	24.9	46.4	0.96	159	
5-015	8	48	0.70	0.23	9	2.3	23.3	47.4	0.93	166	
5-016	16	48	0.70	0.24	3	2.3	19.6	95.8	0.90	168	
5-017	32	48	0.70	0.23	15	1.9	22.9	45.9	1.03	163	
5-018	24	48	0.70	0.23	18	2.3	25.1	45.7	1.04	154	
5-019	32	56	1.01	0.54	12	1.6	27.0	90.7	1.65	152	
5-020	24	56	0.70	0.23	12	1.9	24.8	46.4	1.10	152	(8)
5-021	16	56	1.01	0.55	--	1.8	20.3	47.2	1.46	159	
5-024	24	64	0.70	0.24	--	1.5	19.3	45.6	1.34	154	
5-025	40	64	2.76	2.27	--	1.5	38.5	47.1	4.63	123	
5-026	16	64	1.01	0.54	12	1.6	26.8	264.1	1.58	129	
5-029	40	72	1.01	0.53	9	1.1	30.3	56.9	1.52	130	(9)
5-030	16	72	0.70	0.23	12	1.3	21.8	46.6	1.08	150	(10)
5-031	24	72	0.70	0.23	12	1.3	21.0	59.1	1.06	132	(11)
5-032	32	72	0.70	0.23	12	1.3	21.6	46.6	1.11	131	(12)
5-033	8	72	0.70	0.23	12	1.3	22.8	48.3	1.19	133	(13)
5-034	40	48	2.76	2.28	--	1.3	37.8	48.5	4.79	127	(15)
5-035	20	84	0.70	0.24	12	1.1	20.0	44.3	(1)	134	(14), (16)
5-037	28	84	2.76	2.27	0	1.0	44.2	50.8	4.36	118	
5-038	32	64	0.70	0.23	12	0.9	20.8	50.6	1.29	123	(14)
5-039	12	84	2.76	2.28	--	0.8	36.9	1.0	3.87	--	(17)

Notes:

(1) Results are not available due to equipment malfunction.

(7) Volume of model estimated to be

(8) Model recovered at 15 degrees from vertical.

(9) Modlel deployed into a remolded soil column. Soil was remolded with a 2" diameter by 4" long minivane, mudline to drain, just prior to deployment.

(10) Model recovered at 30 degrees from vertical.

(11) Model recovered at 45 degrees from vertical.

(12) Model recovered at 60 degrees from vertical.

(13) Model recovered at 75 degrees from vertical.

(14) Model recovered at 90 degrees from vertical.

(15) Model inserted into test bed at 20 in/min.

(16) Cable slipped out of pulley track during recovery, making force measurements invalid. No data is reported for the pullout perfromance of this test.