Suction embedded plate anchor test in centrifuge

Zhenhe Song, Yuxia Hu
Department of Civil Engineering, Curtin University of Technology, WA, Australia

Keywords: Plate anchor, centrifuge test, transparent soil, rotation

ABSTRACT

Suction embedded plate anchors (SEPLA) were tested in centrifuge. Normally consolidated (NC) Kaolin clay and uniform transparent soil were used in testing. To investigate the suction installation effect, anchor tests with jacking in installation were also performed. Anchor rotation and loss of embedment were obtained through detailed examination of digital images taken in transparent soil tests. The suction installation showed reduced loss of embedment in uniform transparent soil test; this was not so evident in NC Kaolin clay test. Suction installation showed no obvious effect on anchor capacity factor when anchor was fully rotated and its capacity was fully developed. However, the long term installation of anchor provided increased capacity of anchor.

1 INTRODUCTION

In recent years, oil and gas mining has moved into increasingly deeper water in search of undeveloped fields. For water depths in excess of 500 m, conventional platforms are replaced by floating facilities, anchored to the seabed using catenary or taut-wire moorings. The latter type of mooring imparts significant vertical loading to the anchor, and consequently many different types of anchoring system have been developed (Ehlers et al. 2004). The SEPLA (Suction Embedded Plate Anchor) is one of such systems, which comprises a plate anchor that is penetrated in a vertical orientation using a caisson, and subsequently rotated by applying the anchoring force at some eccentricity until the plate becomes perpendicular to the applied force. This process is schematically illustrated in Figure 1 (Aubeny et al. 2001). It has been conceived to combine the advantage of suction caissons (known penetration depth and geographical location) and vertical loaded anchors (geotechnical efficiency and low cost).

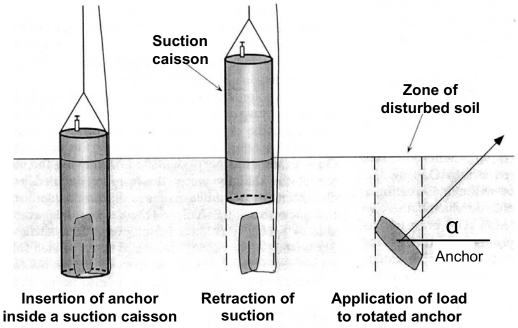


Figure 1 Installation process of SEPLA (after Aubeny et al. 2001)

When a plate anchor is vertically embedded, the anchor will rotate to be perpendicular to the pullout direction. This rotation is termed “keying”. The keying process has been studied numerically (Song et al., 2005) and experimentally (O’Loughlin et al., 2005) in Kaolin clay. The results showed a strong correlation between the loss in embedment and loading eccentricity.

The effect of soil disturbance due to suction caisson installation on plate anchor capacity was investigated through in situ tests (Wilde et al., 2001). Their results showed that, due to soil disturbance, the anchor capacity was reduced 20% in soil with sensitivity less than 2 and 30 % in soil with sensitivity between 2 and 5. This effect in normally consolidated Kaolin clay was also found by Gaudin et al. (2006) in centrifuge test.

This paper investigates the effect of soil disturbance due to suction caisson installation on anchor capacity by centrifuge tests. SEPLAs in normally consolidated Kaolin clay and over-consolidated transparent soil sample were tested at the University of Western Australia to investigate the disturbance effect on plate anchor bearing capacity and loss of embedment during keying.

2 EXPERIMENTAL SETUP

2.1 UWA beam centrifuge and model anchor

The centrifuge tests were carried out at 145 g on a fixed beam centrifuge located at The University of Western Australia, which is a 1.8 m radius Accutronic centrifuge with a payload of 200 kg at 200 g. The model employed for the centrifuge tests comprises a suction caisson, a plate anchor and a mooring line (Figure 2), each at a reduced scale of 1:145. The suction caisson was fabricated from aluminium and has an outside diameter of 30 mm, an internal height of 169 mm and a wall thickness of 0.4 mm, thus modelling a prototype caisson 4.35 m in diameter, 24.5 m high with a wall thickness of 0.58 m. At the tip of the caisson, three vertical slots, 1 mm wide, 17.5 mm high and separated by 90° in plan were cut into the tip of the caisson to accommodate the plate anchor.

A square plate anchor (Figure 2) was machined from stainless steel and was 35 mm high and 1 mm thick, which is 5.075 m high and 0.145 m thick in prototype scale. The padeye was located on the 1 mm thick triangular anchor shank at an eccentricity of 23 mm, which equals to eccentricity ratio e/B = 0.66. The model mooring line was plaited from 4 strands of wire fishing trace in order to replicate a typical prototype anchor mooring lines. The chain was attached to the padeye of the anchor with two load cells (one next to the padeye and another one above the clay).

In addition to the suction installation tests, further tests were performed where anchors were jacked in, using a 6 mm diameter purpose-made tool. As the soil disturbance generated using this method of installation was considered to be negligible, these tests were conducted as benchmark tests for assessing soil disturbance effect in suction caisson installation.

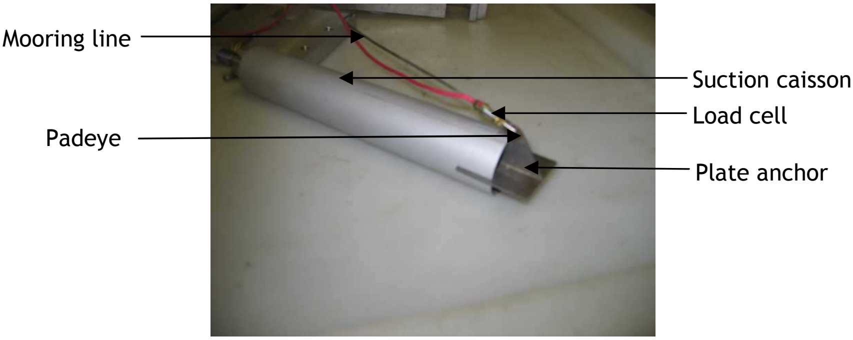


Figure 2 Model plate anchor and suction caisson

2.2 Kaolin Test setup

In order to investigate the influence of the installation process on the performance of the anchor, centrifuge test were conducted in normally consolidated UWA Kaolin clay. The experimental procedure, presented in Figure 3 (a) (after Gaudin et al. 2006), used two actuators to achieve:

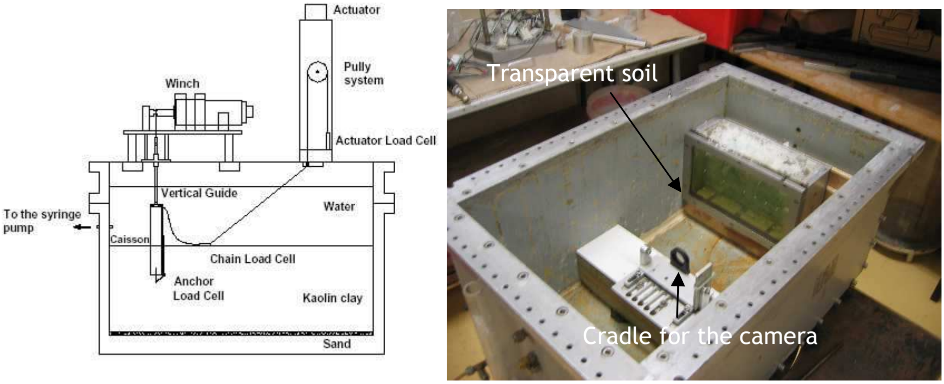
1. Self-weight installation of the caisson. The first actuator released the caisson by unwinding a wire connected to a rigid guideline screwed on the lid of the caisson. The purpose of the guideline was to ensure the verticality of the penetration. A pneumatic valve fixed on the lid of the caisson was left open at this stage, allowing the water to flow out of the caisson.

2. Application of the suction. The pneumatic valve fixed on the lid of the caisson was closed, sealing the caisson. Suction was applied by a syringe pump, connected to the caisson through a flexible hose. The final penetration depth reached after suction installation was about 148 mm for every test, which corresponds to 4.23 times the width of the anchor.

3. Extraction of the caisson. The caisson was extracted by reversed pumping. The pneumatic valve was left closed and the syringe pump was driven backward to inject water inside the caisson. At the end of that stage, the anchor was assumed to be left vertical at the depth reached by the tip of the caisson during the penetration.

4. Pullout of the anchor. The actuator was adjusted to achieve $\alpha = 60$ degrees (Figure 1) inclination at the padeye of the anchor. The anchor was then pulled out at a rate of $v = 0.4$ mm/s. This rate ensured a fully undrained behaviour of the anchor as the normalised velocity vD/C_v is higher than 30 (Finnie and Randolph 1994), where D is the width of the anchor and C_v is the coefficient of consolidation.

The centrifuge testing program includes long term test (LT, reconsolidation was allowed between anchor installation and extraction) and short term test (ST, pullout was commenced right after installation). The reconsolidation time was set up roughly at 1 hour, which corresponds to about 2.5 years in prototype.



(a) Kaolin clay (after Gaudin et al. 2006) (b) Transparent soil

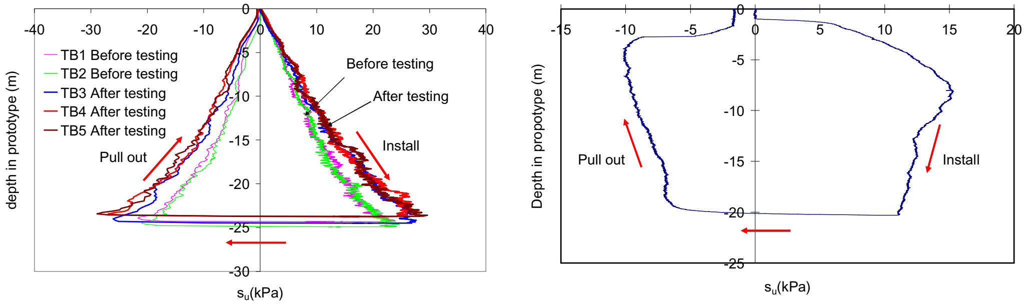
Figure 3 Centrifuge tests set up

2.3 Transparent soil test setup

In order to observe anchor installation and pullout behaviour, tests were also carried out in pre-consolidated transparent "soil" in the beam centrifuge. This transparent "soil", which was made from 6% of fumed silica by weight mixed with a liquid (the liquid is a mixture of 70% of paraffin and 30% of white spirit by volume), has clay-sized particles and exhibits similar geotechnical properties to natural clay (Gill, 1999). The detailed procedure for producing the transparent soil can be found in Gill (1999).

To facilitate optical measurement of the plate anchor keying process, a digital camera was placed within a custom made cradle which supports the camera lens at high acceleration levels. The cradle was mounted securely in a beam centrifuge box, which is 650 mm long, 390 mm wide and 325 mm deep, and oriented so the camera lens axis was perpendicular to the measurement plane. The arrangement of the testing chamber and camera is shown in Figure 3 (b). A Canon S50 camera with a 5 Mega Pixel resolution (2592 x 1944 pixels) was used for digital image capture. Remote triggering of the camera was achieved through a 4.51 g weight resting on the shutter of the camera. The anchor was installed at 145 g using the suction caisson and jacking in tool by jacking them to an anchor centre depth of 105 mm, which equals to 3 times of the anchor width. After installation, retrieval was archived by vented pullout using the actuator and anchors were pulled up at a rate of v = 0.1 mm/s. All tests in transparent soil sample can be considered as short term.

3 RESULTS AND DISCUSSION

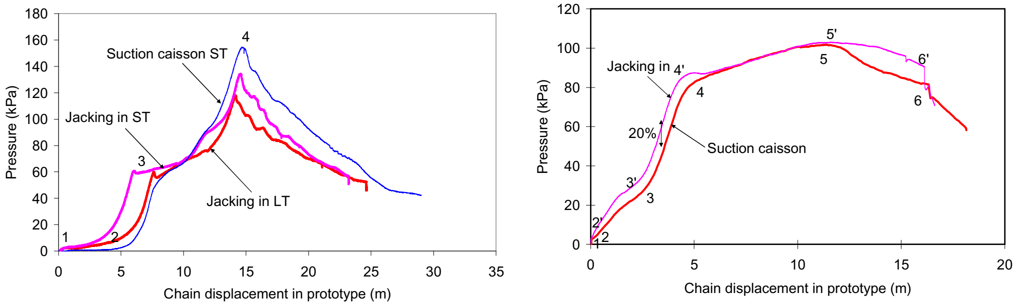


(a) Kaolin clay (b) Transparent soil

Figure 4 Soil strength profiles

Soil strengths of Kaolin clay and transparent soil were determined using T-bar penetrometers (Stewart and Randolph 1991). Undrained shear strength profiles of Kaolin clay is illustrated in Figure 4 (a). The measured shear strength profile may be conveniently described in prototype scale by a constant shear strength gradient of 0.7 kPa/m before testing and of 0.9 kPa/m after testing respectively. The difference is because the swelling and re-consolidation of the sample. As the testing took two and half weeks to complete and the soil swelled and re-consolidated during ramping down and ramping up of the centrifuge. It can be seen from Figure 4 (b) that an average uniform shear strength, s_u = 13 kPa, is achieved once surface effect becomes negligible for the transparent soil.

The anchor pullout responses in Kaolin clay and transparent soil are shown in Figure 5. Digital photos in the transparent soil test and pullout phases were discussed in detail in Song et al. (2005) and Song et al. (2007). The anchor pullout responses in Kaolin clay and transparent soils are displayed in Figure 5. There are four phases observed in overall pullout response: (i): Chain cutting through soil; (points 1-2). (ii): Anchor rotation/keying process; (points 2-3). (iii): Anchor capacity development with full rotation; (points 3-4). (iv): Anchor pullout with full capacity (After point 4). In Kaolin clay test, the pullout resistances drop dramatically after reaching point 4 when anchor capacity is fully developed. This capacity drop is due to the decreasing soil strength when reaching the soil surface. The ultimate pullout resistance for the long term (LT) jacking in anchor is the lowest because this test was performed first among the three tests. The shear strength profile at this stage is of 0.7 kPa/m in prototype (Figure 4 (a)), which is lower than that of 0.9 kPa/m when the short term (ST) jacking in anchor and suction installed anchor were performed.

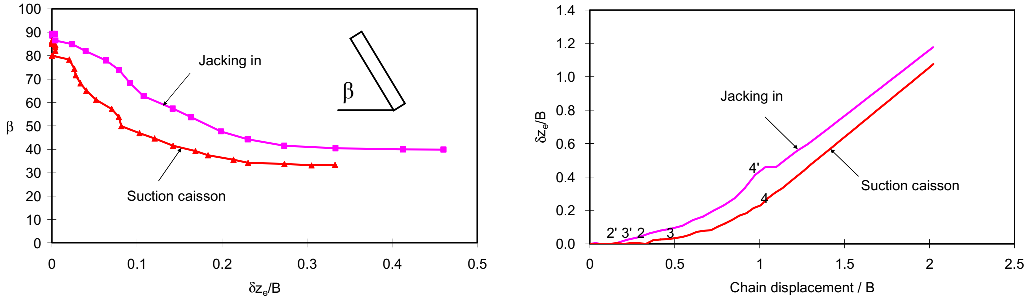


(a) Kaolin clay (b) Transparent soil

Figure 5 Anchor pullout responses

In transparent soil test (Figure 5 (b)), the pullout resistance still increase slightly after the point 4. The increase between point 4 and point 5 is due to the stronger soil found in upper layer (Figure 4 (b)). The suction force underneath the plate anchor is lost at point 6.

From Figure 5 (b) it can be observed that the anchor installed by suction caisson rotates more quickly than the one installed by jacking. In order to exhibit this difference, the anchor rotations after different anchor installation are plotted as the anchor orientation angle β versus the vertical movement of plate anchors in Figure 6 (a), where δz_e is the loss in embedment depth and B is anchor width. The angle β and anchor movement are measured by careful examination of the digital images captured.



(a) Loss of embedment ~ anchor inclination (b) Chain displacement ~ Loss of embedment

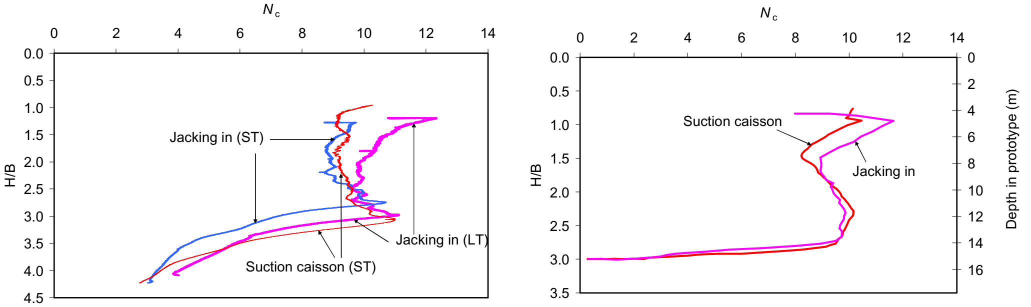
Figure 6 Anchor rotations characteristics in transparent soil

As can be seen from Figure 6 (a), initially the anchor installed by suction caisson undergoes large rotation from vertical position to an orientation angle of 80˚ without any vertical movement due to the soft clay generated by suction caisson installation. And after this the initial rotation anchors with jacking in and suction caisson installation behave in a similar manner. Both anchors are eventually stabilized at about β = 40° (β = 33.7° for suction caisson installed anchor and β = 40.4° for jacking in installed anchor), where anchor is perpendicular to the pullout direction. The loss of embedment is 0.23 B and 0.27 B for the suction caisson installed and the jacking in anchors respectively. Figure 6 (b) shows the relationship between the chain displacement and loss of embedment. It is obvious that once the anchor is fully rotated, after point 3 or 3'), the loss of embedment and chain movement become linear.

The non-dimensional bearing capacity factor N_c is widely used in plate anchor bearing capacity design and defined as:

$N_c = q_u/s_u = Q_u/(A \times s_u)$ (1)

where q_u is the ultimate pullout pressure, Q_u is the ultimate pullout force and A is the plate area.



(a) N_c in Kaolin clay (b) N_c in transparent soil

Figure 7 Breakout factors for plate anchors in Kaolin clay and transparent soil

The breakout factors from the centrifuge tests in Kaolin clay and transparent soil are plotted in Figure 7. The loss of embedment for the anchors in Kaolin clay is estimated by assuming the anchor moving straight forward with steady inclined angle after the anchor is fully rotated into position (Figure 6 (b)). When calculating the factor N_c for transparent soil, local s_u value in Figure 4 (b) is used. This is completed by the careful examination of the images captured. For N_c factor in Kaolin clay, the soil strength profile 0.7 kPa/m is used for LT jacking in anchor and 0.9 kPa/m for ST jacking in and suction caisson installed anchors. As can be seen in Figure 7 (a), maximum breakout factors for jacking in anchors in the Kaolin test is found to be 11.03 and 10.9 respectively for LT test and ST test. After that, the breakout factors stabilize at about 9.8 and 8.9, which is about 9% difference. This may be due to the difference of re-consolidation time. The higher N_c value shown on the graph when H/B < 2 is because the soil heave formed and the very low shear strength near the surface. The maximum N_c for the ST suction caisson installed anchor is 10.6, which is 4% lower than that for the LT jacking in anchor. And it stabilizes at about 9.1, which is 7% lower than that in the LT jacking in anchor. The difference between ST jacking in anchor and suction caisson installed anchor is not evident, which may due to the both soil was disturbed during rotation.

For the anchor in transparent soil, all the tests are set to be ST test. The overall responses of the anchors are similar to those for ST tests in Kaolin clay. The maximum breakout factors are all stabilized at about 10 before dropping down to 8.9.

4 CONCLUSIONS

A series of centrifuge tests has been conducted in order to investigate the influence of the installation process on the behaviour of suction embedded plate anchors. Main findings are summarised below:

In both Kaolin clay and transparent soil tests, there are four stages observed during anchor keying process. Once an anchor is fully rotated and its capacity is fully developed, the pullout capacity factor, N_c is about 9 for all short term tests in both soil samples. In transparent soil test, it is apparent that the suction caisson installed anchor rotates faster than the jacking in anchor. However, this is not so evident in Kaolin clay tests. The long term Kaolin test shows an N_c value 7% higher then that in short term test. The suction caisson installation has no significant effect on anchor capacity during the inclined pullout tested here.

REFERENCES

Aubeny, C. P., Murff, D. J. and Roesset, J. M. (2001) “*Geotechnical Issues in Deep and Ultra Deep waters*”, Proceedings of 10th International Conference of the International Association for Computer Methods and Advances in Geomechanics, Tucson, USA.

Ehlers, C. J., Young, A. G. and Chen, J. H. (2004) “*Technology assessment of deepwater anchors*”, Proc. Annual Offshore Technology Conf., Houston, USA, Paper OTC 16840.

Finnie, I. M. S., and Randolph, M. F. "*Punch-through and liquefaction induced failure of shallow foundations on calcareous sediments*." Proc. Int. Conf. on Behaviour of Offshore Structures, Boston, USA., 217-230.

Gaudin, C., O'Loughlin, C. D., Randolph, M. F., and Lowmass, A. C. (2006). "*Influence of the installation process on the performance of suction embedded plate anchors*." Geotechnique, 56(6), 381-391.

Gill, D. R. (1999). "*Experimental and theoretical investigations of pile and penetrometer installation in clay*," PhD. Thesis, Trinity College, Dublin.

O'Loughlin, C. D., Lowmass, A., Gaudin, C., and Randolph, M. F. (2006). "*Physical modelling to assess keying characteristics of plate anchors*." International Conference on Physical Modelling in Geotechnics 2006, Hong Kong.

Song, Z., Hu, Y., and Randolph, M. F. (2005). "*Pullout behaviour of inclined plate anchor in uniform clay*." The 11th international conference of IACMAG, Turin, Italy, 715-722.

Song, Z., Hu, Y., and Gaudin, C. (2007). "*The Influence of Disturbed Zone on Capacity of Suction Embedded Plate Anchors*." ISOPE 2007, Lisbon, Portugal. (In press).

Stewart, D. P., and Randolph, M. F. "*A new site investigation tool for the centrifuge*." Proceedings Conference Centrifuge '91, Balkema, Rotterdam, 531-538.

Wilde, B., Treu, H., and Fulton, T. (2001). "*Field testing of suction embedded plate anchors*." 11th (2001) International Offshore and Polar Engineering Conference, Jun 17-22 2001, Stavanger, 544-551.