Centrifuge tests on improving offshore foundation systems

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ABSTRACT: The centrifuge testing technique is a suitable method for investigating new ideas for construction methods in the geotechnical field. In particular the small geotechnical centrifuge of the University of Delft has proven to be very convenient for this purpose. The small scale models can be modified quickly and easily. The tests can be reproduced accurately, so that the effect of small changes in the design can be made visible. Several test programs have been carried out in the centrifuge of the University of Delft to examine methods of improving the loading capacity of offshore foundation elements. The paper focuses on improving the loading capacity of circular footings and suction caissons. It was found that parameters, such as roughness, have a significant influence. Some new ideas for suction caissons were tested. An unexpected observation was that the pullout capacity could be improved by removing a part of the caisson.

1 INTRODUCTION

Several types of foundation systems are in use in the offshore industry. Some of them are used to fix floating structures, while others are used to support vertical loads. A typical example of the latter are spudcans, which are large circular conical footings used for bearing mobile platforms (jack-up units). Foundations of this kind can exhibit problems in sliding behavior when they are founded on sand. Several test programs have been carried out in the centrifuge to analyze the sliding behavior, and the experimental results were compared with the governing foundation criterion for a site-specific integrity assessment (Allersma, 1997). However, an interesting question that presents itself is how far the sliding resistance can be improved. The small centrifuge was used to test some new design concepts.

A more generally applicable foundation element is what is known as a suction caisson. The main attraction of this system is the convenient installation method. A caisson with a diameter of 9m and a height of 10m can be installed in a few hours using only a pump. The caissons are subjected predominantly to horizontal loading when they are used as an anchoring system for floating structures. However, other applications exist in which the caissons are subjected to vertical loading. An obvious example would be the support of a gravity load, but the caissons may also be subjected to a vertical pullout load, for example in tension leg platforms, where the load has a cyclic character.

In order to improve the loading capacity of suction caissons, several centrifuge tests have been carried out to simulate new design concepts. The small centrifuge appeared to be very suitable for this task. The small models lend themselves to easy modification, and the accurate reproducibility of the tests ensures that the effects of slight differences in design can be made visible.

Several interesting, and in some cases unexpected, results were obtained. Some of the ideas tested would seem to have potential application in engineering practice.

2 TEST FACILITY

2.1 *Centrifuge facility*

The tests were performed in the geotechnical centrifuge of the University of Delft. The centrifuge (Allersma, 1994a) is a relatively small device with a diameter of 2.5m and a maximum sample weight of approximately 300N. The maximum space available for the model and the actuator is $400 \times 400 \times 400 \mathrm{mm}^3$. The small size of the equipment and samples has proven to be very convenient in operation.

A two-dimensional loading system (Allersma, 1994b) was used in the test program (Fig.1). An accurate and almost frictionless translation in two perpendicular directions was provided by tempered steel shafts and linear ball bearings. The horizontal

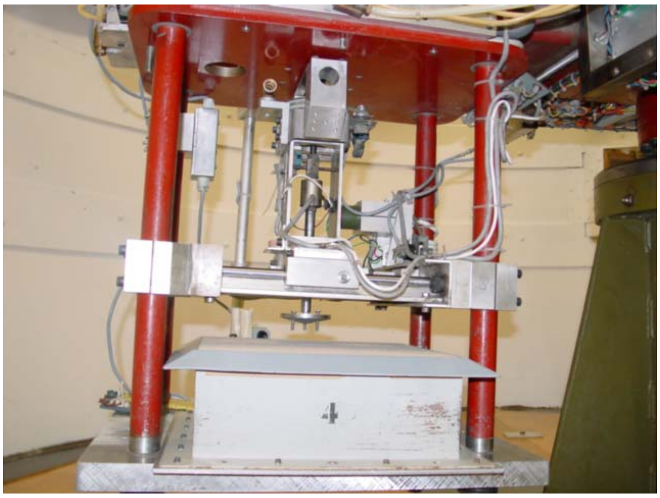


Fig.1 Photograph of the two-dimensional loading system.

load (max. 2kN), vertical load (max. ±5kN), horizontal displacement (150mm), and vertical displacement (30mm) can be adjusted independently by means of small DC motors, load sensors, and displacement transducers. The loading device is controlled by a PC, which is located in the spinning part of the centrifuge and is accessible via slip rings. The fact that the measuring signals do not have to travel over long lines or slip rings means that the measuring and control system is relatively insensitive to noise.

The loading path during a test can be defined in advance and entered into a computer program. The program is written in a common computer language, so that it can be modified easily by the user.

2.2 *Model preparation*

An important aspect of the centrifuge modeling technique is the preparation of the sand bed. In order to visualize the effect of slight design variations, it is important for the sand beds to be reproduced accurately, for which purpose a computer-controlled sand pouring machine has been developed (Allersma, 1994b). The density of the sand sample can be controlled by keeping the falling height constant during raining. The medium-dense sand beds showed a high degree of reproducibility, with a standard deviation of mean porosity of 0.2%. The height of the sand layer that was used was 100 mm, with a ground area of 250x250 mm^2. In general, dry sand was used with a $D_{50} = 0.2$ mm. Most of the tests were performed with medium dense sand with the following parameters: $\theta = 33^o$; E = 15000 kPa; $\gamma = 17$ kN/m^3; porosity n = 37%. Because drained conditions were being simulated, dry sand was used.

3 SPUDCAN FOUNDATIONS

Spudcans are large circular (e.g. d = 20 m) conical footings used to support jack-up units. The footings are actually designed for clay soils. The penetration depth in clay bottoms is 0.5 to 1 times the diameter of the footing, in which case sufficient horizontal load can be mobilized to eliminate any possibility of sliding. However, when the footings are used on sand, only limited penetration is possible. A common governing foundation criterion for a site-specific integrity assessment is the sliding of the windward leg. Wave action results in a partial unloading of the windward leg and some bending of the long legs (80 m), whereby the footings are subjected to horizontal loading. In a previous test program (Allersma, 1997), the sliding behavior was examined and compared with the usual design criteria. It was found that some of the criteria are fairly critical. This prompted the performance of tests to examine methods of improving the sliding capacity.

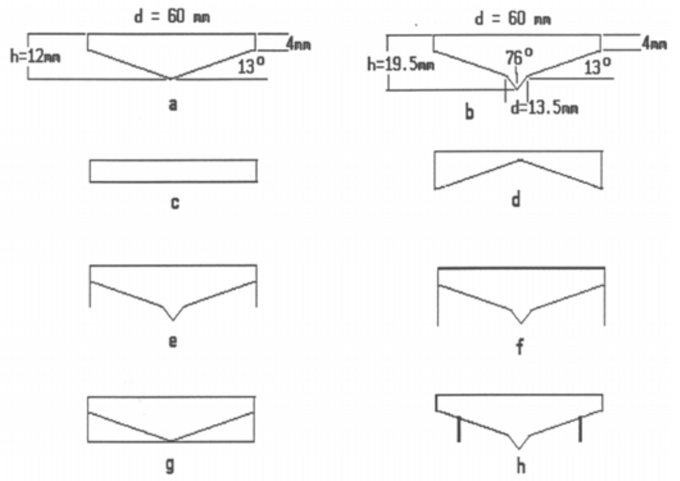


Fig.2 Different modifications to influence the sliding capacity of spudcans.

The tests were performed at 150g. At this g-level, a diameter of 14.4m is simulated, taking into account that the effective stress in dry sand is 1.6 times greater than in saturated sand. The dimensions of the model spudcan and several variants are shown in Fig.2. Type a) is considered to be the standard spudcan. Because tipped spudcans are not uncommon, type b) was included to investigate what influence the tip has. Type c) is a flat footing and d) represents an unconventional shape. The effect of skirts in combination with a tip is demonstrated with footing types e) and f). Type g) is equipped with three wings on the conical surface and type h) has three pins in combination with a tip. Furthermore, some types were tested with both a smooth steel surface and with a rough surface (covered with sand paper).

An example of a diagram of a sliding test is shown in Fig.3. Initially, the footing was subjected to a vertical pre-load of 150N, after which the load was decreased to 50N. The horizontal load was increased while holding the vertical load constant. Failure is defined as the occurrence of a vertical displacement. Each test was performed twice and plotted on the same figure. The close fit of the two diagrams demonstrates the reproducibility of the test procedure.

The sliding capacity of the different types of footings are summarized in Table 1, where the factor for the smooth spudcan without tip was given a value of 1 as a reference. It is interesting to note the significant influence of roughness.

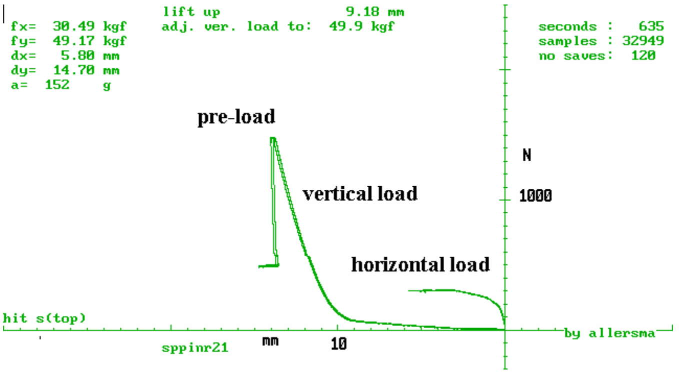
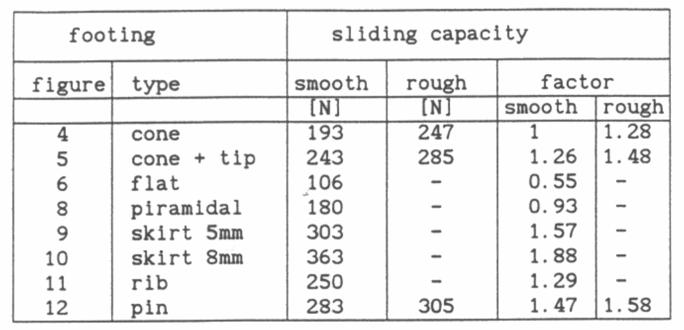


Fig.3 Typical diagram of a sliding test on a spudcan foundation.

Table 1 Comparison of the sliding capacity of different types of footings.



footing		sliding capacity			
figure	type	smooth	rough	factor	
		[N]	[N]	smooth	rough
4	cone	193	247	1	1.28
5	cone + tip	243	285	1.26	1.48
6	flat	106	-	0.55	-
8	piramidal	180	-	0.93	-
9	skirt 5mm	303	-	1.57	-
10	skirt 8mm	363	-	1.88	-
11	rib	250	-	1.29	-
12	pin	283	305	1.47	1.58

Making the surface of the spudcan as rough as possible may well be the cheapest way of increasing the sliding capacity. The tip also appears to have a significant influence, and a tip with a rough surface increases the sliding capacity by almost 50%. While it is no surprise that skirts are effective, they are probably a relatively expensive solution. The ribs seem to have the same effect as a tip. The effect of three pins (to the same depth as the tip) was surprising, where, especially in combination with a rough surface, they appear to have the same effect as a skirt.

It is striking that the flat footing yields a much lower sliding capacity than the conical types. The main purpose of testing the pyramidal footing was to examine whether this shape yields a larger vertical load than a flat footing with a rough surface. The centrifuge tests showed no significant difference.

3 SUCTION CAISSONS

Several test programs have been carried out to investigate the behavior of suction caissons subjected to different loading conditions. In the first instance, commonly applied caisson types were used. The parameters that were varied were the loading angle, attachment point and the height to diameter ratio (Allersma et al., 2000). It was found that the pullout load increases when the attachment point is lowered and when the loading is closer to the horizontal. As may be expected, larger caissons yield a larger bearing load, both horizontally and vertically. A question that arose was whether smarter solutions exist for increasing the bearing load than simply making the caissons bigger.

3.1 *Horizontal loading*

In this application, a long cable or chain is attached to the caisson in order to anchor floating structures. The caisson is loaded approximately horizontally, at an angle of 15° to the horizontal axis. The attachment point is h = 2H/5, where h is the distance between attachment point and tip and H is the total height. Having found that larger diameters increase the anchor capacity, a cheaper variant in which the increasing diameter is simulated by vertical wings (Fig.4) was investigated. Two different wing sizes were tested with a caisson with a diameter of D = 30mm. In Fig.5 it can be seen that the effect of wings is relatively insignificant. Wings that increase the caisson surface area by 20% had no effect whatsoever. An increase in the bearing capacity of only 10% was measured when the pile surface was increased by 50% using wings. Fig.6 shows some of the results (tests end FEM calculations) of increasing the caisson diameter by 50%. It appeared in this case that the horizontal bearing capacity increases by approximately 30%. The reason that strips are less effective can be explained by the diagram of the failure surface, as shown in Fig.7. Strips allow the soil to flow fairly easily around them to fill the space formed during caisson displacement. This means that the volume of the mobilized soil plug differs little from that of a caisson without strips. Increasing the diameter, however, causes a significantly larger mobilized soil plug volume.

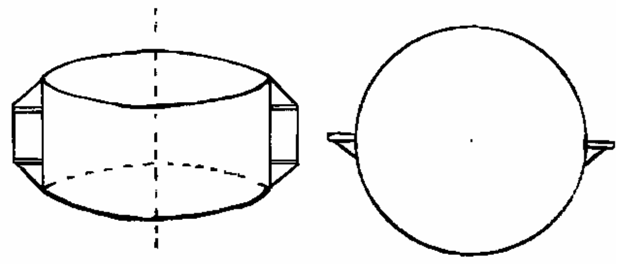


Fig.4 Using wings instead of increasing the diameter.

Because the soil around the top of a caisson has a low stress level, it is interesting to investigate how far the top section contributes to the bearing capacity. Especially when suction caissons are used in soft soils, it is believed that the upper part makes no significant contribution to the horizontal bearing capacity. In order to examine this phenomenon, a test series was carried out with piles that were penetrated to an equal depth, and where different lengths of the top section were removed. The original height of the pile was H = 50mm. In all tests, the attachment h = 2H/5, and the loading angle was 15° to the horizontal. The results of tests in sand are shown in Fig.8. Each height was tested twice in order to demonstrate the reproducibility of the test procedure. It is striking that the bearing capacity increases with decreasing caisson height. There appeared to be an optimum when the height was decreased by 30%. In this case, the horizontal bearing capacity increased by almost 30%. After the optimum, the effect decreases with decreasing height. However, even when half the height was left, the bearing capacity was still 16% higher. An explanation for this phenomenon is that, in the case of a full-size caisson, part of the friction resistance is between caisson and soil. However, when the top is removed, more friction has to occur in the soil itself, which yields a larger bearing capacity. The experimental results were compared with 3-dimensional FEM calculations. It was found that the calculations show a similar tendency.

Some tests were performed to investigate whether a similar behavior could be observed in clay. It appeared that the effect in clay was less pronounced, but, in this material too, shorter caissons have a larger bearing capacity. Some orientational tests have shown that the vertical pullout load also increases with increasing caisson height. These findings should stimulate the development of techniques to install suction caissons below the sea floor.

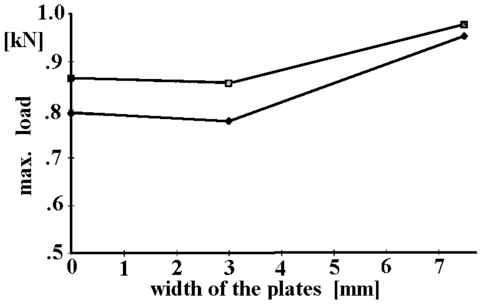


Fig.5 Effect of wings on the horizontal bearing capacity, duple tests.

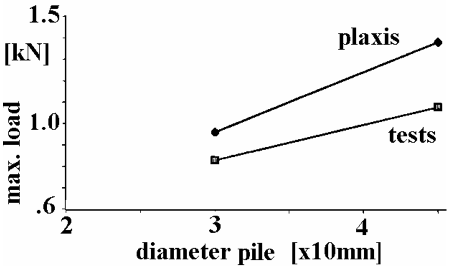


Fig.6 Effect of diameter on the horizontal bearing capacity.

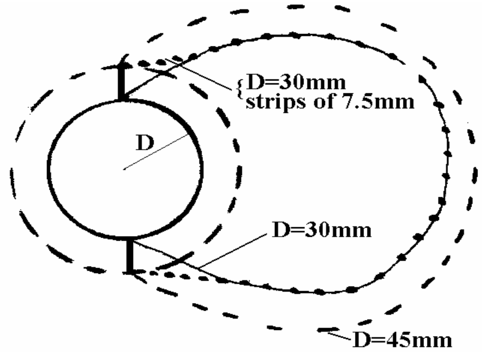


Fig.7 Diagram to demonstrate the difference in failure mode with strips of a larger diameter.

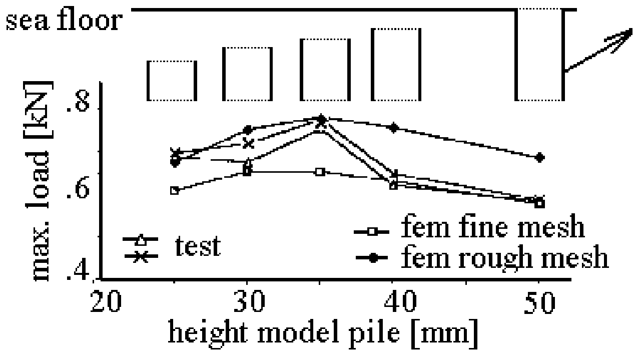


Fig.8 Horizontal bearing capacity of a caisson in sand after removing the top section of the caisson.

3.2 *Vertical loading*

In the interests of further increasing the vertical pullout capacity of suction caissons, an idea based on the umbrella anchor was tested. This technique uses a full-size caisson with a dome to install two segments that are joined by a hinge at a given depth. After installation, the dome section is removed and

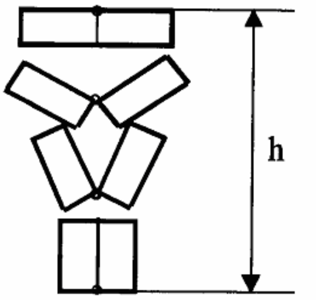


Fig.9 Diagram showing the operation of the umbrella mechanism.

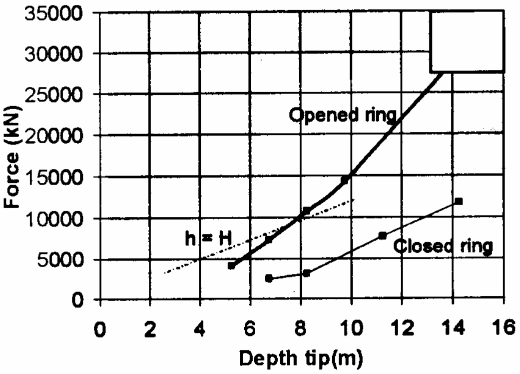


Fig.10 Comparison of the pullout capacity of the open and closed caisson, with load given in prototype values.

the hinged section is pulled up until the structure opens fully (Fig.9). Small-scale tests at 1g have shown that a length approximately equal to or greater than the caisson height was required to open the structure completely. The aim of the centrifuge tests was to investigate the difference in pullout capacity between a closed and an opened caisson. Therefore, no attempt was made to test the actual opening mechanism. Instead, two models were made, simulating the two conditions of interest, and they were installed during the preparation process of the sand box. The results of loading tests performed in the centrifuge at 150g are shown in Fig.10. If the pullout load is compared for structures at the same depth it is clear that the open caissons yields a higher pullout load. However, a good comparison requires account to be taken of the necessity of raising the caisson by at least 1 caisson height. This effect is demonstrated by the line h=H in Fig.10. In this light it can be seen that the umbrella mechanism has no advantage at low depths. At depths greater than 8m, however, it was found that the opened caisson starts to yield a larger pullout load. There is probably a transition to another failure mechanism at that depth.

3.3 *Maintaining suction*

Suction caissons are generally used for long-term foundation applications, for which it is impractical to increase the pullout resistance by active suction. However, it would be possible to maintain the suction if the anchor load only persisted for a relatively short period. Short anchoring system loads of this kind occur when stabilizing a vessel with cranes mounted on deck for the purpose of transporting large units. The advantage of a vessel compared with a crane barge is its speed, but a disadvantage is its instability in waves, which severely hampers crane load position control. One way of improving the vessel's stability would be to use pre-tensioned cables anchored to the sea floor, where suction caissons are envisaged as a temporary anchoring system. The suction caissons are installed in the usual way by means of a pump. After installation, the pump remains attached and is used to maintain a suction pressure during the few days that the crane is in operation. A problem in this application is that the height of the usual suction caissons is too great, so that they hang in the water in the lifted position, causing an unacceptable drag on the vessel. Furthermore, numerous applications are in relatively shallow water areas (10-20m). Consequently, it is worthwhile investigating whether a limited caisson height can be compensated for by a larger area, and to what extent the shallow water can be compensated for by active suction. It would also be worthwhile investigating various anchoring system configurations, while keeping within the limits of constructional feasibility.

In the first instance, centrifuge tests were carried out to investigate the effect of active suction (Allersma et al., 2003). A diagram of the test setup is shown in Fig.11. A small model of a suction caisson was installed in a sand (D_{50}=0.1mm) layer at 1g conditions. The caisson was attached to a loading system to measure the vertical pullout resistance. A pre-defined suction pressure was maintained by means of a small computer-controlled gear wheel pump, using the signal from a pressure transducer.

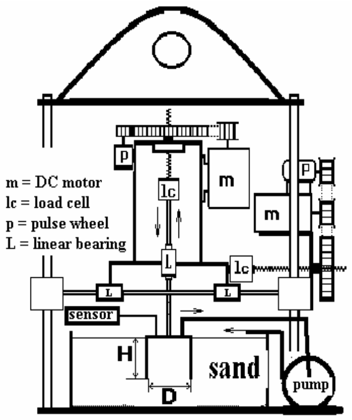


Fig. 11 Diagram of the test setup to simulate active suction in the centrifuge.

Fig.12 shows the relationship between the active suction pressure and the vertical pullout capacity, which is expressed as a load per unit area. It can be seen that the additional pullout capacity increases linearly with increasing suction. Tests at 1g and 30g were carried out. The 30g test was performed at 1/3 of prototype scale. In the 1g tests, the contribution of the friction was too small to be measured. Apparently the tangent of the relationship is independent of the g level. This supports the idea that the prototype bearing capacity can be deduced by extrapolation, as is demonstrated in Fig.13. It was found that 4 units, each consisting of three caissons with a height of 4.5m and a diameter of 9m are needed to yield sufficient bearing capacity (ca. 90 MN) at a depth of 15m to stabilize the vessel. Constructional preferences and issues surrounding the optimum shape gave rise to a test program in which different configurations are compared with each other. The different types used are shown in Fig.14. All systems have almost the same surface area and height, and the in-line caissons are in contact with each other. Comparison of the uplift capacity of two in-line caissons with a single caisson has shown that the profiles of the ratio of normalized uplift capacity to suction pressure are very similar. Fig.15 compares three in-line caissons with a single caisson and a sardine-can-shaped caisson. This test series revealed some differences between the different caisson shapes. The single caisson shows a lower normalized uplift capacity than the unit with the three in-line caissons. Because some arching may be expected in the narrow space between the caissons, it would seem reasonable to expect a larger uplift capacity. It may be also be expected that the additional soil body underneath the caisson would have a greater volume when more caissons are in line. With a single caisson, the soil body has a roughly conical shape. If the caissons are small enough and close enough together, a bridge may be formed between the soil bodies, resulting in a larger additional soil volume per caisson. In the case of the sardine-can-shape, the additional soil body would be expected to be wedge shaped, rounded at the ends. This results in a larger volume than with three widely-spaced single caissons.

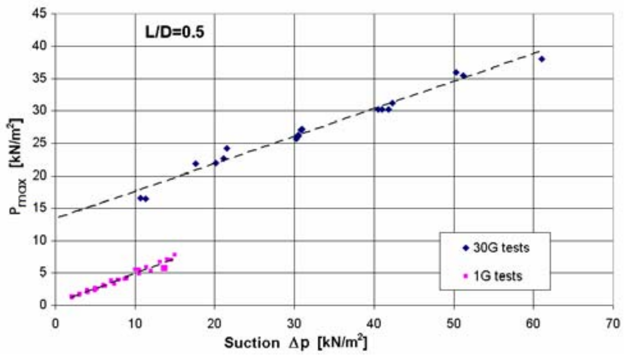


Fig.12 Vertical pullout resistance of caisson during active suction.

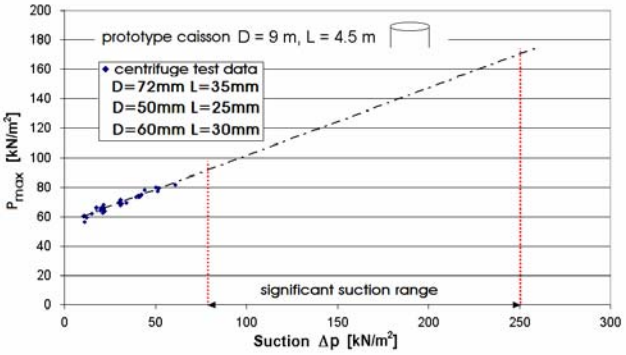


Fig.13 Conversion of the centrifuge results to prototype values.

Fig. 14 Photograph of different caisson types used to examine the effect of the shape.

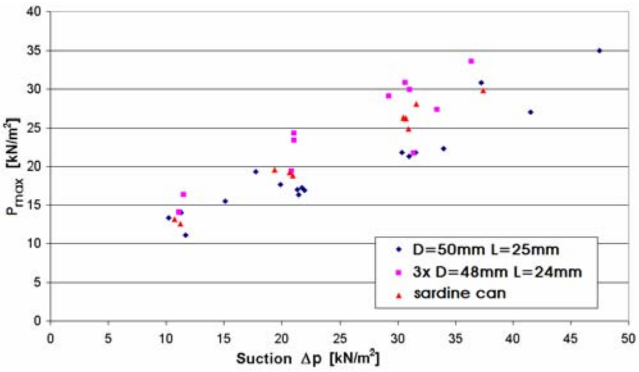


Fig.15 Comparison of a single caisson with three in-line caissons and a sardine-can-shaped device.

4 CONCLUSIONS

Several test series have been carried out in the geotechnical centrifuge of the University of Delft to examine some ideas for improving the capacity of foundation systems. The small size makes the centrifuge very suitable for performing trial and error tests. The models of the foundation elements can be modified with simple tools and techniques. The small soil containers allow a quick and accurate preparation of the soil layers. The reproducibility of the sample preparation allows the effect of small changes in design to be made visible.

In spite of the small size, relatively complicated tests can be performed. An example is the tests on caissons with active suction, in which both the load and the suction pressure have to be controlled in flight.

Several interesting phenomena and tendencies have been observed. Some of them are also predicted by FEM calculation. It seems likely that some of the findings will be of interest in engineering practice.

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