Components of Suction Caisson Capacity Measured in Axial Pullout Tests

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Abstract

Laboratory experiments are being conducted to study the behavior of suction caissons used for deep offshore moorings. Results from nine caisson pullout tests were used to quantify the components of axial capacity. Tests with a 100-mm diameter caisson prototype, installed using dead weight or suction, were performed in a 1.1-m thick deposit of kaolinite. Large tanks of normally consolidated clay, selected to simulate common seafloor conditions, were prepared by consolidating a kaolinite slurry. Axial pullout tests were carried out on caissons inserted using dead weight only or dead weight plus suction pressure, on caissons pulled with a vented or sealed top cap, and with rapid (undrained) versus slow (drained) pullout. Measured axial capacities are interpreted in terms of the weight of extracted soil, side resistance on the caisson walls, and reverse end bearing capacity at the tip. For rapid pullout with a sealed top cap, the test results indicate an external side resistance factor (α) of 0.5 to 0.8 and a reverse end bearing factor (N'_c) of 13 to 21.

Introduction

A suction caisson is a large, closed-top steel tube that is lowered to the seafloor, allowed to penetrate the bottom sediments under its own weight, and then pushed to full depth with differential pressure produced by pumping water out of the interior. Suction caisson anchors are an attractive alternative for providing fixed anchorage for offshore structures because they can be installed reliably in deep water, have a large axial and lateral holding capacity, and can be recovered for re-use in other locations.

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Most worldwide experience with this technology has involved relatively short, large-diameter caissons with vertical loads applied at the center of the top plate. However, the conditions in many deep-water locations require different design configurations. Typical sediments in the deep Gulf of Mexico, for example, are normally consolidated and underconsolidated, highly plastic clays. To develop the desired capacity in these soft soils, longer caissons are needed and, to maximize lateral capacity, mooring lines are attached well below the mud line. While the offshore industry is deploying suction caissons in these configurations, a number of design issues remain unresolved (Clukey 2001; Gilbert and Murff 2001). There is a paucity of performance data on suction caisson behavior, especially for long, slender caissons subjected to inclined lateral loads applied below the mud line.

This paper is concerned with the axial pullout capacity of relatively long suction caissons in soft clay. While taut mooring systems in deep water can impart large lateral forces, axial capacity often controls the design of a suction caisson when the load is applied at a high inclination below the mudline (Clukey 2001).

A number of investigators have tested scale models of suction caissons in geotechnical centrifuges (e.g., Clukey et al. 1995). Centrifuge tests allow for scaling effects and produce results quickly, but some measurements are difficult on small models and some scaling laws are hard to satisfy. A few field tests have been reported (e.g., Tjelta et al. 1986); other field tests have been performed but are not reported in the open literature. Field and centrifuge tests are expensive, making it difficult to study all variables of interest. Model tests conducted under 1-*g* in the laboratory allow for evaluating a wider range of conditions, although the results do not scale up to field dimensions and the tests are time-consuming to perform. Model tests on axially loaded suction caissons have been reported by Steensen-Bach (1992), Rao et al. (1997), Whittle et al. (1998), El-Gharbawy and Olson (1999), and others. One-*g* model tests are useful in better understanding caisson behavior and can support the development of numerical models.

Laboratory tests with a 100-mm diameter suction caisson model are being conducted in tanks of normally consolidated clay. Aspects of this study have been detailed by Olson et al. (2003a), Rauch et al. (2001; 2003), and Luke et al. (2003). Here, components of the caisson's pullout resistance are studied using data from nine model tests. The results include measured capacities when the prototype caisson is inserted using dead weight and/or suction pressures, extracted rapidly versus slowly (undrained versus drained soil conditions), and pulled with a vented or sealed top cap.

Test Methods

Instrumentation. The model caisson (Fig. 1) was constructed from a 102-mm (4.00-in.) diameter anodized aluminum tube with a wall thickness of 0.81 mm, which gives a thickness-to-diameter ratio similar to that of a typical full-scale caisson. The model can be inserted to depths up to about 860 mm. An aluminum bar (3.2 by 12.7 mm in cross section) is welded to the lower half of the model as a padeye for attaching a cable for lateral load tests. No internal stiffeners are present.

Tests are conducted by inserting the model into soil deposits prepared in large steel tanks. To maintain vertical alignment during insertion and pullout, a rod

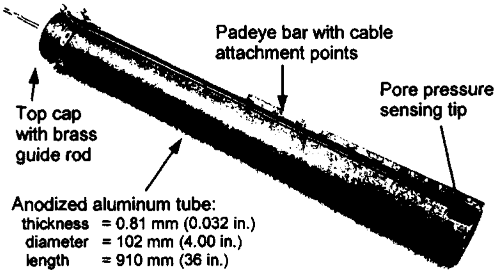

Figure 1. Prototype caisson used in the model tests.

connected to the caisson top passes through bushings on a fixture mounted on top of the tank. The rate of insertion and removal is manually controlled using a winch and wire cable. Caisson displacements are recorded using a linear displacement transducer, while axial forces are measured with a 110-N (25-lb) load cell. Water pressures can be measured inside the top cap and at five locations on the caisson wall. The pore pressure sensing tips (Fig. 1) consist of porous bronze patches epoxied to the caisson wall and covering the ends of the sensing lines, which are connected with small plastic tubes to pressure transducers mounted separately from the caisson.

Test bed soil. To represent the soil conditions at many deep offshore sites, tests are conducted in a normally consolidated clay. After considering various soils, it was apparent that only kaolinite would yield an acceptable consolidation time and final thickness in the test bed deposits. The selected kaolinite was "Hydrite R" (Dry Branch Kaolin Co., Dry Branch, Georgia). The supplier reports a median particle size of 0.8 mm and a specific gravity of 2.58. Tests indicated that the liquid limit is between 54 and 58, and the plastic limit ranges from 31 to 34.

The test bed deposit was prepared by allowing a slurry of "Hydrite R" to consolidate under self weight (Olson et al. 2003b). The slurry was mixed to an initial water content of about 164% (liquidity index of 5.6) inside a steel tank measuring 1.2 by 2.4 m in plan and 1.8 m high. With double drainage, about eight months were required to consolidate the soil from an initial slurry thickness of 1.56 m to a final thickness of about 1.09 m. Soil water contents, determined from samples acquired with a small diameter piston sampler, were used to establish the final profile of total unit weight (Fig. 2a) and vertical effective stress (Fig. 2b) in the test bed.

Undrained shear strengths in the test bed soil were determined from T-bar penetration tests (Stewart and Randolph 1994) conducted with a 25-mm diameter by 100-mm long, smooth acrylic T-bar. The T-bar test is considered more reliable than a cone penetrometer test because the penetration resistance is not affected by overburden and water pressures, and the bearing factor is better defined. Undrained shear strengths (Fig. 2c) were determined using a bearing factor of 10.5 for the T-bar (Stewart and Randolph 1994). The undisturbed strength profile was obtained from an initial penetration, while the remolded strength was determined from repeated penetrations at the same location. The s_u/σ'_v of the undisturbed soil was about 0.2 over most of the depth, while the sensitivity varied between 2.3 and 1.7 (Fig. 2d).

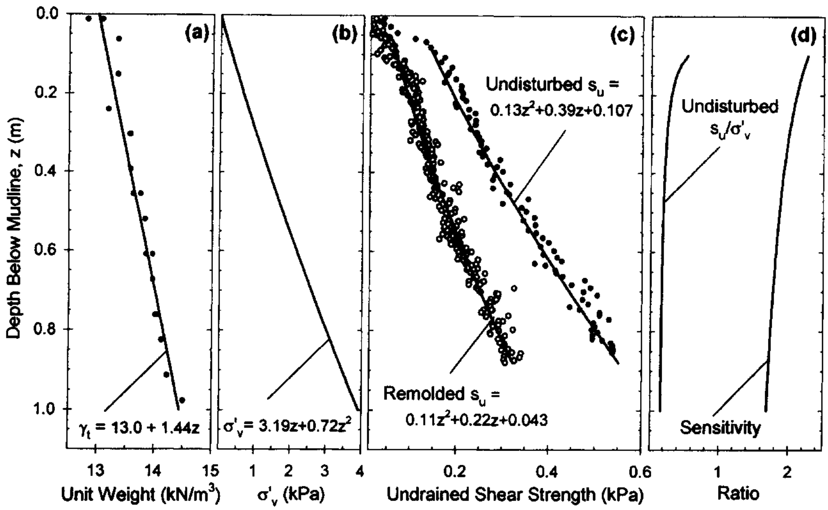

Figure 2. Profiles of (a) total unit weight, (b) vertical effective stress, (c) undrained shear strength, and (d) sensitivity and s_u/σ'_v in the consolidated test bed soil.

Caisson tests. Nine axial load tests were conducted as summarized in Table 1. The center-to-center spacing between adjacent test locations, as well as the distance between the side walls of the test tank and the center of each test location, was three caisson diameters (300 mm).

The caisson was pushed to full penetration with dead weight in three tests. In six tests, dead weight was used to install the caisson to about 250 mm; suction was then applied to insert the caisson to full depth. Data from the installation phase in these and other tests are presented and interpreted by Rauch et al. (2003).

Based on measurements of the pore water pressures (Olson et al. 2003a), all tests included a minimum set-up time of 48 hours following insertion to ensure full dissipation of excess pore water pressures on the exterior caisson wall.

For an extraction test with a vented top, the unused pressure ports in the cap were left open. Water (or air) could then flow into the caisson during pullout and the cylinder (plug) of soil inside the caisson was left behind in the soil deposit. For the sealed top cap tests, all of the ports were sealed. Under these conditions, suction developed inside the top cap and the interior soil plug was pulled out of the deposit with the caisson.

Rapid extraction tests (undrained soil conditions) involved pulling the caisson out of the soil at a rate between 5 and 20 mm/sec. To achieve drained soil conditions in a slow pullout test, the caisson was extracted in increments of about 1 mm. The next 1-mm increment was not applied until the excess pore water pressures measured along the interior and exterior caisson walls had dissipated to less than ±0.3 kPa. Approximately 30 minutes were required to dissipate the pore water pressures generated in each increment of movement.

Table 1. Summary of nine model tests with rapid pullout of the (a) vented and (b) sealed caisson, and (c) slow pullout of the vented caisson.

Test ID	*Installed by Dead Weight (DW) or Suction (S)*	*Maximum Depth of Insertion by*		*At Maximum Pullout Resistance*			
		Dead Weight (mm)	*Suction (mm)*	W_{soil} *(N)*	Q'_{tip} *(N)*	Q_{side} *(N)*	α
(a) Rapid pullout with a vented top cap (no soil plug)							
1-022702	DW	854	None	16	--	--	--
1-040802	DW	833	None	9	1	101	0.67
1-030502	DW + S	279	821	16	1	82	0.55
1-041002	DW + S	279	808	7	1	82	0.57
(b) Rapid pullout with a sealed cap (with a soil plug)							
1-030102	DW	858	None	107	40	78	0.97
1-030802	DW + S	279	819	103	38	77	1.04
1-031002	DW + S	279	808	102	38	73	1.01
1-041502	DW + S	229	794	98	37	82	1.17
(c) Slow pullout with a vented top cap (no soil plug)							
1-042502	DW + S	229	812	0	0	85	0.58

Analysis of Pullout Resistance

The forces acting on the caisson during extraction are indicated in Fig. 3. For both the vented and sealed conditions, the resistance to axial pullout (Q) can be written:

$$Q = W_{caisson} + F_{press} + W_{soil} + Q_{side} + Q_{tip} \tag{1}$$

where the terms are defined as follows. $W_{caisson}$ is the self weight of the caisson (in air) plus any added surcharge weight. F_{press} represents forces on the caisson due to water pressures, including hydrostatic pressure on the top of the caisson cap, pressure inside the top cap during vented pullout, and buoyancy effects, which vary when the caisson is partially submerged. W_{soil} is the weight of soil being pulled out with the caisson, including soil adhering to the side walls and, when the top is sealed, soil and water in the caisson interior. Q_{side} is the total shear resistance along the interior (vented case only) and exterior vertical sides of the caisson. Q_{tip} is the total reverse end bearing force. In design practice, the capacity equation is usually written in an equivalent form using the net reverse end bearing resistance (Q'_{tip}), but Eq. 1 is more convenient for analyzing the model test results.

When the top cap is vented, Q_{side} develops on both the interior and exterior surfaces and W_{soil} includes the weight of soil adhering to both surfaces. When the top cap is sealed, the interior soil plug moves with the caisson, so Q_{side} acts only on the caisson exterior and W_{soil} includes the weight of the soil plug. The reverse end bearing force, which acts downward to resist pullout, develops only with undrained soil conditions where extraction generates a suction pressure at the caisson tip. If the

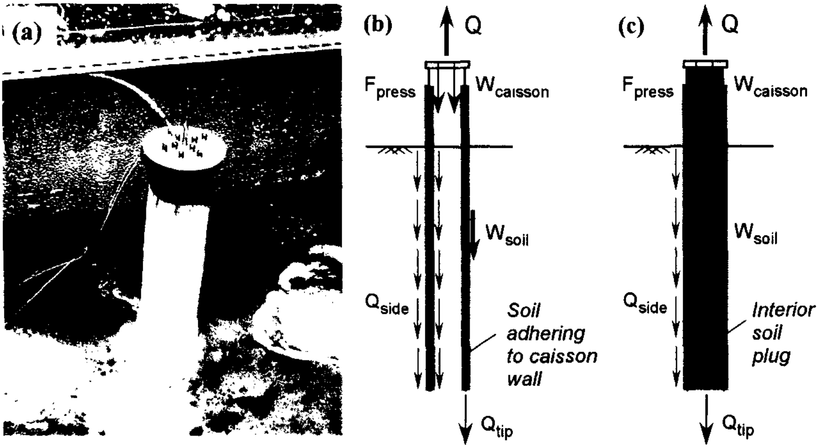

Figure 3. Caisson pullout: (a) photograph of test, and free body diagrams for extraction of a (b) vented or (c) sealed caisson.

caisson is vented, Q_{tip} acts on the thin cross sectional area of the caisson and is small. When the caisson top cap is sealed, a much larger reverse end bearing force develops over the end area of the caisson plus the soil plug, which is pulled out with the caisson.

The total end bearing force (Q_{tip}) on the caisson can be computed from bearing capacity theory. For undrained ($\phi = 0$) soil conditions, $N_q = 1$ and $N_\gamma = 0$. The overburden stress resists penetration of the tip during caisson installation, but acts to push the caisson out of the soil during pullout. Hence, for caisson extraction, the appropriate expression for the total reverse end bearing force is:

$$(Q_{tip})_{extraction} = (N'_c s_u - \sigma_v) A_{tip} \quad (2)$$

where N'_c is the bearing capacity factor with appropriate corrections for depth and shape, s_u is the undrained shear strength at the tip, σ_v is the total vertical stress at the tip elevation, and A_{tip} is the cross sectional area of the tip. The net reverse end bearing resistance (Q'_{tip}) is defined as:

$$(Q'_{tip})_{extraction} = N'_c s_u A_{tip} \quad (3)$$

In analyzing the pullout data, σ_v was calculated by integrating the equation for the unit weight of the test bed soil (Fig. 2a) and s_u was obtained from the undisturbed strength profile (Fig. 2c) at the elevation of the caisson tip. Consistent with design practice, Q_{tip} was computed based on the undisturbed soil strength. However, once the caisson capacity is exceeded, the tip is pulled through a zone of partially remolded soil, resulting in a somewhat reduced post-failure tip resistance.

The values of N'_c and A_{tip} depend on whether the caisson is sealed or vented during extraction. The internal soil plug is not pulled out with the vented caisson, so the reverse end bearing resistance can be modeled by treating the caisson tip as a strip footing (shape factor = 1) having a width equal to the caisson wall thickness. Since the wall thickness is much less than the depth for even shallow penetrations, the depth factor can be assumed to have a maximum value of 1.5 (Skempton 1951) throughout the pullout test. Using N_c = 5.14, the appropriate bearing factor is N'_c = 7.7. Since A_{tip} is small (equal to the cross sectional area of the caisson tube, 297 mm^2), Q'_{tip} contributes little to the pullout resistance of the vented caisson.

When the internal soil is pulled with the sealed caisson, reverse end bearing pressure develops over the tip area of the caisson tube plus the end area of the soil plug. The effective area of the caisson tip is then much larger (A_{tip} = 8142 mm^2), so the tip capacity contributes considerably more to the pullout resistance (Table 1b). Calculations were made using N_c = 5.14 and a shape factor of 1.2 for a circular tip. With the depth exceeding 2.5 times the diameter, a depth factor of 1.5 was used (Skempton 1951). The bearing factor is then N'_c = 9.3.

Given the measured or computed values of $W_{caisson}$, F_{press}, W_{soil}, and Q_{tip}, the side shear resistance (Q_{side}) was determined from Eq. 1. To compare the maximum capacities from different rapid pullout tests, the unit side resistance was normalized with respect to the shear strength of the soil to obtain the ratio α:

$$\alpha = \frac{Q_{side}}{A_{side}\, s_{u,avg}} \tag{4}$$

where A_{side} is the surface area of the caisson wall where side shear resistance develops, and $s_{u,avg}$ is the average undrained shear strength over the length of the caisson, computed from the trend line in Fig. 2c for the undisturbed soil strength.

Measured Pullout Capacity

Rapid pullout with a vented top cap. The caisson was pulled rapidly from the soil with a vented top cap in four tests. In all cases, the caisson came out of the test bed covered with a layer of soil on the inside and outside surfaces (Fig. 3a), providing evidence of shearing through the soil. With the top vented, the internal soil plug remained in the deposit (Fig. 3b).

The side resistances measured during vented pullout are plotted versus axial displacement in Fig. 4a. The weight of adhered soil (W_{soil}), which was assumed to be constant during pullout, was determined by weighing the caisson after it was fully extracted. The maximum pullout capacity developed with vertical displacements of 5 to 13 mm, or 5 to 13% of the caisson diameter. The pullout resistance then dropped off sharply, apparently due to the decreased shear strength of the remolded soil around the caisson. As the caisson was extracted from the soil, the axial resistance declined further with the reduced surface area contributing to Q_{side}.

Values of W_{soil}, Q'_{tip}, Q_{side}, and α for the ultimate capacity are given in Table 1a. The load cell was over-ranged in the first test (1-022702) and the peak load was not recorded; data from this test are reported because it shows the weight of soil extracted with the caisson, as well as the consistency in the measurements after failure (Fig. 4a). For vented pullout without an internal soil plug, W_{soil} and Q'_{tip} were

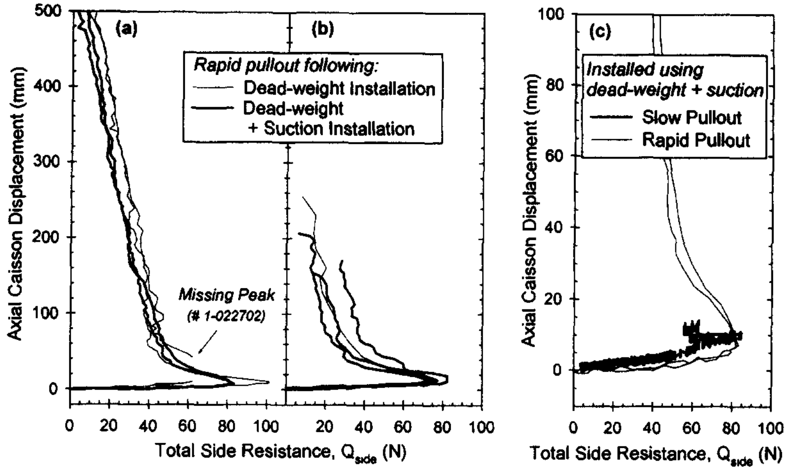

Figure 4. Measured side resistance: (a) rapid pullout with a vented top, (b) rapid pullout with a sealed top, and (c) slow versus rapid pullout with a vented top.

relatively small (Table 1a) and most capacity developed from side resistance along the caisson walls. The relative contributions from side shear on the caisson interior and exterior could not be distinguished, so an average value of α is reported.

The peak side resistance was about 25% higher in the single test where the caisson was inserted completely using dead weight (Table 1a). The post-peak side resistance of the suction-installed caisson was also less during pullout (Fig. 4a). The possibility of having lower side shear resistance following suction installation has been the subject of recent discussion (Clukey 2001; Gilbert and Murff 2001). However, the lack of duplicate test results makes it difficult to draw a firm conclusion from this data.

Rapid pullout with a sealed top cap. The caisson was pulled rapidly from the soil with a sealed top cap in four tests. The internal soil plug was thus pulled out of the test bed with the caisson (Fig. 3c), greatly increasing the weight of adhered soil and the influence of end bearing on the uplift capacity.

In a preliminary test with a sealed top, the soil plug was weighed after being completely extracted with the caisson, but the hole left in the test bed collapsed and disturbed a large zone of soil. To preserve adjacent test locations, all remaining tests with a sealed caisson were halted after about 150 to 250 mm of displacement, well after the peak pullout capacity was recorded. At this point, the caisson was vented and the interior soil was allowed to slide back into the deposit. This procedure minimized the area disturbed in the test bed, but also prevented the direct measurement of W_{soil}. Instead, W_{soil} was determined by estimating the weight of the soil plug and assuming the soil adhering to the caisson exterior was half the average weight of soil extracted in the vented caisson tests.

In all four tests with a sealed top cap (Fig. 4b), the maximum pullout capacity developed in about 13 mm of displacement, or 13% of the caisson diameter. The pullout resistance then dropped off sharply, presumably as a result of soil disturbance. The pullout resistance continued to decline as the caisson was withdrawn, due to the reduced wall surface area in contact with the soil. Values of W_{soil}, Q'_{tip}, Q_{side}, and α for the measured ultimate capacity in each test are given in Table 1b. Side resistance developed only on the caisson exterior when the interior soil plug was extracted with the caisson, so α (Eq. 4) was computed with A_{side} equal to the outside surface area.

Slow pullout with a vented top cap. One slow, incremental pullout test with a vented top cap was conducted to measure axial capacity under drained soil conditions. The peak load was reached in 5.5 hours after about 11 mm of axial displacement (Fig. 4c).

Given the drained soil conditions, the pullout capacity measured in this test was attributed entirely to side resistance; that is, it was assumed that W_{soil} and Q_{tip} were zero. Earlier model tests (El-Gharbawy and Olson 1999) showed that failure under drained conditions occurs by sliding at the soil-caisson interface, with no soil adhering to the caisson walls. Because the test was conducted with a vented top cap, the soil plug was not pulled with the caisson and W_{soil} was thus zero. Also, as long as drained conditions prevent the development of suction pressures, tensile stresses cannot be sustained at the soil/caisson interface and the tip resistance is zero.

In Fig. 4c, the side resistance from the slow pullout test is compared to that measured in the corresponding rapid pullout tests, with suction installation and vented pullout. The observed side resistances under drained and undrained soil conditions are similar. The pullout capacity (maximum Q_{side}) was 85 N in the slow pullout test, corresponding to an α value of 0.58. The drained side shear capacity of a deep foundation is often predicted using effective stress and the ratio β:

$$\beta = \frac{Q_{side}}{A_{side}\sigma'_{v,avg}} \tag{5}$$

where $\sigma'_{v,avg}$ is the average vertical effective stress along the length of the caisson. For a maximum side resistance of 85 N, the value of β was 0.12.

Components of Axial Capacity for Sealed, Rapid Pullout

The values of α for rapid pullout (Tables 1a and 1b) differ substantially for the vented and sealed caisson. Interpretation of the sealed caisson tests are complicated by the uncertainty associated with the values of W_{soil}, N'_c, and α. The total side resistances determined from the vented pullout tests are believed to be more accurate because the contributions of W_{soil} and Q_{tip} are relatively small.

Note that the α values reported for the vented tests (Table 1a) are average values for the interior and exterior surfaces. In reality, the internal and external side shear forces may differ due to differences in the radial effective stresses on the inside and outside surfaces of the caisson following insertion. However, values of the average α for the vented caisson are consistent with those measured in tests with a thin aluminum plate inserted vertically into the soil. Eleven such tests were conducted in the same test bed using a plate that was 100 mm wide by 800 mm long and 0.8 mm thick. While considerable scatter was observed (Fig. 5), the results indicate that α

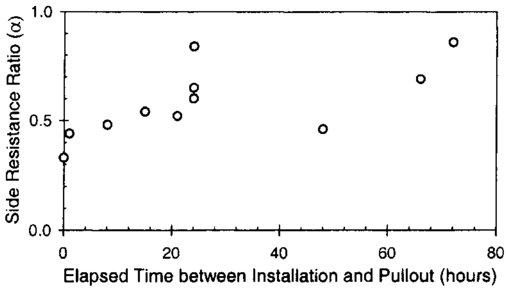

Figure 5. Side resistance measured during rapid pullout of a thin plate.

was between 0.46 and 0.86 after full set-up. The values of α determined in the vented pullout tests (Table 1a) fall in the middle of this range.

Given these results, it is reasonable to assume that α is between 0.5 and 0.8 for the external side resistance on the sealed caisson. This is smaller than the values reported in Table 1b, indicating that the value of N'_c or the weight of the soil plug may be larger than assumed. Data from centrifuge model tests (House and Randolph 2001) also suggest N'_c is greater than 9.3 for reverse end bearing on a sealed suction caisson.

Different combinations of soil weight, end bearing, and side resistance that would produce the capacity measured in the four tests with the sealed caisson were investigated. These results are plotted in Fig. 6 in terms of W_{soil}, N'_c, and α. The

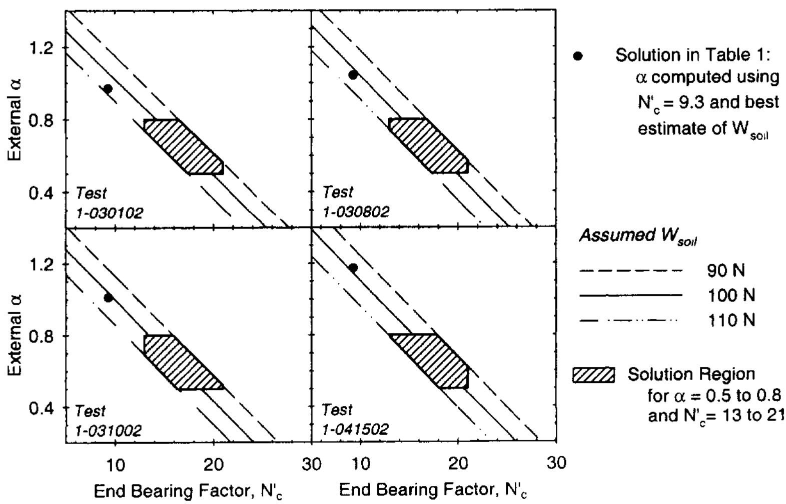

Figure 6. Combinations of soil weight, side resistance, and reverse end bearing that give the peak capacity measured in four rapid pullout tests of the sealed caisson.