STEEL CATENARY RISERS - RESULTS AND CONCLUSIONS FROM LARGE SCALE SIMULATIONS OF SEABED INTERACTION

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ABSTRACT

This paper deals with the seabed interaction at the touchdown point (TDP) of deepwater steel catenary risers (SCR's) as investigated within Phase 3 of the STRIDE JIP.

The paper describes back-analysis and conclusions from a test programme that involved a 110m (360-ft) long 0.1683m (6-5/8 inch) diameter SCR at a tidal harbour which had seabed properties similar to those of the deepwater Gulf of Mexico. The top end of the pipe string was actuated using a PLC controller to simulate the wave and vessel drift motions of a spar platform in 1000m (3,300-ft) water depth, both in-line and transverse to the SCR plane. The pipe was fully instrumented to provide tensions and bending moments along its length. Tests were performed at high and low tide.

A pipe/soil interaction model for soil suction was used to predict and back-analyse the response of the harbour test riser. The test data and analytical models achieved good correlation between the tensions and bending moments, indicating that the model could be used to predict suction response from both wave and slow drift vessel motions.

KEY WORDS: Steel Catenary Riser (SCR), Touchdown Point (TDP), Soil Suction

Introduction

Deepwater oil and gas fields usually have seabeds of soft clay. ROV surveys of installed catenary risers have shown deep trenches cut into the seabed beyond the TDP, apparently caused by the dynamic motion of the riser.

Storm and current action on a deepwater production vessel can pull the riser upwards from its trench, or laterally against the trench wall. The suction effect of the soft seabed on the riser, coupled with trench wall interaction, could cause an increase in the local riser stresses (due to tighter riser curvatures and higher tensions) than those predicted ignoring these effects.

As part of the STRIDE III JIP, 2H Offshore Engineering Ltd conducted a test programme to investigate the effects of seabed interaction on catenary riser response and wall stresses. The objective was to assess the importance of seabed/riser interaction, and to produce finite element (FE) analysis techniques to predict the measured response.

Pre-Analysis

Initially, FE analysis was performed to predict the motions of a 6-inch diameter SCR attached to a spar platform in 1000m (3,300-ft) water depth in the Gulf of Mexico, Figure 1. Day-to-day and extreme environmental load-sets were applied using the FE program Flexcom-3D (MCS, 1999), including wave and drift effects both in and out of the riser plane. The riser motions near the seabed were recorded as output from these analyses, and in particular the local velocity of the riser as it peels away from the seabed.

A second FE model was then used to simulate the planned test set-up. This was comprised of a welded steel pipe that represented the bottom 110m (360-ft) of the full-scale riser, Figure 2. The model simulated a linear actuator at the top end. The actuation cycles were varied within the FE model until similar SCR motions were obtained for both the reduced size model and the full depth case. These actuator motions were then used in the design of the actuator rig for the intended tests, allowing the base of a deepwater riser to be simulated at full scale.

Test Set up

The test programme was conducted at a harbour location in the west of England. Here the seabed is known to have properties similar to a deepwater Gulf of Mexico seabed. This is made up of soft clay, with an undrained shear strength of 3 to 5 kPa, and a naturally consolidated shear strength gradient below the mudline. Further geotechnical properties are given in Table 1. The sea current velocity in the test area as the harbour filled or emptied was almost negligible, and any trenches formed by the testing remained unchanged over numerous tide cycles.

Geotechnical Parameter	Value
Moisture Content, w	104.7%
Bulk Density, ρ	1.46 Mg/m^3
Dry Density, ρ_d	0.73 Mg/m^3
Particle Density, ρ_S	2.68 Mg/m^3
Liquid Limit, w_L	87.6%
Plastic Limit, w_P	38.8%
Plasticity Index, I_P	48.9%
Average Organic Content	3.2%
Specific Gravity, G_S	2.68
Undisturbed Shear Strength at 1D	3.5 kPa
Remoulded Shear Strength at 1D	1.7 kPa
Sensitivity of Clay at 1D	3.3
Coefficient of Consolidation, c_V at 1D	0.5 m^2/year
Coefficient of Volume Compressibility, m_V at 1D	15 m^2/MN

Table 1 – Geotechnical Parameters of Clay Soil

A 110m (360-ft) long 0.1683m (6-5/8 in) diameter welded steel "riser" was suspended from an actuator on the harbour wall, Figures 2 and 3, and run out across the seabed to a set of mud anchors. Further pipe details are given in Table 2. The seabed over this area was flat and undisturbed, and careful probe tests were done to check that there were no hidden obstacles below the mudline.

Test Rig Parameter	Value
Pipe outer diameter	0.1683m (6-5/8")
Wall thickness	6.9mm
Pipe material	APL 5L Grade B, 448.2x10^6 N/m^2 yield
Height of nominal position above seabed	9.65m
Length of chain at actuator	3.85m
Length of pipe	110m
Mean water level	3.5m

Table 2 – Summary of Test Rig Parameters

The test set-up allowed the use of a number of virgin test corridors at the flattest part of the harbour seabed. It was important that these corridors were undisturbed before the testing. To ensure this, the riser was floated to the various positions using temporary buoyancy, then the outgoing tide allowed it to settle onto the seabed.

The riser was fixed at its top end to an actuator unit. This comprised a heavy-duty truss frame with a 3m (10-ft) linear ball screw driven from one end by a motor with displacement feedback control via PLC, Figure 4. The riser was attached to the ball screw nut via an adjustable cable. This allowed the top tension in the riser to be tuned to the prescribed value of 56.5kN, which set the TDP at 64.2m from the actuator. The linear screw could be swivelled to operate in vertical or horizontal directions. This system applied the prescribed motions accurately to the top end of the harbour test riser, and produced the vertical and lateral pipe motions which were necessary at the seabed. This meant linear ramps, simulating vessel drift, and sinusoidal motions of different amplitudes and frequencies, simulating wave loading. In addition the whole actuator frame was designed to move on a set of 10 m long rails, simulating a large transverse excursion of the vessel and pulling the riser laterally from its trench while pipe stresses were monitored.

The primary instrumentations comprised full bridge strain gauge sets which were welded at 13 axial positions along the riser and spanned the dynamic TDP area, Figure 2. Each position provided vertical and horizontal bending strain on the pipe. In addition, a triaxial accelerometer unit was mounted just above the nominal TDP. There were tension load cells at the top and bottom of the pipe string, and strain gauges measuring shear force at the connection between pipe and actuator. All instrumentation was hardwired to a multi-channel logging station which was able to monitor in real-time at 40 Hz.

Test Program

The test corridors used included: an open trench, an artificially deepened trench, a backfilled trench and a rigid seabed, Table 3. For each test corridor a series of tests was conducted to examine the effects of slow drift (pull up and lay down tests) and dynamic motions (day-to-day and second order motions). Table 4 has a definition of the actuations referred to within this paper.

Test Corridors	Test Corridor Title	Description/Notes
1	First Trench	Initial trials, no data recorded
2	Open Trench	Formed naturally by riser self weight and vertical/lateral motions
3	Artificially Deep Trench	The trench was artificially deepened
4	Backfilled Trench	The artificially deep trench was backfilled with clay
5	Rigid Seabed	Steel planks were placed over the trench and under the riser to simulate a rigid seabed

Table 3 – Description of Trench Corridors

The test matrix for test corridors 2 – 5 is shown in Table 5. The matrix shows that pull up and lay down tests were conducted on every test corridor, however the wave motions were only conducted on test corridor 2 (open trench) and test corridor 5 (rigid seabed).

The pull up and associated lay down tests were typically conducted as a series of 5 consecutive pairs. The first pull up test is considered to be on undisturbed clay as the riser was allowed to consolidate the clay soil in the trench. Table 6 shows the consolidation time and the sea level of the first pull up tests. The subsequent tests in the pull up and lay down series are considered to be on remoulded clay.

Actuation Reference	Offshore Equivalent Motion	Travel at Actuator
Dynamic @ near / nominal / far	Heaving storm wave about either the 0.5% WD near, nominal, 1.1% far vessel position	Vertical sine wave, +/- 0.4m, 25 second period about the -0.4m datum, 0m datum, +1.0m datum
Lateral dynamic	Surging or swaying storm wave about nominal	Horizontal sine wave, 0m datum, +/- 0.4m, 18 second period
Pull-up	Spar failed mooring drift speed, near 0.8% to far 1.4% WD	-0.8m to +1.4m @ 0.1m/s and 0.01m/s
Lay-down	Spar failed mooring drift speed, far 1.4% to near 0.8% WD	+1.4m to –0.8m @ 0.1m/s and 0.01m/s

Table 4 – Actuation Definitions and Parameters with Equivalent SCR motions

Test Corridor	2	3	4	5
Description	Open Trench	Artificial Trench	Backfilled Trench	Rigid Seabed
In Water Tests				
Pull-up / Lay down	3, 4, 7, 8, 10, 11, 13, 14 (C,D)	3, 4 5, 6	1, 2	1, 2
Dynamic @ Near	5	-	-	3
Dynamic @ Nominal	6	-	-	4
Dynamic @ Far	-	-	-	5
Lateral Pull Out	-	-	-	-
Lateral Dynamic	16	-	-	-
In Air Tests				
Pull-up / Lay down	1, 2, 13, 14 (A,B)	1, 2	3, 4	6, 7, 10, 11
Dynamic @ Near	9, 12	-	-	8, 12
Dynamic @ Nominal	-	-	-	9, 13
Dynamic @ Far	-	-	-	14
Lateral Pull Out	17, 18, 19, 20	-	-	15
Lateral Dynamic	15	-	-	16

Table 5 – Test Matrix with Test Reference Numbers

Consolidation Time (hours)	Sea Level (m)				
	0	1.0 – 1.5	1.5 – 2.0	2.0 – 2.5	2.5 +
Rigid Seabed	5-6, 5-10	-	-	5-1	-
4	-	2-3	-	4-1	3-3
12	2-1, 3-1	-	-	-	-
16	2-13	-	-	-	3-5
72	4-3	-	-	2-10	-

Table 6 – Summary of First Pull Up Tests

Results

The results from the harbour test riser are presented as bending moment traces versus actuator position at strain gauge locations. Figure 5 shows an example of the bending moment data from a strain gauge during a first pull up test and the associated lay down test. A negative bending moment corresponds to a sagging bend in the riser. If the lay down test is considered to represent the ‘no soil suction’ case and the pull up test representing the ‘with soil suction’ case the two bending moment traces can be compared directly. Both the pull up and lay down bending moment traces start from the –0.8m actuator position with bending moments of around -0.5 kNm. The lay down bending moment trace decreases steadily to a minimum value of –5.5kNm at an actuator position of 0.5m where it levels off. In contrast, the pull up bending moment trace does not change until the actuator has moved to the –0.3m actuator position. This indicates that the soil suction force is holding the riser in place. The bending moment then decreases rapidly to peak at –11 kNm at an actuator position of 0.5m, which is twice the lay down bending moment. The pull up bending moment trace then increases to join the lay down bending moment trace at the 1.2m actuator position.

From this example, it can be seen that the peak bending moment during a near to far pull up test is twice that of the peak bending moment seen during the associated lay down test.

Figure 6 shows the bending moment trace of a pull up and lay down test pair on the rigid seabed. It can be seen that the pull up and lay down tests are virtually identical, and shows that the peak in the bending moment trace during the pull up test with the riser on the clay soil is due to soil suction, and not a result of the actuation system or hysteresis/inertia effects.

The effect of soil suction on a first pull up and the associated lay down test along the riser are shown in Figure 8. The location of strain gauge positions A, D, F, J, K and M along the riser are shown in Figure 7. The pull up test (2-10) and the lay down test (2-11) were conducted in test corridor 2, with an actuator pull up rate of 0.1m/s after 72 hours consolidation. This simulated a slow drift motion. Descriptions of the pull up and lay down bending moments follow:

Position A – this location is free hanging when the riser is in the near (lowest) actuation position. As the riser is pulled up the strain gauge shows a small decrease (around 0.3kNm) in the bending moment as it is pulled up into a straighter part of the catenary.

Positions D and F – these locations show the greatest change in bending moment due to soil suction. They were positioned close to the nominal TDP, are in contact with the seabed in the near riser position and are free hanging when the riser was pulled up.

Positions J and K – these locations are in contact with the seabed for much of a pull up test, only becoming free hanging when the actuator position is close to the 1.0m. However they do show that the soil suction holds the riser to the seabed

Position M – This location is in contact with the soil at both near and far actuator positions.

The influence of repeated loading, pull up velocity and consolidation time on soil suction was also investigated. The observations on these aspects of response are given below:

Repeated Loading – Figure 9 shows the bending moment response of strain gauge location D during a first pull up (test 3-5), a sixth pull up (test 3-5E) and an associated lay down (test 3-6). These shown that after the first pull up soil suction increases the magnitude of the bending moment peak by 85%. However, for the sixth pull up the peak bending moment increase drops to 20%. This shows a 76% reduction in the bending moment response, and indicates that the soil suction force has reduced between the first and sixth pull up tests.

Figure 10 shows a summary of the minimum bending moments from pull up test series 3-5 compared to lay down test 3-6. It is shown that the soil suction force reduces by 66% between the first and second pull up tests, and then reduced further by around 4% for each subsequent test.

Pull Up Velocity – Consecutive pull up tests 2-1C (fourth pull up) and 2-1D (fifth pull up) were conducted after repeated loading with pull up velocities of 0.1m/s and 0.01m/s, respectively. The results, Figure 11, show that on remoulded clay the pull up velocity has little effect on the bending moment response.

Consolidation Time – Figure 12 shows the effect of consolidation time on strain gauge positions C and D during pull up tests 3-3 (4 hours consolidation) and 3-5 (12 hours consolidation). With increased consolidation time the magnitude of the bending moment response at strain gauge location C increases by 3kNm (58%) and at location D by 2kNm (23%).

From study of the harbour test data additional interaction effects was observed due to soil suction, including suction release and a suction kick, both of which are described below:

Suction Release – After the pull up test actuation was complete (the pipe had been pulled to the top of the actuator) the bending moment response at strain gauges J and K was seen to continue to change. This effect, not seen on the lay down tests, is due to the mobilised suction force dissipating and allowing the riser to move into the static equilibrium position.

Figure 13 shows how the bending moment response of strain gauge locations C, J and K and the corresponding actuator position change with time. The vertical blue lines show the start and end of the pull up test. It can be seen that the bending moments do not change over the 10s before the pull up tests starts. Once the test begins all strain gauge locations show a bending moment response similar to those previously observed, Figure 8. After the tests has finished the bending moment response at strain gauge C remains constant. However the bending moment response of strain gauges J and K continue to change for 15s and 18s respectively.

This indicates that if a riser is left statically after soil suction has been mobilised the suction slowly dissipates and the riser moves into the equilibrium state, which has little or no soil suction.

Suction Kick – Figure 14 shows the bending moment response of fast pull test 3-5, conducted with a sea level of 2.6m. It can be seen that when the actuator moves past 0.6m the bending moment responses of strain gauges A, C, D and J start to oscillate. This appears to be due to a rapid release of soil suction, and is termed a suction kick.

These observations of the test data shows some of the effects that influence the soil suction force, including repeated loading, changing the pull up velocity and the length of the consolidation time. The tests also showed some effects of soil suction on the harbour test riser, including the suction kick and suction release. The test data was also used to refine and calibrate the 2H Offshore Engineering Ltd soil suction model.

Analytical Modelling

An analytical model of the harbour test riser was produced to calibrate the 2H Offshore Engineering Ltd soil suction model. The analysis was conducted using both the ABAQUS and ANSYS finite element codes.

The soil suction curve used in the analytical modelling was the upper bound curve based on the previous STRIDE 2D pipe/soil interaction work, Willis (2001). The soil curve, Figure 15, consists of 3 sections: suction mobilisation, the suction plateau and suction release, described below:

- Suction mobilisation – As the riser initially moves upwards the suction force increases from zero to the maximum value
- Suction plateau – The suction force remains constant as the riser moves further upwards
- Suction release – Under further upward movement the suction force reduces from its maximum to zero at the break-out displacement

The analytical model was created to match the final harbour test riser as closely as possible. The model dimensions were taken from surveys of the riser and the seabed profile conducted during the testing program. The model for each analytical test corridor was then calibrated to the ‘as built’ riser by changing the length of the top cable.

Comparisons between results obtained using the analytical model and the harbour test riser are conducted using two methods. The first compares the test data from a single strain gauge location to that of a similar point on the analytical model. The magnitudes of the bending moments at the start of the analytical model are matched to those of the harbour test riser to account for the effects of the uneven seabed. The analysis using no soil suction (green line), Figure 16, is compared to the lay down test (blue line). The analysis using the upper bound soil curve (black line) is compared to the pull up test (red line). Comparisons between the results from the analytical modelling and test corridors 2 and 4 are shown in Figures 16 and 17 respectively. It can be seen that the analytical model using the upper bound soil suction curve predicts the test data very well.

The second method of comparing test and model results is achieved using the bending moment envelopes from the analytical predictions for the no suction and with suction models. These are compared to the maximum and minimum of the strain gauge locations during pull up and lay down tests, Figure 18. As before, the green and black lines represent the no soil suction and the upper bound soil suction models respectively (Note that the top most black line is on top of the green line). The red and blue lines show the minimum and maximum bending moments from pull up (with soil suction) and lay down (no soil suction) tests. The difference between the red and blue lines is the effect on the bending moment of the soil suction.

It can be seen that the analytical bending moment envelopes compare well to the test data ranges; the no soil suction model predicting the lay down test data ranges well. The effect of soil suction is also predicted well, with strain gauges C, D and F showing a similar response to the upper bound soil model. The analytical model also predict the response of strain gauges J and K, which exhibit a lower change in bending moment during the pull up test than lay down test.

The analysis shows that the effects of soil suction can be predicted using the 2H Offshore Engineering Ltd soil suction model with the appropriate soil suction curve.

Conclusions

The full-scale tests provide a valuable basis for evaluation of SCR soil interaction and validation of numerical models. A numerical model has been developed based on small-scale tests and validated using the full-scale response measurements. This suggests that numerical models can be developed to predict full-scale response in various geographical locations based upon small-scale pipe/soil interaction tests using soil representative of the location .

Soil suction is shown to occur and produces differences in bending moment response between a pull up test and a subsequent lay down test. Comparisons of pull up and lay down response from the range of tests conducted produced the following key findings:

- A sudden vertical displacement of a catenary riser at its touchdown point (TDP) after a period at rest could cause a peak in the bending stress that travels along the riser. Such an event may occur from a vessel failed mooring line, or a move away for drill rig access.
- Soil suction forces are subject to hysteresis effects. For example, once the seabed/riser interface has been disturbed, subsequent seabed/riser interface contacts produce less suction effect.
- The soil suction force is dependant on the consolidation time.
- Pull up velocity has little effect on the bending moment response on a remoulded seabed.
- Soil suction can cause effects such as the suction kick
- Following any actions resulting in pull-up, the mobilised soil suction will dissipate, and the riser will move into an equilibrium position with no or little no soil suction.

The analytical modelling of the harbour test riser used a soil suction curve developed from 2D pipe/soil interaction tests with the 2H Offshore Engineering Ltd soil suction model. The analytical models predict the harbour test riser bending moment measurements well.

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STRIDE Phase III details

Lead Engineering Contractor:	2H Offshore Engineering

Participants:

BP	Statoil	Aker
Chevron	Texaco	Brown & Root
Conoco	TotalFinaElf	Single Buoy Moorings
Norsk Hydro	Vastar	Sofec
		Stolt Offshore

Programme manager:	Offshore Technology Management

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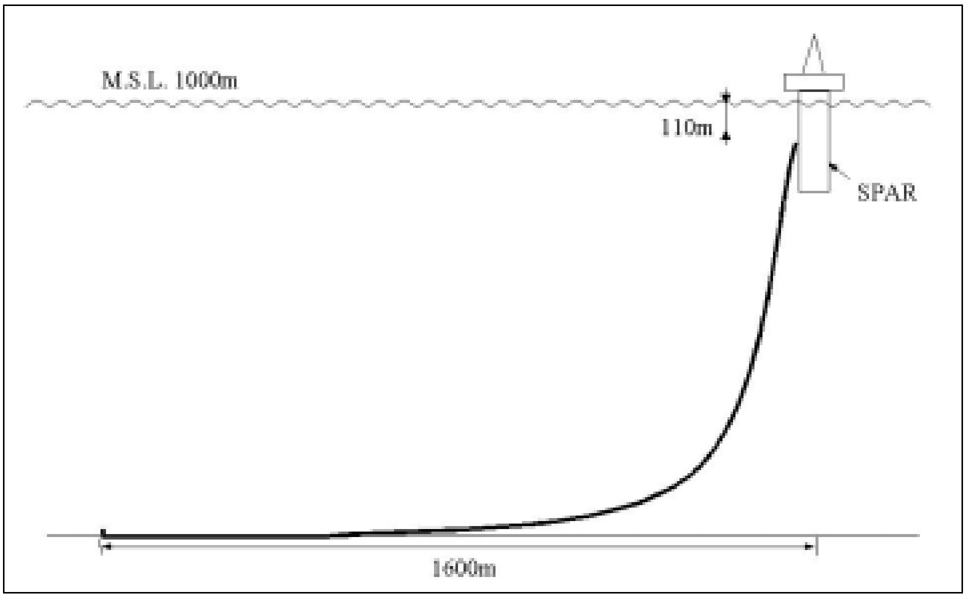

Figure 1 – Full Scale Riser Configuration

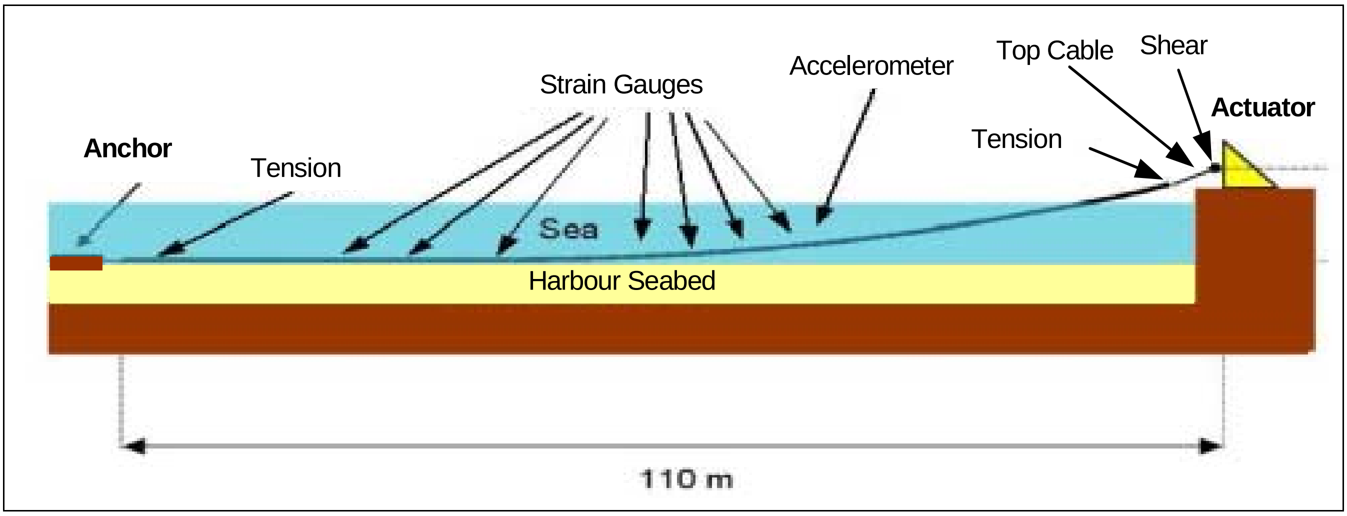

Figure 2 – Harbour Test Set-Up Schematic

Figure 3 – Harbour Test Site at Low Tide

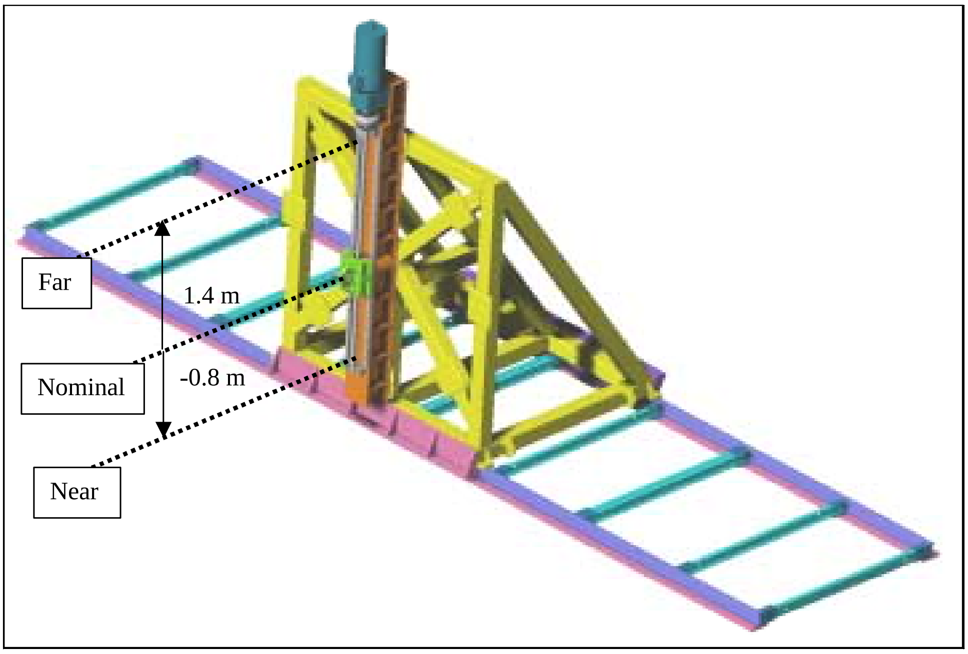

Figure 4 – Actuator Unit and Rails

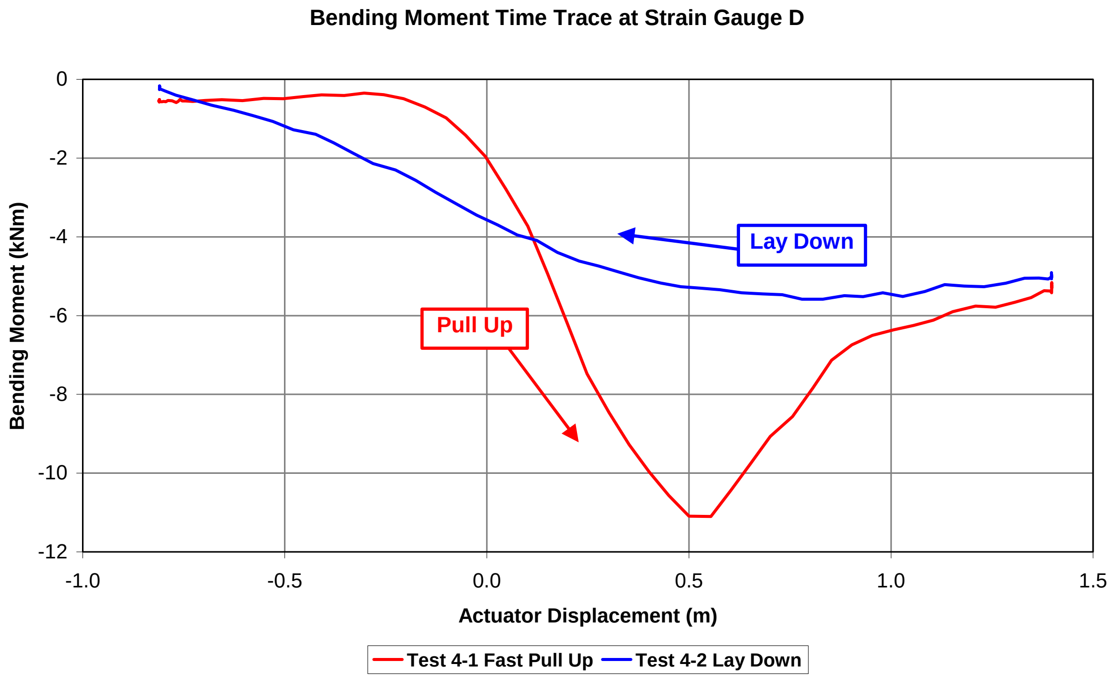

Figure 5 – Suction Peak for Fast Drift Case

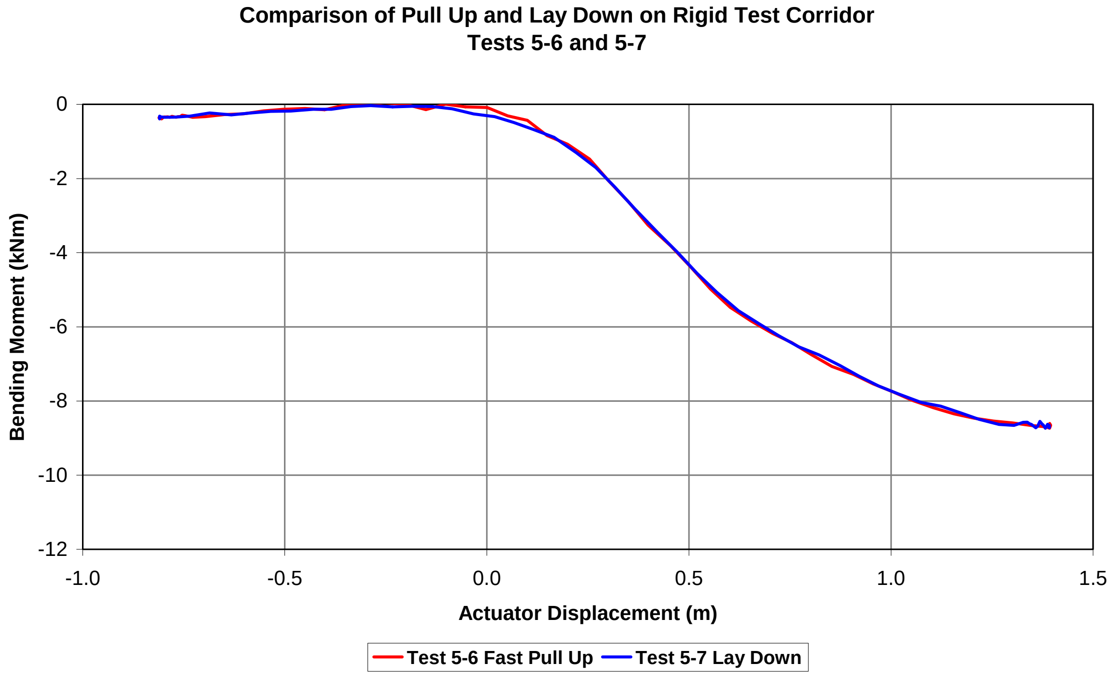

Figure 6 – Comparison of Pull Up with Lay down Tests in the Rigid Test Corridor

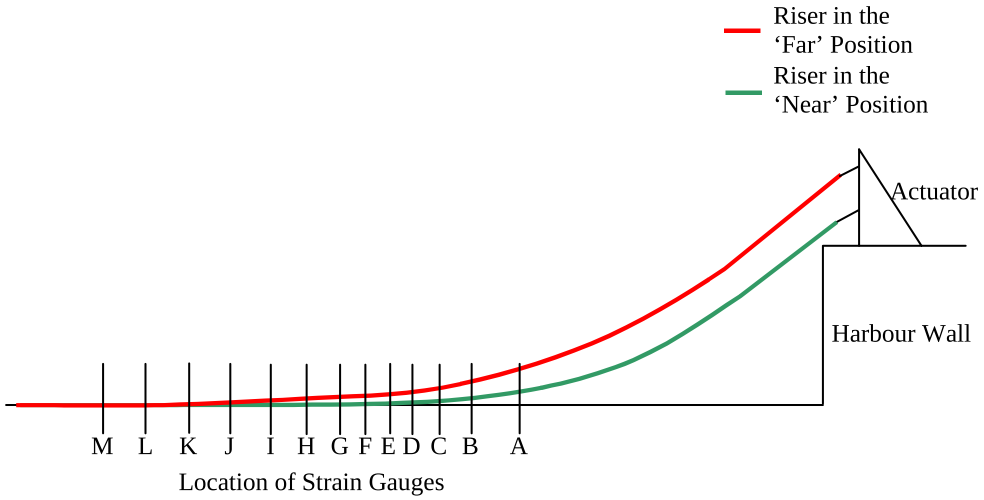

Figure 7 – Location of Strain Gauges Along Risers

Red Lines – Pull Out (0.8% Near to 1.5% Far), Test 2-10, **Blue Lines – Lay Down** (1.5% Far to 0.8%Near), Test 2-11

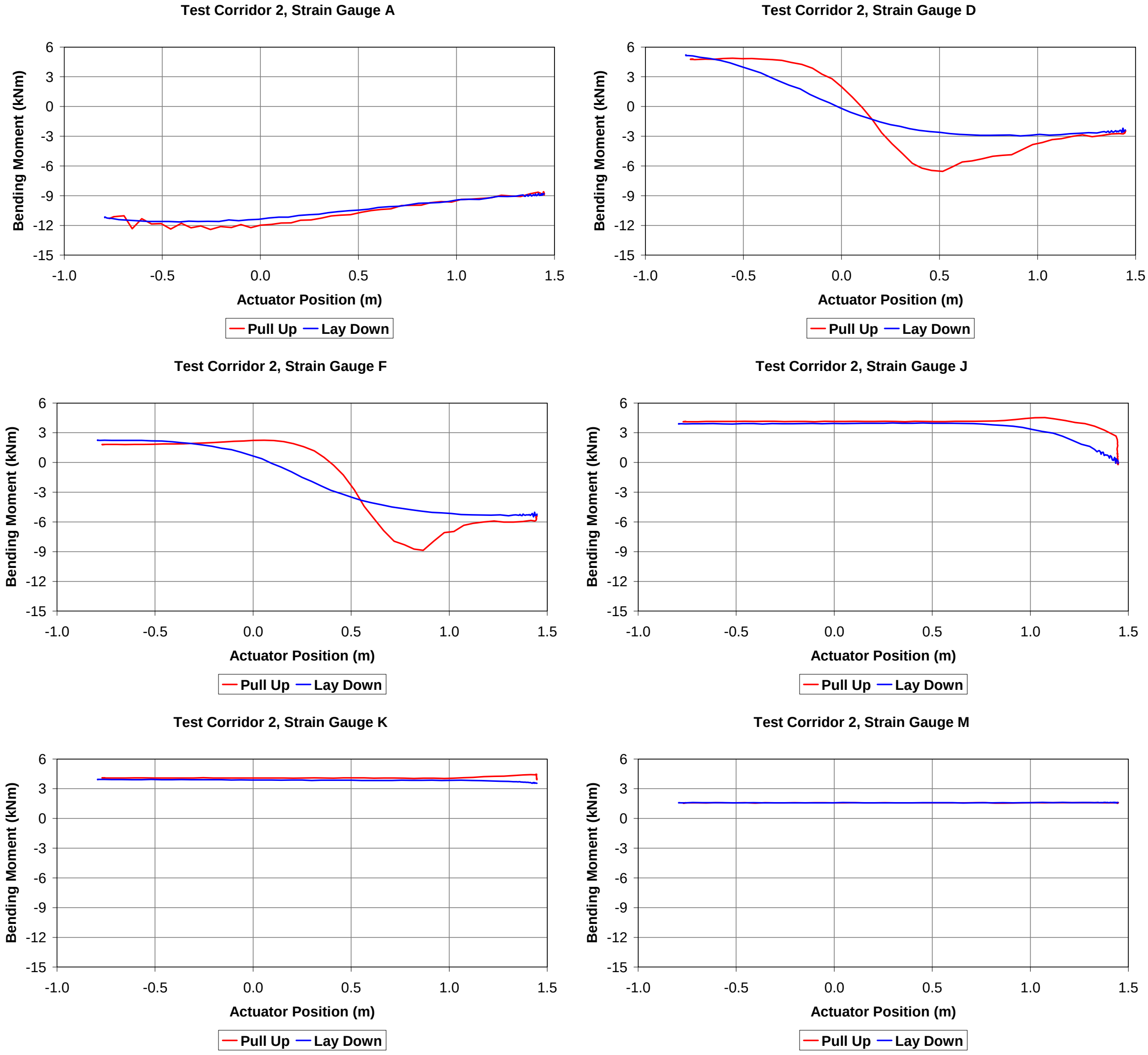

Figure 8 –Test Area 2 – Natural Trench

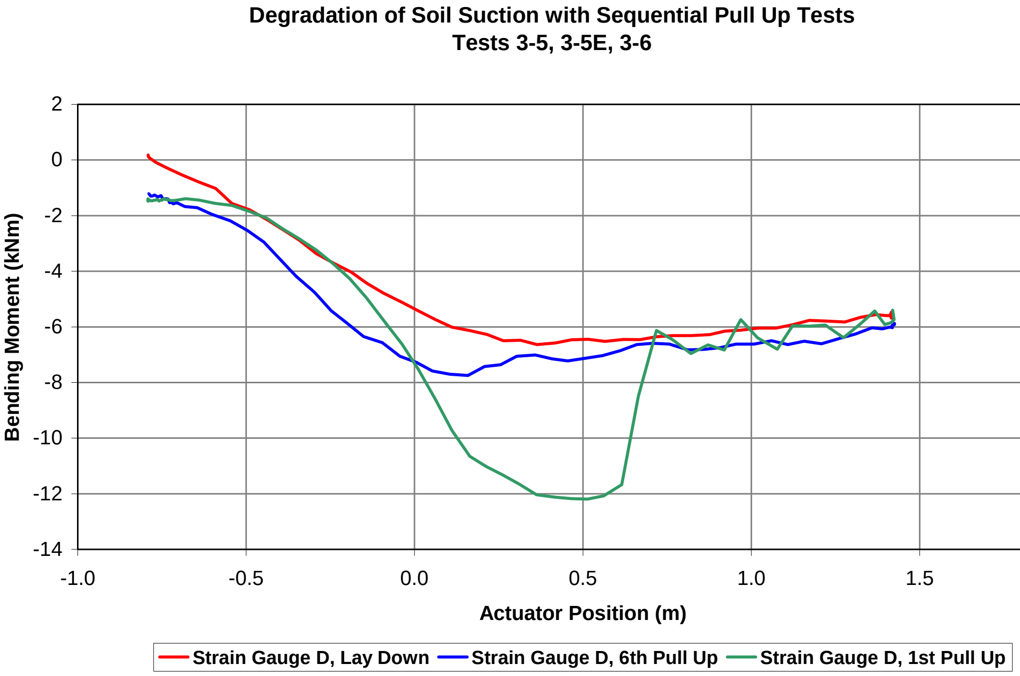

Figure 9 – Comparison of a First Pull Up Test with a Subsequent Pull Up Test

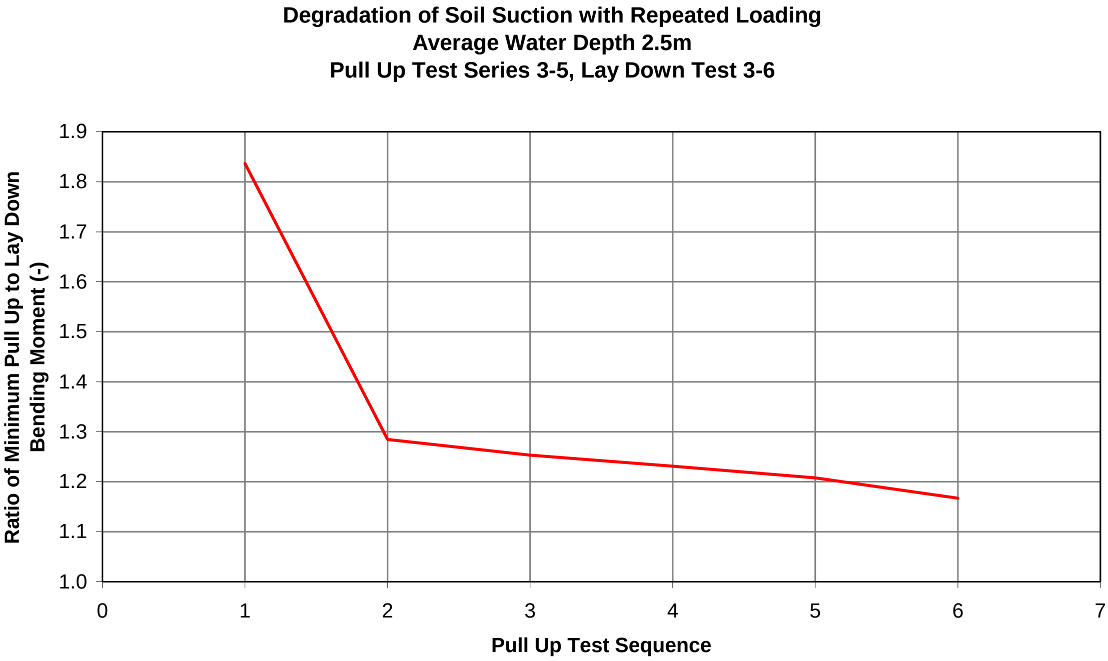

Figure 10 – Effect of Repeated Loading on Bending Moment Response

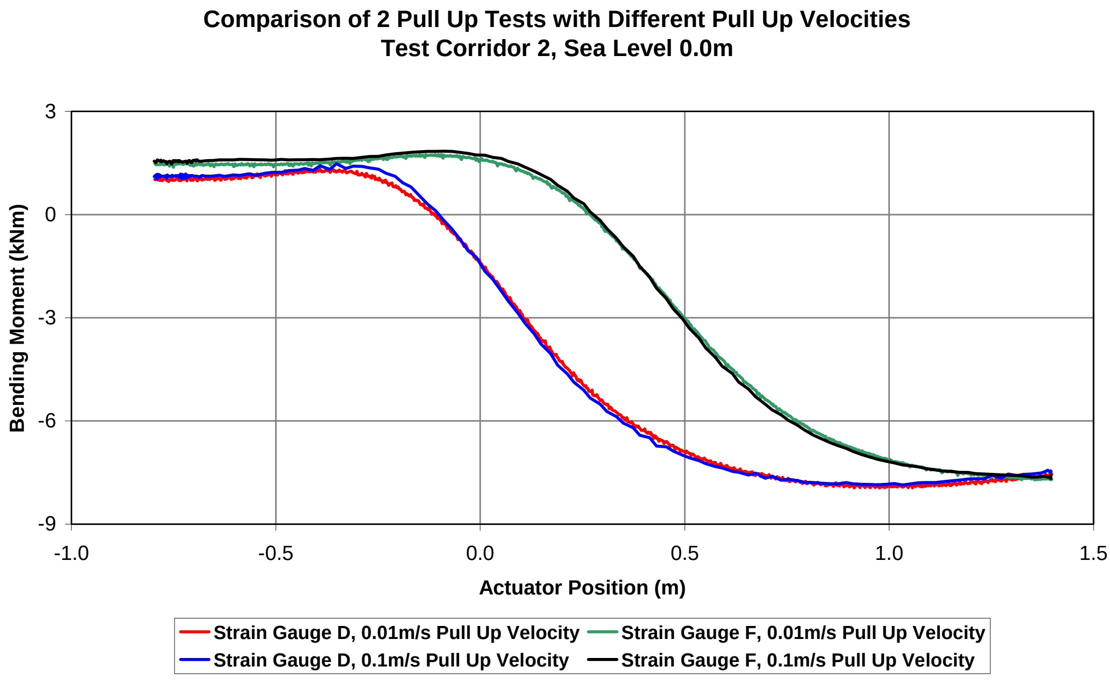

Figure 11 – Comparison of Pull Up Velocities

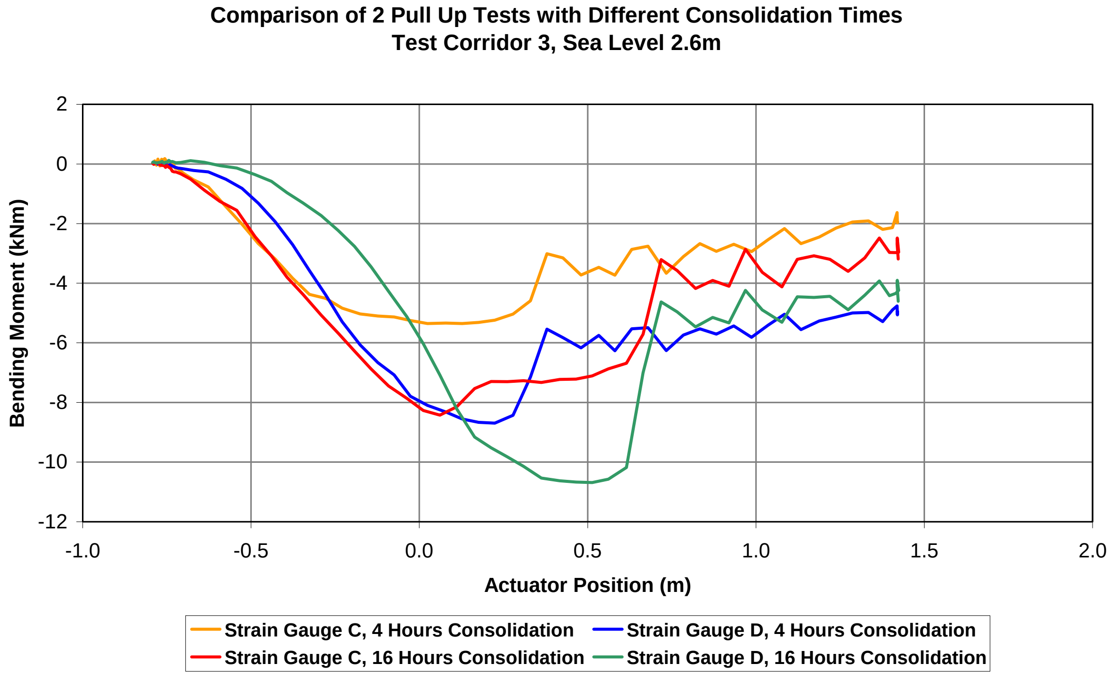

Figure 12 – Comparison of 2 Different Consolidation Times

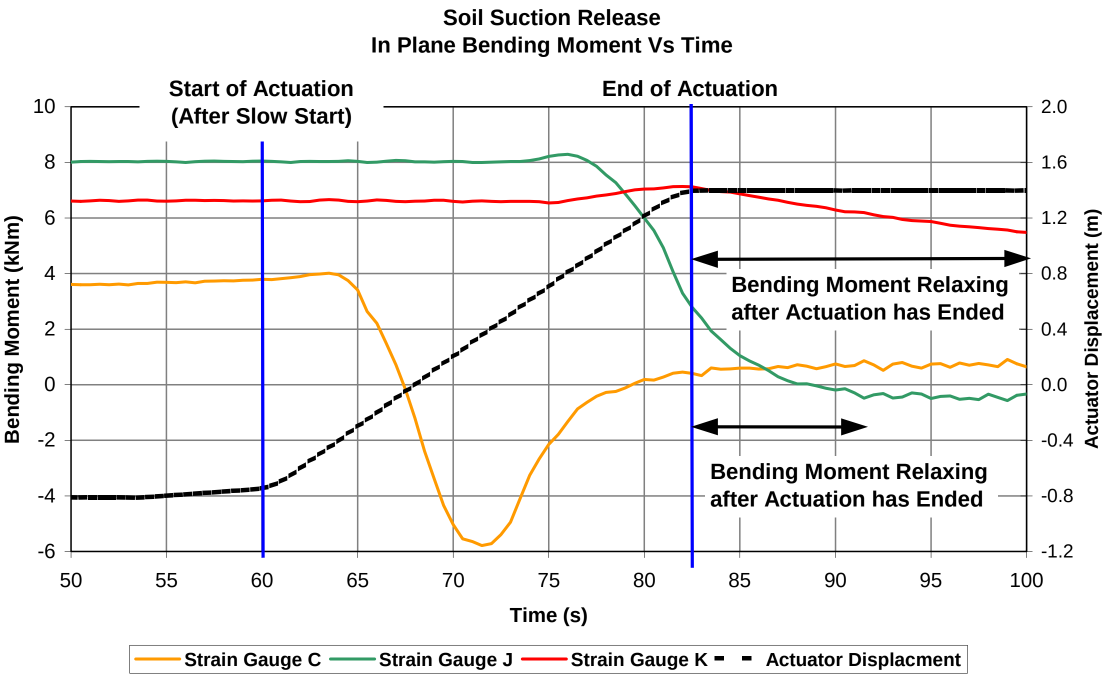

Figure 14 – Evidence of Suction Release with Time

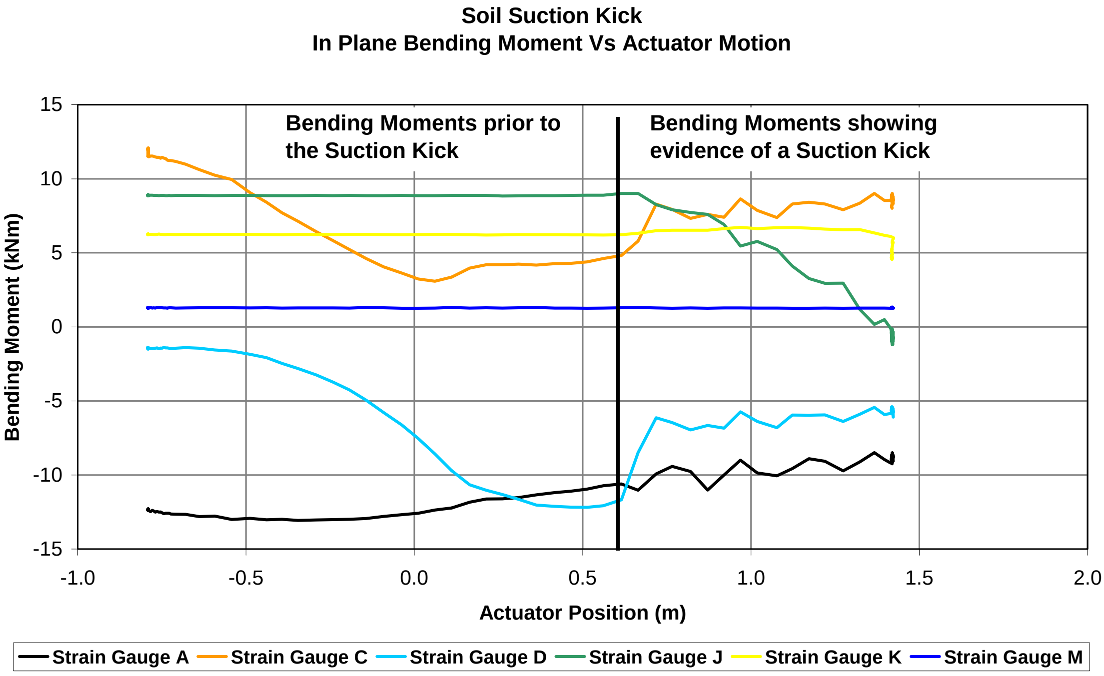

Figure 13 – Evidence of a Suction Kick

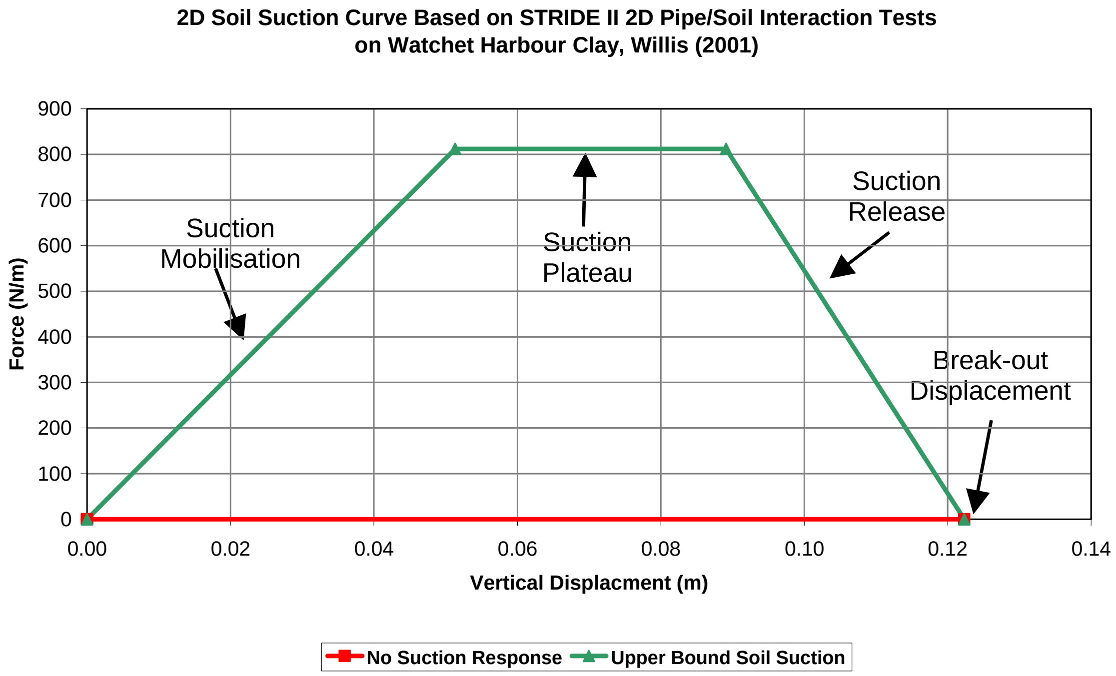

Figure 15 – Soil Suction Models Used in Post-Analysis

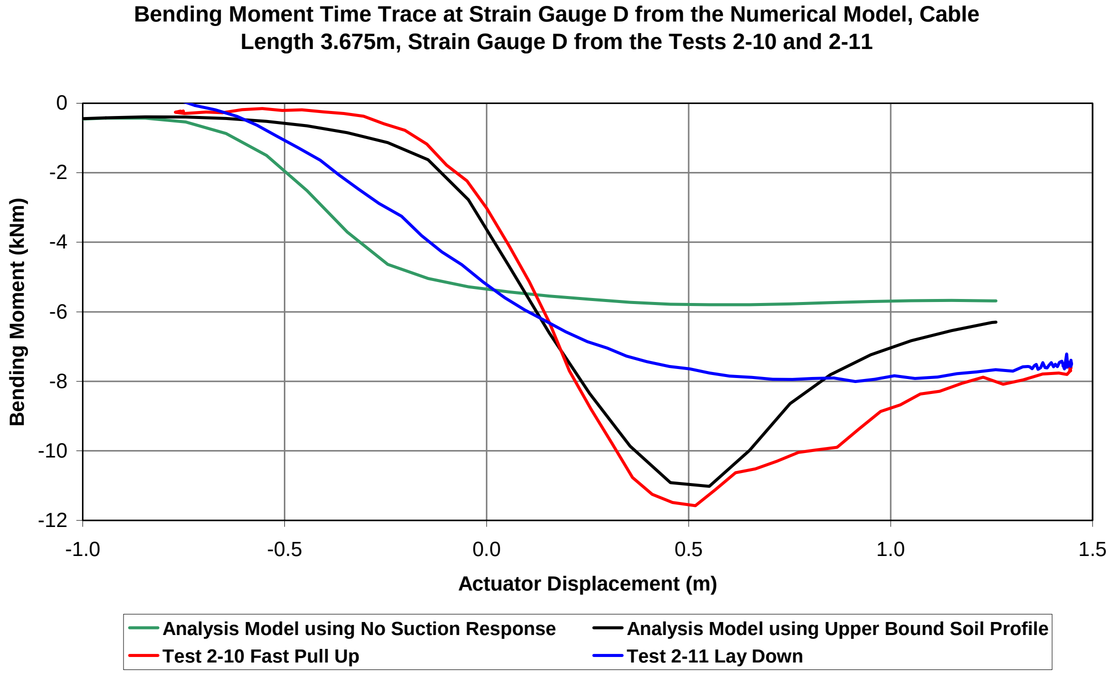

Figure 16 – Comparison of Test Data with Analytical Model for Test Area 2

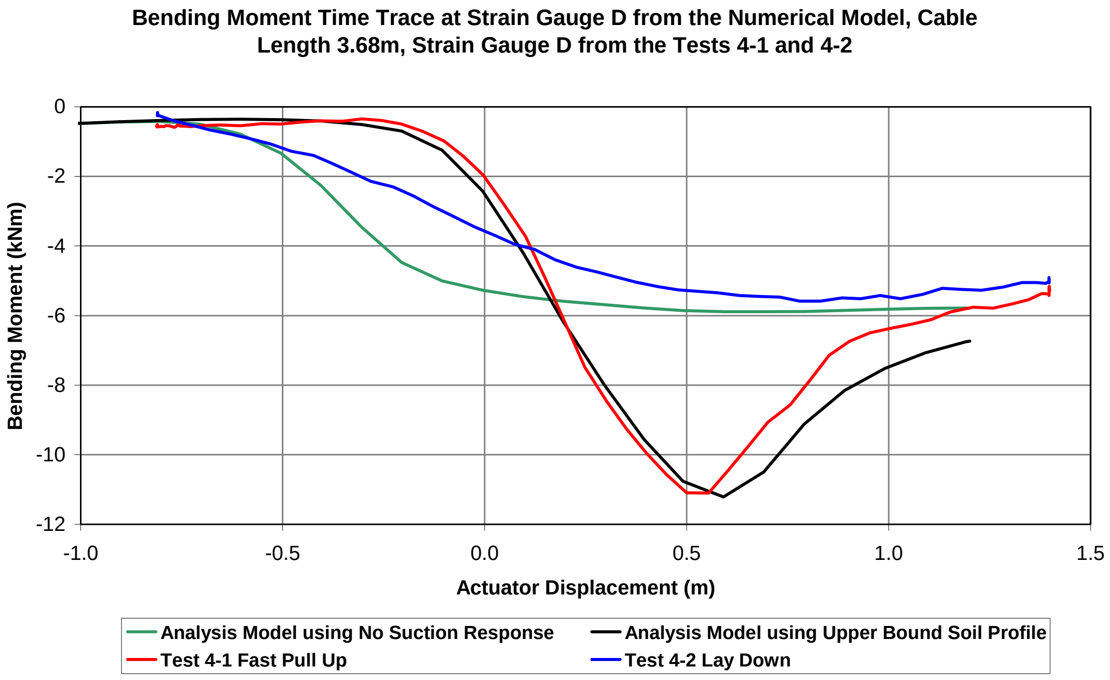

Figure 17 – Comparison of Test Data with Analytical Model for Test Area 4

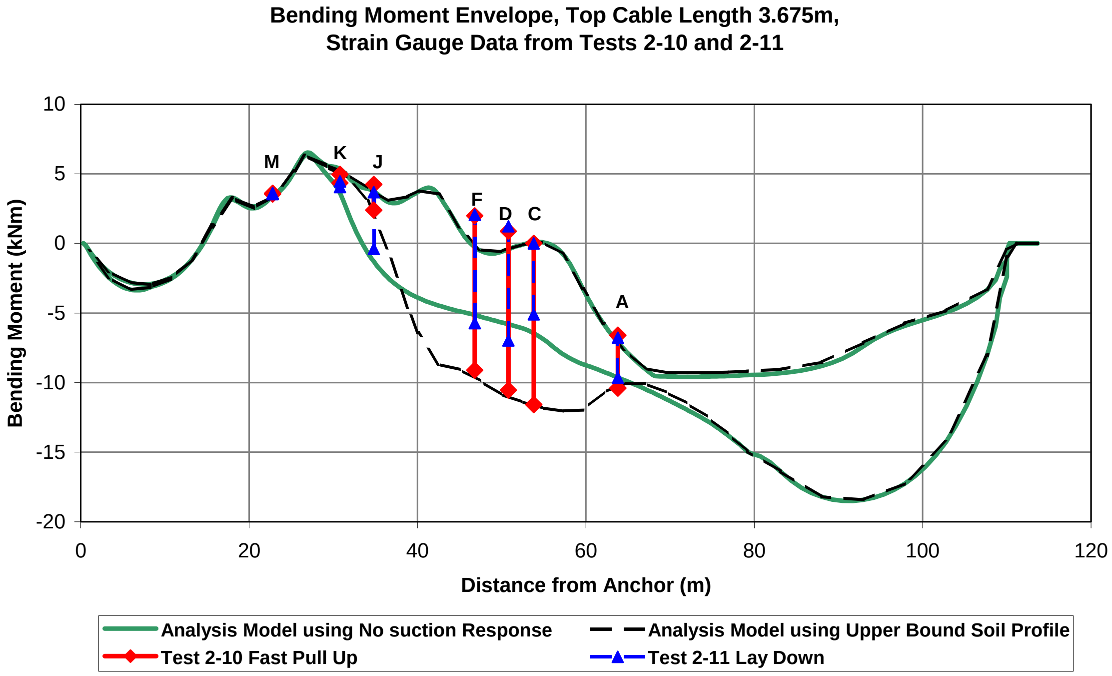

Figure 18 – Comparison of Test Data and Analytical Bending Moment Envelope