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Centrifuge Modelling of Pipeline-Soil Interaction in Calcareous Sand

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Summary Previous research work on modelling pipe–soil interaction has been focused on pipelines in terrigenous sands and clays of the North Sea and the Gulf of Mexico. The foundation response in such soils is very different from that in the calcareous sediments that predominate off the coast of Australia. An investigation into pipeline/soil interaction in calcareous sediments conducted on a centrifuge is presented in this paper. A total of 25 model tests were undertaken on a segment of pipe modelling a 1 m diameter prototype pipeline shallowly embedded in four uncemented calcareous sand samples. The test facility, experimental program and test results are described. The effects of the loading history, the installation method and the depth of embedment are discussed.

1. INTRODUCTION

In offshore hydrocarbon development, pipelines are the most efficient method of transporting oil and gas products from offshore fields to onshore production plants. The cost of the pipelines represents a significant proportion of the development budget of a new hydrocarbon field. To minimise the cost, the selection of pipe on-bottom weight and protection method, as determined by the geotechnical stability, is critical. As a consequence, pipeline-soil interaction under different loading environments is a pivotal issue in pipeline design.

In an attempt to achieve good predictions of pipeline-soil interaction, a large amount of research work has been carried out during the last two decades. A variety of physical model tests have been performed in terrigenous sands and clays of the North Sea and the Gulf of Mexico. Some representative results from these work were given by Paulin et al. (1995), Brennodden et al. (1986), Lieng et al. (1988), Morris et al. (1988), and Brennodden et al. (1992) for buried and unburied pipelines respectively.

Among all these physical modelling results, none of them has shown pipeline performance in calcareous soils. All results for unburied pipelines are obtained from full-scale tests with the potential of high cost and long period. To avoid these shortcomings, a centrifuge was employed to perform the experiments in this project. All tests were conducted in uncemented calcareous soils. The centrifuge, soil samples, pipe installation method, test procedure and test results are described in the corresponding sections.

2. EQUIPMENT AND SAMPLE PREPARATION

2.1 Centrifuge

The centrifuge is an Acutronic Model 661 Geotechnical Centrifuge (Randolph et al., 1991). It has a swinging platform at a radius of 1.8 m with nominal working radius of 1.55m, and is rated at 40 g-tonnes. The platform seats standard "strongboxes" which have internal dimensions of 390 mm wide by 650 mm long by 325 mm high. The headroom of 900 mm allows for mounting equipment above the box to allow "in-flight" events to be performed.

2.2 Actuators

Apart from the strongbox that contains the soil, the key pieces of equipment relevant to these tests are the cone actuator. It sits on top of the strongbox, and permits vertical and horizontal movements to be imposed on models. The horizontal travel on the cone actuator allows repositioning of the actuator in-flight, to allow multiple cone model tests to be performed without stopping the centrifuge.

2.3 Model Pipeline Segment

The 160 mm long model pipeline segment is a 20mm diameter, 3 mm wall thickness aluminium pipe, with a solid section at the centre into which the load cell and the loading actuator were fitted. No attempt was made to model the self-weight of a prototype pipe, as the effective self-weight is controlled entirely by the loading actuator. All centrifuge tests were conducted at 50g so that the pipe represents a prototype pipe of 1 m diameter.

2.4 Sample Preparation

The testing was commenced using a seabed soil. The soil was sieved through a 1 mm screen prior to sample preparation. Particle size distributions for the material, after removing the coarse particles, are shown in Figure 1.

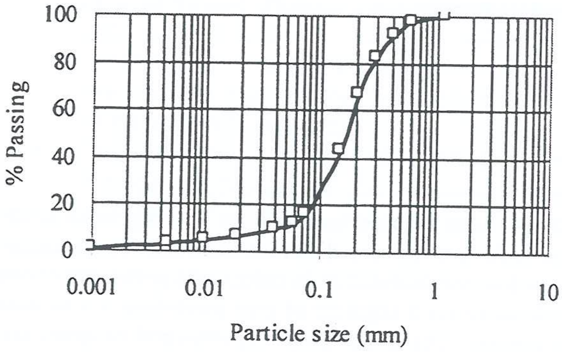

Figure 1 Particle distribution

The dry soil was mixed with water under a vacuum for several hours to remove air from the mixture. The slurry was then carefully placed in the strongbox above a fine to medium grained sand drainage layer of 120 mm thickness. The initial thickness of the slurry was about 140 mm. The sample was then consolidated under 50 kPa on the compressor for about 18 hours. The weight and the thickness of the soil were then measured for soil density calculation.

3. TESTING PROGRAM AND PROCEDURE

3.1 Testing Program

A total of 25 pipe tests were conducted on the model pipeline segment, with four soil samples being prepared. The general arrangement was shown in Figure 2. The types of tests undertaken are as follows.

- Pipe installation without horizontal loading, monotonically penetrating the pipe to prescribed load V_{max}, and unloading to the load level V_0 at which the pipe sideswipe or probe tests will be conducted.
- Sideswipe tests, where the vertical position of the pipe was held constant while it was pushed laterally. The tests were performed both on normal-penetrated ($V_0=V_{max}$) pipe and on over-penetrated ($V_0<V_{max}$) pipe.
- Probe tests, where the vertical load on the pipe was held constant while the pipe was pushed laterally. Two different pipe installation methods were adopted in probe tests, pushed-in method and trenching method. Both normal-penetrated pipe probe tests and over-penetrated pipe probe tests were conducted on the pushed-in pipe, while V_0 = 4 kN/m was selected for all trenched pipe probe tests.

3.2 Testing Procedure

Prior to starting self-weight consolidation of the samples on the centrifuge, a cone penetrometer and actuator were mounted on the strong box. At the completion of consolidation at 50 g, two cone penetration tests were conducted. The penetrating rate was 0.1 mm/s to ensure the test was performed fully drained.

After the completion of the two cone penetration tests, the centrifuge was stopped and the cone penetrometer was replaced by the model pipeline segment and load cell. The actuator was positioned over the pipe test site and the centrifuge accelerated to 50 g. Pipe tests were then carried out.

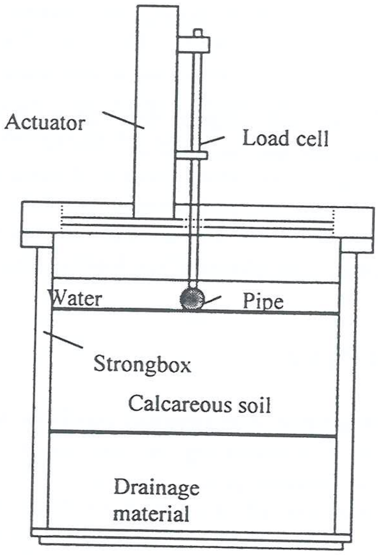

Figure 2 General arrangement of test package

4. TEST RESULTS

4.1 Sample Conditions

The method of sample preparation and the loading rate was kept as constant as possible to minimise differences between each sample, and to minimise the error in soil resistance caused by drainage conditions. The average density and water content measured for each sample are listed in Table 1. The average gradients of cone penetration resistance measured with the 2 MPa (10 mm diameter) cone before and after pipe tests are also listed in this table.

4.2 Pipeline Installation – Pipe Load-Unload Tests

During over-penetrated pipe tests, the pipe was firstly penetrated into the soil until the vertical load was equal the prescribed value V_{max} and then unloaded to get the vertical stress hold load V_0. Hence a load-unload test was actually performed in this installation process. Typical results from these load-unload tests are shown in Figure 3.

Table 1 Summary of soil sample conditions

Sample	γ (kN/m^3)	ω (%)	γ_d (kN/m^3)	e*	CPT Gradient (kPa/m)
1	18.1	30.5	13.9	0.824	340
2	18.5	31	14.1	0.837	480
3	18.6	31.3	14.2	0.845	420
4	18.6	31.6	14.2	0.853	410

*Obtained by assuming $G_s = 2.70$ and soil was fully saturated.

Table 2 Summary of k_{ve} and k_{vp} values

Test	V_{max} (kN/m)	V_0 (kN/m)	k_{vp} (kN/m/m)	k_{ve} (kN/m/m)
1-7	80	40	400	7200
1-8	80	20	260	10000
1-9	80	10	370	6300
2-4	80	4	330	8600
2-5	80	8	350	6000
2-6	80	20	340	7000
2-7	80	20	350	7500
3-1	20	4	320	10500
3-2	40	4	380	6900
3-3	80	4	390	7500
4-8	100	4	420	7700

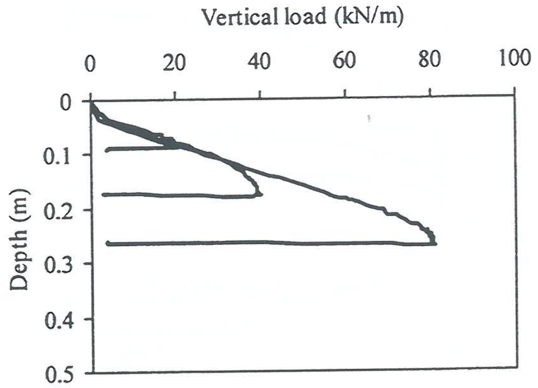

Figure 3 Pipeline vertical load-displacement response

The vertical load required for penetrating the pipe increased approximately linearly with depth, despite an increase in the contact area between pipe and soil as penetration increased. The gradients of the loading line and unloading line are listed in Table 2. In this table, k_{vp} describes the gradient of loading line while k_{ve} describes the gradient of unloading line. The gradient of loading line is around 350 kN/m/m, and the gradient of unloading line around 7000 kN/m/m. It may be concluded that the gradient of the unloading line is about 20 times greater than that of the loading line for the soil samples used in this study.

4.3 Horizontal Load-Displacement Response

4.3.1 Sideswipe tests

Sideswipe tests were undertaken to effectively trace out the shape of the yield surface (Tan, 1990, and Martin, 1994) of the foundation under combined vertical and horizontal loading. This technique has been successfully applied to pipe-soil interaction problems (Zhang et al., 1999b). Test results are summarised in Table 3 with typical ones shown in Figures 4 and 5.

Table 3 Summary of sideswipe test data

Test	V_{max}, V_0 (kN/m)	H_{max} (kN/m)	V_1 at H_{max} (kN/m)	H_{max}/V_{max}	V_1/V_{max}
1-1	3.7, 3.7	0.43	1.66	0.12	0.46
1-2	9.6, 9.6	1.3	4.8	0.14	0.5
1-3	19.1, 19.1	2.6	9.9	0.14	0.52
1-4	39.5, 39.5	6.6	17.1	0.17	0.43
1-5	79.1, 79.1	14.2	34	0.18	0.43
1-6	77.7, 10	7.6	10.4	-	-
1-7	80, 20	9.5	20.1	-	-
1-8	78.9, 39	12.6	34	0.16	0.43
1-9	77, 57	14.4	40.2	0.19	0.52

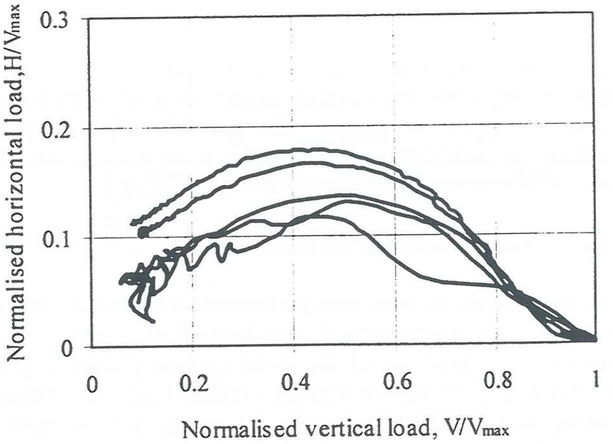

Figure 4 Sideswipe at $V_0 = V_{max}$

The relationship between horizontal load and displacement, as well as the yield surface agreed very well for the two series of sideswipe tests. As the pipe was displaced laterally, the horizontal load initially increased to a peak, while the vertical load dropped. After the peak horizontal load was reached, both vertical and horizontal loads reduced to approximately constant values.

The yield envelopes shown in Figure 4 are approximately parabolic in shape, with the horizontal load reaching a peak of about 15% of the peak vertical load. The vertical load corresponding to the peak horizontal load was between 43% and 52% with an average of 47% of the peak vertical load. It is worth mentioning that Tan (Tan, 1990) has suggested H_{max} occurred at a value of $V/V_{max} \approx 0.46$. This feature probably suggested that the yield envelope has a vertical load axis intercept at negative vertical load (thus intersecting the horizontal load axis at a positive value). An intercept on the horizontal load axis represents passive soil resistance, and the negative intercept on the vertical load axis does not indicate that the pipeline has significant uplift capacity.

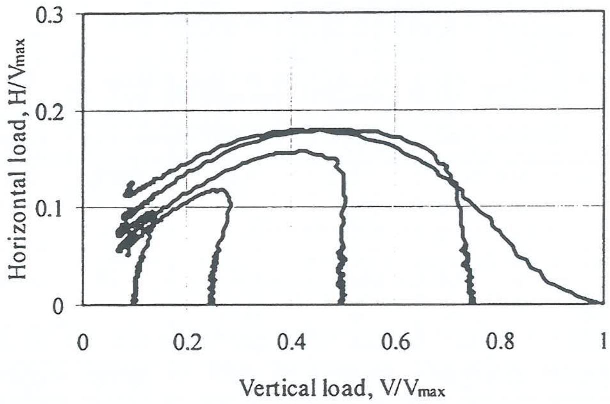

Figure 5 Sideswipe at $V_0 < V_{max}$

Results from over-penetrated pipe sideswipe tests, as plotted in Figure 5, show that the loading points initially travel through an elastic region at almost constant vertical load before reaching the yield surface. The loading point moving along the yield surface as soon as it reached the yield point.

4.3.2 Pushed-in pipe probe tests

Two types of probe tests were performed to define the limiting horizontal resistance (Gottardi and Butterfield, 1993), and the expansion or shrinkage of the yield surface (Stewart, Zhang and Randolph, 1998), for a given vertical load after different loading history. The first type of probe test is normal-penetrated pipe probe test, where the vertical load was corresponding to the initial embedment, i. e., $V=V_{max}=k_{vp}z_0$. The second type of probe test is the over-penetrated probe test. In these tests, the vertical load was fixed at a predetermined value, say, 4 kN/m, at different initial penetrations.

Normal-penetrated pipe probe tests

The results from normal-penetrated pipe probe tests are summarised in Table 4 with typical results shown in Figure 6. For each test the maximum horizontal load was estimated from the data, although the pipe was not always pushed far enough to define this load exactly, or the capacity of the load cell was reached. The horizontal loading curve levelled when the horizontal load approximately equals the vertical load.

Test data revealed that the expansion of the yield envelope was related to the vertical load or the initial embedment of the pipe, as the vertical displacement increment increased with the increasing of pipe initial embedment. The initial gradient of displacement was about 0.6, and has been shown not to depend on the initial embedment. The data did not indicate a direct relation between initial stiffness of horizontal loading with pipe initial embedment or load level, but most likely a constant value, as shown in Figure 6.

Table 4 Summary of normal-penetrated pipe probe tests

Test	V (kN/m)	z_0 (m)	H_{max} (kN/m)	δz (m)	Initial (dz/dx)
2.1	4	0.073	3.9	0.043	0.4
2.2	10	0.085	11.6	0.226	0.6
2.3	20	0.104	20.9*	0.31	0.6
3.1	4	0.037	3.3	0.067	0.7
3.2	8	0.085	7	0.122	0.4
3.3	16	0.104	18.1	0.25	0.7
3.4	4	0.082	3.4	0.03	0.3
4.6	4	0.018	3.0	0.049	0.4

* Limited by load cell capacity.

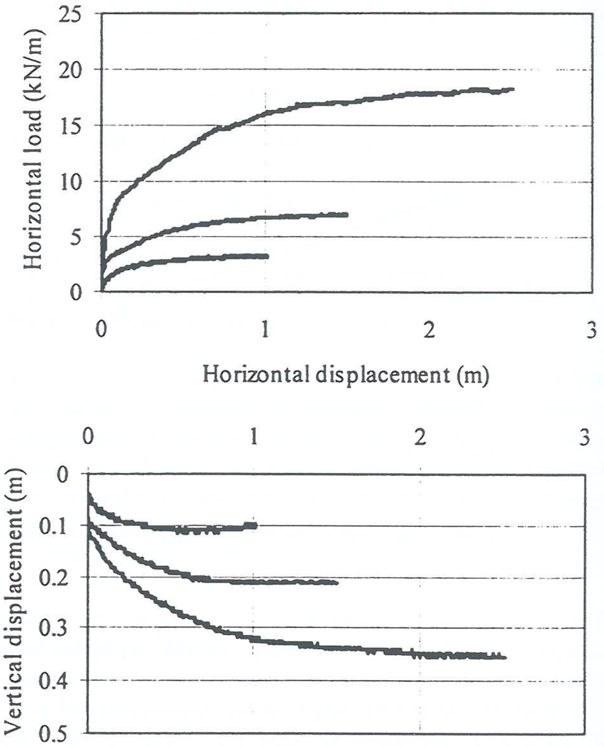

Figure 6 Normal-penetrated pipe probe test results
a) Horizontal load development; b) Pipe displacements

Over-penetrated pipe probe tests

As shown in Table 5 and Figure 7, over-penetrated pipe probe tests revealed different trends compared with those from the normal-penetrated pipe probe tests. During the first stage of horizontal displacement, pipe movement was always upwards when the over-penetration ratio V_{max}/V_0 was larger than about 10, and there was considerable post-peak softening of the horizontal load.

Table 5 Data from over-penetrated pipe probe tests

Test	V_{max}, V_0 (kN/m)	z_0 (m)	H_{max} (kN/m)	δz (m)	Initial dz/dx
2.4	80, 4	0.24	3.6	-0.1	-0.15
2.5	80, 10	0.24	4.2	-0.01	-0.03
2.6	80, 20	0.24	16.8	0.056	0.06
3.5	40, 4	0.17	3.7	0.012	0.08
3.6	80, 4	0.27	4.6	-0.19	-0.19
3.7	100, 4	0.30	4.4	-0.213	-0.21

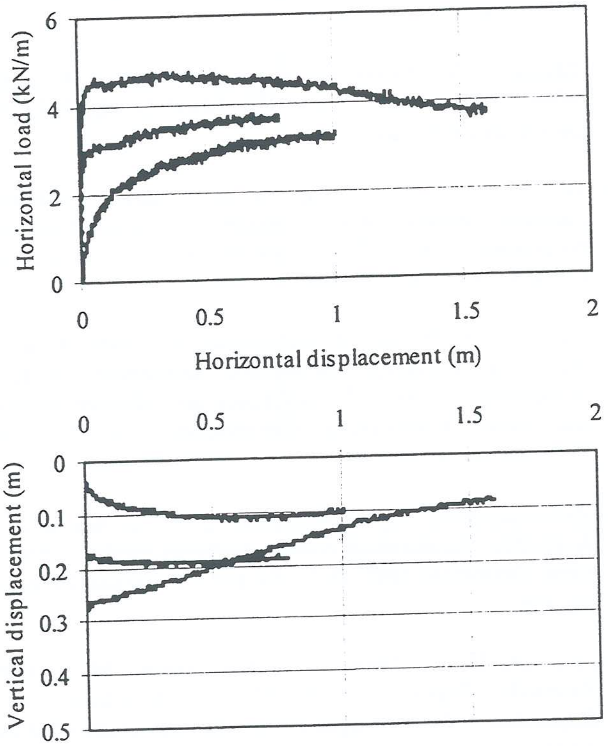

Figure 7 Over-penetrated pipe probe test results
a) Horizontal load development; b) Pipe movement

4.3.3 Trenched pipe probe tests

Some probe tests were conducted on trenched pipelines in order to investigate the effects of installation method. The trench depth varied from 0.16 m to 0.84 m in prototype scale. A 4 kN/m vertical load was applied to the trenched pipe after spinning up in order to model the pipe self weight, and then horizontal load was applied and the probe test performed.

Test data is summarised in Table 6 with typical results shown in Figure 8. The data suggested that the peak horizontal load, the gradient of pipe initial displacement and pipe upward movement all increased with the increasing trench depth. However, the values of upward movement and the initial displacement gradient were much smaller than that from pushed-in pipe probe tests at a similar initial embedment.

Figure 8 shows that the initial stiffness of the pipe horizontal load-displacement curve was much lower than that given in Figures 6 and 7, suggesting that the pushed-in process resulted in a larger horizontal load, a higher initial horizontal stiffness and a larger gradient in pipe displacement curve. This is probably caused by the densification of the soil around the pipe by the push-in process.

Table 6. Data from trenched pipe probe tests

Test	Depth (m)	H_{max} (kN/m)	δz (m)	Initial dz/dx
4.1	0.16	3.7	-0.05	-0.116
4.2	0.28	4.8	-0.13	-0.123
4.3	0.67	8.8	-0.34	-0.398
4.4	0.84	11.7	-0.92	-0.483

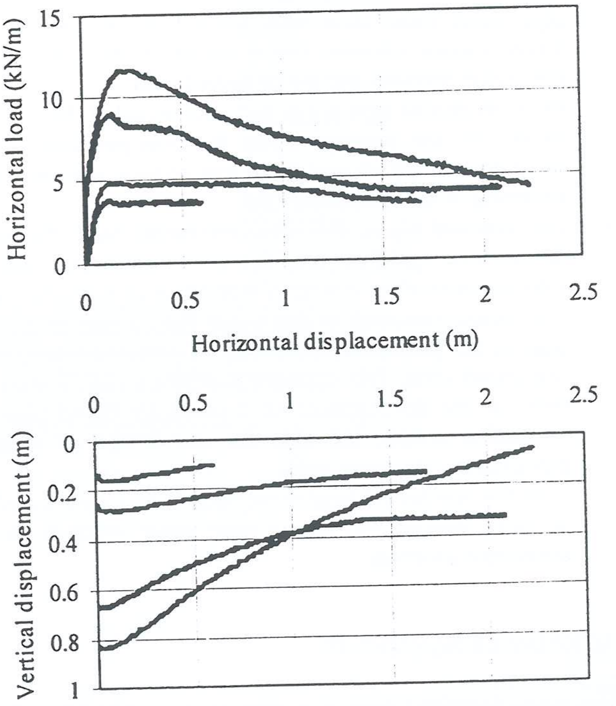

Figure 8 Trenched pipe probe test results
a) Horizontal load development; b) Pipe movement

5. SUMMARY AND COUNCLUSIONS

Twenty-five pipe tests were carried out on a fixed beam centrifuge at 50 g to investigate pipeline load-displacement response in calcareous sand. The three primary objectives of this experimental work were to define the yield surface for a pipeline under combined vertical and horizontal loads, to derive the hardening parameters of pipe-soil interaction and to investigate the effects of load history and installation method on pipeline response. As a result, the following conclusions were reached.

- Centrifuge modelling is a suitable technique for determining the features of pipe-soil interaction of shallowly buried pipelines in calcareous sand.
- The vertical stiffnesses of pipe loading and unloading are about 350kN/m/m and 7000 kN/m/m respectively. It implies that the stiffness of pipe reloading may be much greater than that in the initial loading. A further test programme is required to investigate this property of pipe-soil interaction.
- The yield surface of pipe-soil interaction under combined vertical and horizontal loads is parabolic in shape. At the critical state of pipe-soil interaction, pipe horizontal load of about 15% of its maximum vertical load was reached when the vertical load was about 47% of the maximum vertical load.
- The peak horizontal loads approximately equal to the vertical loads were recorded from the normal-penetrated pipe probe tests. Data from these tests did not show a direct relation between initial displacement gradient and horizontal stiffness and initial embedment.
- Over-penetrated pipe probe test data revealed that the pipe movement was upwards when the over-penetration ratio larger than about 10, and there was considerable post-peak softening of the horizontal load.
- For trenched pipes, the peak horizontal load, the initial displacement gradient and the initial horizontal stiffness were much smaller compared with those of pushed-in pipe.
- The results presented in this paper form a part of the data base of the geotechnical stability of offshore pipelines on calcareous soils. This database provides a corner stone not only for the development of a plasticity based pipe-soil interaction model, but also for the design of offshore pipelines in calcareous soils.
- A further test programme is required to elucidate the effect of cyclic loading and excess pore water pressure on this interaction problem.

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