The influence of the g-level for anchor tests in sand

L'influence du niveau de g pour les tests d'ancrage en sable

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ABSTRACT: Physical model tests in geotechnics are quite often performed in a centrifuge, because then the stresses are the same in model and prototype, leading to comparable stress-strain behaviour. However, in theory for a pure friction material as sand, it should be possible to get the same results in a reduced stress 1-g model as in an N-g model. This was checked in a series of anchor pulling tests. The anchor was pulled through a sand bed and a gravel berm. Tests were run with the same set-up at 80-g and at 1-g. The pulling force was measured as a function of time.
Results show that there is a clear distinction between the 1-g and 80-g tests. The pulling force was relatively higher in the 1-g tests. This means that also for a pure friction material, stresses has to be the same in model and prototype.

RÉSUMÉ : Des essais sur modèles physiques en géotechnique sont souvent effectuésen centrifugeuse, parce que les contraintes sont les mêmes dans le modèle et le prototype, ce qui offre un comportement contrainte-déformation comparable. Cependant, en théorie, pour un matériau purement frottant comme du sable, il devrait être possible d'obtenir les mêmes résultats dans un modèle 1-g aux constraintes réduites, comme dans un modèle à N-g. Ceci a été vérifié dans une série de tests de traction d'ancre. L'ancre a été tirée à travers un lit de sable et une berme. Le tests à 80-g et à 1-g ont été effectués d'un arrangement identique. La force de traction a été mesurée en fonction du temps. Les résultats montrent qu'il y a une distinction claire entre les tests 1-g et les tests 80-g. La force de traction est relativement plus élevée dans les essais 1-g. Cela signifie que pour un matériau purement frottant, il faut que les contraintes soient identiques dans le modèle et le prototype.

KEYWORDS: centrifuge tests, scaling, anchor tests, friction material.

1 INTRODUCTION

Dragging anchors can be a real threat for pipe lines located at the sea bottom. With the number of pipelines and cables increasing as well as the number and size of the ships, it can be expected that this threat will increase in the future.

Pipelines and cables that cross shipping lanes are usually protected by gravel berms. The berm has to be stable against the chain of the anchor and the anchor itself. Some damage to the berms is allowed, but the pipeline and cable has to be protected, even for the heaviest anchors that can be expected. These berms are designed by experience and traditionally tested using large scale (scale around 1:5) model tests. Some first attempts have been made to simulate the process numerically using the so-called 'rigid body technique', see the visualisation of a numerical result in Figure 1. This is a promising path, see also leQin (2010), but up to now not ready to be used in a design.

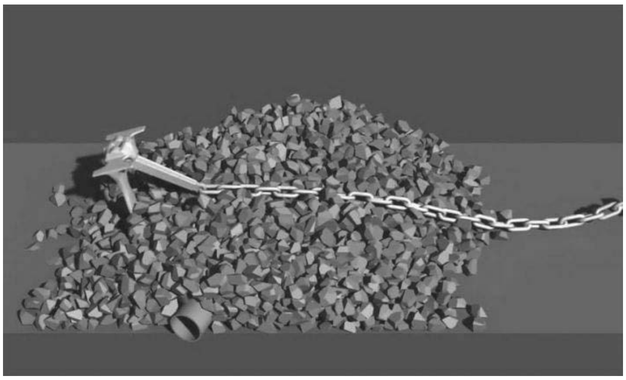

Figure 1.Visualisation of numerical simulation of an anchor passing a berm using 'rigid body dynamics' (Bezuijen, 2011).

To avoid the relatively expensive large scale model tests, it is also possible to use a centrifuge model. The advantage of a centrifuge model is that a much smaller model is possible and still the stresses are the same in model and prototype. For a 1-g scale model the stresses in the model will always be smaller than in the prototype, see Table 1.

However, in theory for a pure friction material as sand, it should be possible to get the same results in a reduced stress 1-g model as in an N-g model. This was checked in a series of anchor pulling tests. The anchor was pulled through a sand bed and a gravel berm. Tests were run with the same set-up at 80-g and at 1-g. The pulling force was measured as a function of time.

This paper presents the scaling rules, the set-up and results of the 1-g and 80-g tests will be described in the paper.

2 SCALING

2.1 *N-g scaling*

In a centrifuge model the length is N times smaller than in the prototype and the acceleration N times higher. The scaling relations the relevant parameters are presented in Table 1. As usual in centrifuge modelling the sand is not scaled from prototype to the model, because the sand grains are much smaller than the dimensions of the anchor, but the gravel material is scaled and N-times smaller in the model compared to prototype.

It is difficult to fulfil the scaling rule for the velocity. It is necessary that the velocity is the same in model en prototype when dynamic scaling is assumed, but the velocity has to be even N times higher in the model compared to prototype when consolidation is the dominant mechanism. Since ships dragging anchors can still have a velocity of several metres per second, it is rather difficult, even to achieve the 'dynamic' scaling rule. In our tests an anchor velocity of 100 mm/min = 0.00167 m/s is used (for higher velocities it would be difficult to control and monitor the process during the test). This velocity will create a drained behaviour of the sand in the model while a partly drained behaviour in prototype is expected (see Van Lottum et al, 2010) and a drained behaviour in the gravel for both model and prototype conditions. Further it is assumed that dynamic forces are limited during the anchor dragging.

Table 1. General scaling laws with scaling factor *N*.

Parameter	scaling law model/prototype Ng-model	1g-model	Unit
Length	1/*N*	1/*N*	m
Mass	$1/N^3$	$1/N^3$	kg
Force	$1/N^2$	$1/N^3$	N
Stress	1	1/N	kPa
Time (dynamic)	1/*N*	$1/\sqrt{N}$	s
Time (consolidation)	$1/N^2$	$1/N^2$	s
Velocity (dynamic)	1	$1/\sqrt{N}$	ms^{-1}
Velocity (consolidation)	N	N	ms^{-1}

2.2 1-g conditions

The scaling in 1-g conditions is also presented in Table 1. It appears from the table that the stresses will be N times lower in the model compared to prototype. This means that also the strength of the soils has to be N times lower. For a soil with an undrained shear strength, as clay, this is difficult to achieve. However, for a pure friction material this is rather easy, because the N-times lower stress results automatically in a lower strength, assuming that the friction angle remains constant for the various stress levels.

Using dynamic scaling, the same scaling law for the velocity (Froude scaling) as in 1-g hydraulic modelling tests is found. However, when consolidation is dominant, again the velocity in the model has to be N times higher than in the model. As in the centrifuge model, it is assumed that the anchor will behave drained in both the sand and the gravel layer.

2.3 Conclusions scaling

The scaling laws cannot be fulfilled completely with respect to the prototype. However, assuming that consolidation is more important than dynamic forces, the error made because of assuming undrained behaviour in the sand and drained behaviour in the gravel is exactly the same in both models. This makes a good comparison possible between the 1-g and N-g 1:80 g models.

3 TESTS PERFORMED

3.1 Test set up centrifuge tests

Tests were run at 80 g in a specially developed container of L x W x H: 1.80 x 0.5 x 0.5 m, see Figure 2 and Figure 3. The length was necessary since a berm can be damaged not only by an anchor, but also by the anchor chain that removes stones on the berm before the anchor reaches the berm. The container is placed on a water reservoir, so that the water level can be changed during the test (by adding water from the reservoir or vice versa). This is of importance for such a long container, since during spinning up and spinning down, water movements in the container can destroy the soil model (sand and anchor berm). Therefore the water level was increased after spinning up and decreased before spinning down.

A pulley system was constructed on top of the container, see Figure 4, to be able to drag the anchor over the full length of the container using a hydraulic plunger with a stroke of 0.5 m. As usual in the Geo-Centrifuge of Deltares tests were performed under reduced air pressure conditions of 50-60 mbar. More details on the set up can be found in Van Lottum et al. (2010).

The anchor used in the tests was an AC-14 anchor. The model is shown in Figure 5. The model anchor and anchor chain were made of stainless steel using a 3-D print technique and cast with the so called lost wax method. The anchor and chain is printed in wax, which is replaced by stainless steel. By this technique an accurate scaled copy of the original was obtained.

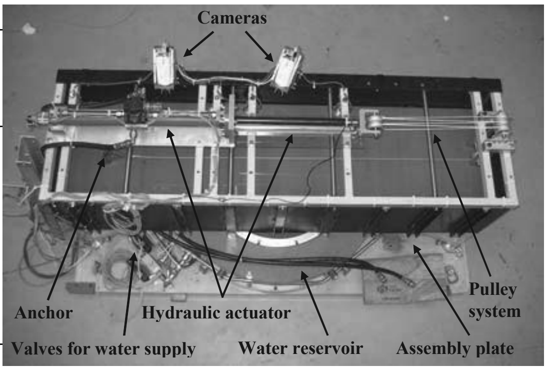

Figure 2. Anchor dragging test setup on assembly plate

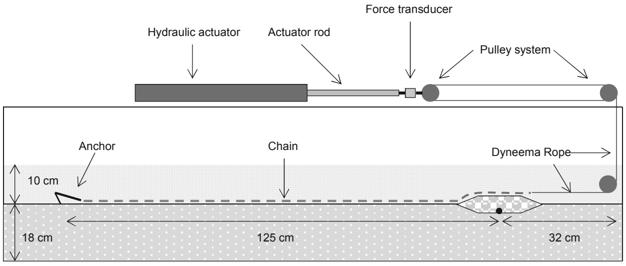

Figure 3. Sketch set-up

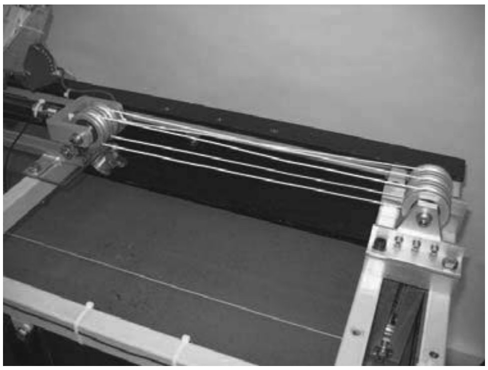

Figure 4. Pulley system in test set up.

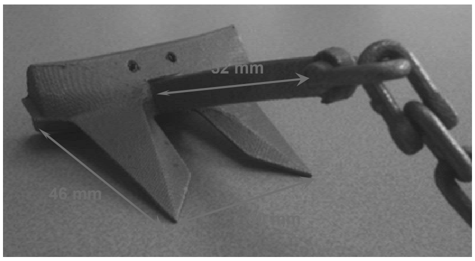

Figure 5. Model AC-14 anchor.

The soil model consists of a homogeneous sand layer of Baskarp sand (d_{50}= 135 μm) with a relative density of 65 – 75% and a peek friction angle of 40 degrees. On the sand a pipe line of 13 mm diameter and a gravel berm was placed (d_{50}=5.3 mm), see Figure 6. The porosity of the gravel was around 40% and the peek friction angle 48 degrees.

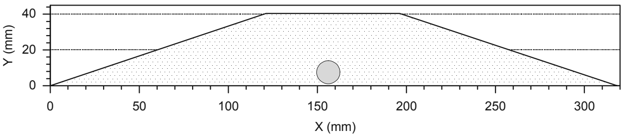

Figure 6. Dimensions of model berm

Tests were performed under saturated conditions with 0.15 m of water on top of the sand bed. The anchor was pulled through the sand bed until it was on the top of the berm. During the test the displacement of the plunger and the force of the plunger were measured continuously. After the test the water table was lowered to create some capillary forces to keep the anchor in position during spinning down. Back at 1-g the position of the anchor was carefully measured, see Figure 7.

Figure 7. Carefully measuring the position of the anchor after a test.

3.2 *1-g tests*

The set-up for the 1-g tests was exactly the same as for the centrifuge test. The same soil preparation technique, container, plunger and pulley system were used only now the tests were run outside the centrifuge at normal 1 g conditions under atmospheric pressure. Measurements performed during the tests and after the tests were the same as in the centrifuge. Three tests were performed.

4 TEST RESULTS

4.1 *Corrections on measurement data*

The parameters of importance are the penetration and the displacement of the anchor and the pulling force on the anchor.The penetration was measured after the test. The other parameters were determined during the test from the displacement of the plunger and the force that was measured on the plunger. The cable used in the pulley system was ∅ 3 mm dyneema cable with a maximum pulling strength of 5 kN. In order to limit elongation during the test, the cable was pre-stressed with a force of 2.8 – 3.0 kN. However, there still was some elongation of the cable. Furthermore, there will be friction in the pulley system. A dummy test was performed to correct for the friction both at 1-g and 80-g. In this test the Dyneema cable was connected with a spring connected in the centrifuge and an extra force transducer was located between the spring and the cable. Such a transducer could not be placed between the anchor and the cable during the real tests because the dimensions of the transducer and the necessary electrical cables would influence the test results. In the tests, the force on the cable at the spring and the force on the plunger were measured. The results of the measurements are presented in Figure 8. Due to friction in the system, the results differ depending on the direction of movement. The movement from left to right in the plot is the movement during anchor pulling. It appears that, apart from very small puling forces at plunger displacements around -120 mm, during pulling the pulling force as measured in the cable with the force transducer near the spring is always about 0.75 times the force measured with the force transducer at the plunger (and divided by 5 to correct for the pully system). This is only possible when the friction in the system increases linearly with the pulling force. This correction was applied in Figure 9.

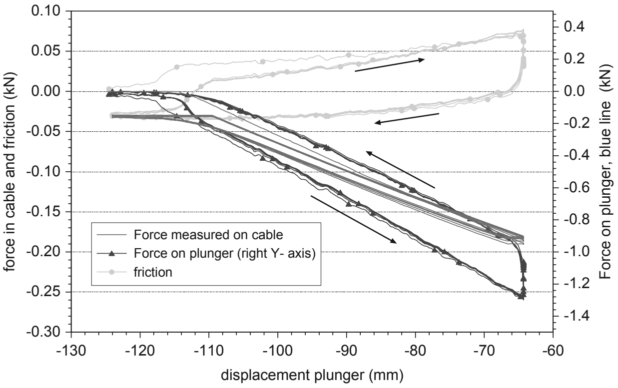

Figure 8: Comparison forces measured in a dummy test on the cable and on the plunger at 80g.

The correction for the elasticity of the cable was only performed for the 80-g tests. Due to the much smaller forces this was not necessary for the 1-g tests. The elasticity of the cable can be seen at the end of a test. When the anchor is pulled to its final position (on top of the berm) the pulling force is decreased retracting the plunger, while the anchor remains at the same position (controlled by the cameras). This allowed for higher pulling forces to measure is the elastic deformation of the cable. For low pulling forces there is an additional mechanism, the cables sag due to gravity. The last mechanism is only of importance for low pulling forces. Only the elastic relaxation is of importance during anchor pulling. Figure 9 shows the movement of the plunger as a function of pulling force during relaxation as measured in a test.

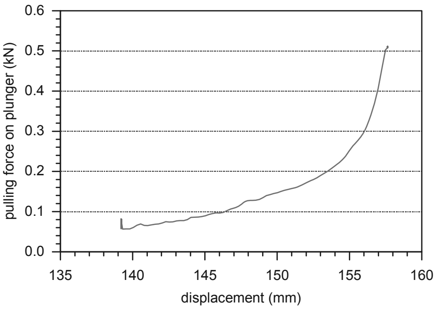

Figure 9. Relaxation of cable and sagging at the end of a 80 g test. The slope of the steep vertical part of the measured plunger force is determined by the elastic strain. The flatter part at low pulling force is caused by sagging of the cables.

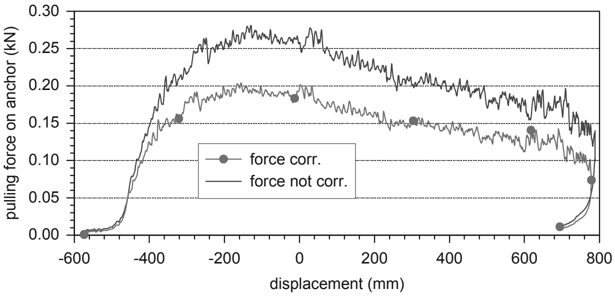

Figure 10. Pulling force and displacement with and without corrections on both force and displacement for a 80 g test.

Young's modulus is about 4 kN/m, measured at the plunger, thus Young's modulus of the cable is 4/25=0.16 kN/m.

The influence of the corrections for both the displacement and the force on the results are shown in Figure 10.

It is clear that the correction for the displacement hardly influences the results even at 80 g, but that the influence of the correction for the friction force is considerable.

4.2 Observations and results

In the 80-g tests the AC-14 anchor appeared to be a reasonable stable anchor. This means that pulling the anchor with the device described above, the anchor digs into the sand and does not rotate or rotated partly (up to 90 degrees). This was different for the 1-g test. In this test the anchor rotated 180 degrees around its pulling axis in front of the berm. In the model anchor the flukes were fixed (different from a real anchor). This means that when the anchor rotates, the flukes are pointing upwards and the anchor will not dig into the sand or the gravel berm. To avoid that the rotation of the anchor dominates all results the last test was performed with the anchor just in front of the berm and it was pulled over a short distance only.

The measured force displacements of both the 80-g tests and the 1-g tests are shown in Figure 11. The forces measured in the 80-g tests were divided by 80 to make them comparable with the results of the 1-g tests. Perfect scaling would mean that the 80-g test is 80 times higher, see Table 1. Thus dividing this force by 80 should result in the same value as the result of the 1-g test; Figure 11 shows that this is not the case. The force measured in the 1-g test is relatively higher.

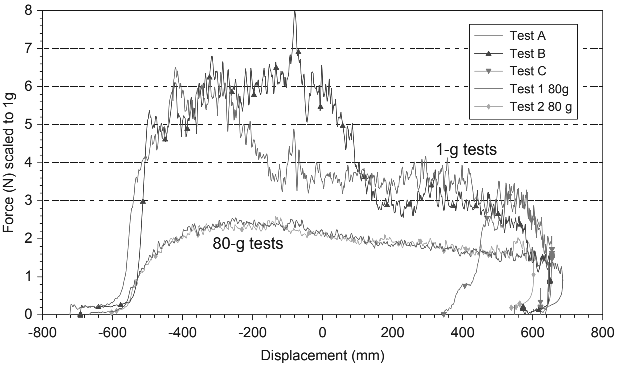

Figure 11. Force versus displacement for 1-g and 80-g (scaled, see text) tests.

Due to the rotation of the anchor just in front of the berm in 2 of the 3 tests, there is only one measurement of the maximum penetration of the anchor in the berm. This was on average 25.4 mm for the 80-g tests and 21.8 mm for the 1-g test. The difference is visible on the pictures taken after the test. After a 80-g test, Figure 12 the anchor flukes are completely in the berm (one fluke is visible in the picture but this is because the gravel is taken away for the measurement of the position of the fluke, the fluke in the upper part of the picture shows the original situation). Figure 13 shows that after the last 1-g test the flukes do not completely penetrate into the berm.

Figure 12. Position of anchor at the end of an 80-g test.

Figure 13. Position of anchor at the end of last 1-g test.

5 DISCUSSION

All results indicate that the soil and berm at the low stress levels of a 1-g test behave relatively stronger and stiffer than at the original stress level that is present during an 80-g test. If the stresses are not properly scaled, but lower than in reality; the soil behavior in a model test is stiffer and stronger than in the prototype. This means that also for purely friction materials as tested here, the proper representation of the stress-state is important. To test the protection efficiency of a berm against anchor dragging, 1:5 scale tests at 1-g are quite common. Looking at the results of this research, it is very likely that the results of these 1:5 scale model tests underestimate the penetration depth of the anchor in prototype, which is the primary objective of these tests, because that determines whether or not a pipe line is sufficiently protected. At a scale 1:5 the error will be smaller than at the scale 1:80 tested here, but can still be of importance.

6 CONCLUSIONS

Comparing the results of anchor tests at a scale 1:80 at the original stress level in a centrifuge with the results of a further identical 1:80 test at 1-g with thus a reduced stress level, led to the following conclusions:

- The drag forces at 1-g are higher than 1/80 of the drag forces at 80-g .
- The stability of the anchor is less during the 1-g tests.

The penetration depth is lower in a 1-g test (only one test result)

- Consequently the results indicate that in general a 1-g scale model test underestimates the penetration depth of the anchor and therefore overestimates the protection efficiency of the berm.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Bezuijen A. (2011), Rigid body calculations (personal communication).

LeQin Wang, HongKiat Chia. (2010*) Optimization study of pipeline rock armour protection design based on finit element analyses.* Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering OMAE2010 © *2010 ASME.*

Van Lottum H., Luger H.J., Bezuijen A. (2010) Centrifuge anchor dragging tests in sand and clay. Proc. *Physical Modelling in Geotechnics – Springman, Laue & Seward (eds)© 2010 Taylor & Francis Group, London, ISBN 978-0-415-59288-8* 1063-1068.