

Uplift of Offshore Pipelines

by

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I hereby declare that, except where specifically indicated, the work submitted herein is
my own original work.

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Technical Abstract

Offshore and onshore oil and gas pipelines are often buried in soil. In addition to providing protection from surface damage from trawlers and anchors, the soil provides thermal insulation and resistance to upward bending of the pipeline. This upwards bending is known as upheaval buckling (UHB). The pressure and temperature of the working conditions (160°C, 70MPa) of the pipeline are much greater than the as-laid conditions (4°C, 0MPa). The resulting thermal expansion gives rise to an axial elongation of the pipe, causing the pipe to buckle upwards. With increasing out-of-straightness, the buckling load of a pipeline section decreases. In design, it is therefore important to know the maximum available resistance provided by the soil cover and the displacement of the pipeline required to mobilise the maximum resistance.

The overall objective of the project is to investigate the resistive properties of a particular cohesionless sand (Hostun sand, $I_D = 0.52$, $D_{50} = 0.47\text{mm}$) using centrifuge modelling, to expand the data for testing existing hypotheses. The soil properties are typical of those of seabed sands. The tests focus on the monotonic pipeline uplift force-displacement relationship to investigate the effect of higher H/D ratios, how the mobilisation distance can be predicted at the peak uplift force, and the effect of particle size. There is also a focus on the modelling of physical models in monotonic pipeline uplift in cohesionless soils to determine how well the centrifuge model predicts full-scale behaviour.

Analysis of the experimental results show that the current industry design practice to predict the maximum uplift resistance is valid for a cover:pipe diameter (H/D) ratio between 2 and 10. The design code however is unconservative with respect to mobilisation distance prediction, being based on excessive stiffness. A range of 0.4 and 0.8 is proposed for the uplift factor, f_p , which agrees with previous literature for a finer sand, and disagreeing with the design code. The mobilisation distance is broadly in agreement with the hypothetical exponential relationship $\frac{\delta_f}{D} = 0.02e^{\left(\frac{1}{2}\frac{H}{D}\right)}$, proposed by Wang, (2010). For $D/D_{50} > 18$, $\frac{R_{peak}}{\gamma'_{HDL}}$ does not vary significantly with N or D/D_{50} , but an increase in mobilisation distance is observed with increasing centrifuge g level.

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NOMENCLATURE

<i>Symbol</i>	<i>Meaning</i>
D	Pipe diameter
F	Simplified uplift factor
f_p	DNV uplift factor at peak uplift resistance
H	Soil cover depth, measured from pipe crown to soil surface
H_c	Soil cover depth, measured from pipe centre to soil surface
L	Pipe length
N	Centrifugal acceleration as multiples of g ($=9.81\text{N/mm}^2$)
R	Net soil downwards resistance to upheaval buckling
R_{peak}	Peak soil downwards resistance to upheaval buckling
A	DNV tri linear design curve coefficient
B	DNV tri linear design curve coefficient
γ'	Submerged soil unit weight
Δ	Mobilisation distance
δ_f	Mobilisation distance at peak uplift resistance

1 INTRODUCTION

1.1 Background

Offshore and onshore pipelines are often buried in soil. In addition to providing protection from surface damage from trawlers and anchors, the soil provides thermal insulation and resistance to upward bending of the pipeline. This upwards bending is known as **upheaval buckling (UHB)**. At working conditions (160°C, 70MPa), the steel pipeline undergoes thermal expansion, performing at a temperature and pressure higher than the installation conditions (4°C, 0 MPa). It is this thermal expansion of the pipeline that is the driving force of UHB, as illustrated in Figure 1-1. The backfill soil acts to restrain the pipeline from expanding, inducing an axial compressive force in the pipeline which drives the pipe upwards. Upheaval buckling occurs when the upwards component of the axial force is greater than the downwards force from pipeline stiffness, pipeline self weight and soil cover, which can result in pipeline failure.

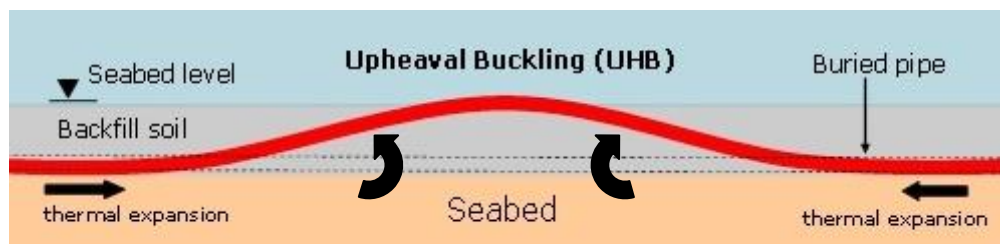


Figure 1-1: Upheaval Buckling Mechanism

The upheaval buckling phenomenon is similar to Euler buckling; the buckling load of a column (pipeline) decreases with out-of-straightness. If a strut is initially perfectly straight, a force is not required at the midspan to halve the effective length, but stiffness is (i.e. bracing members theoretically carry no load). In order to keep a strut (or pipe) that is initially curved in equilibrium, a lateral load is required. If the distance required to mobilise this lateral load is large, the pipe will become less straight and a greater load will hence be required. Consequently the stiffness of the soil is important. In pipeline design, it is therefore important to know the maximum available resistance provided by the soil cover and the displacement of the pipeline required to mobilise the maximum resistance.

Figure 1-2 illustrates the damaging effect of upheaval buckling. Remedial work and revenue loss as a result of UHB can cost millions of dollars whilst also forming an environmental hazard. Hence the pipeline must be covered with sufficient soil to prevent this upheaval buckling effect and keep the pipe in its original position.

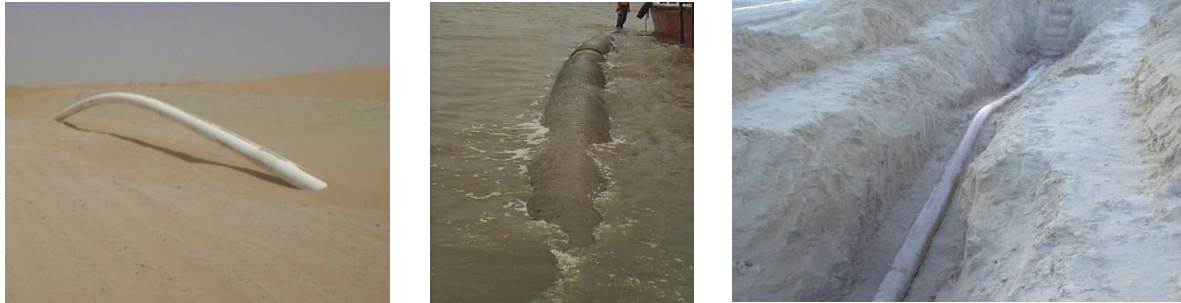


Figure 1-2: Real Upheaval Buckling Examples

1.2 Objectives

The overall objective of the project is to investigate the resistive properties of a particular cohesionless sand (Hostun sand, $I_D = 0.52$, $D_{50} = 0.47\text{mm}$) using centrifuge modelling, to expand the data for testing existing hypotheses. The soil properties are typical of those of seabed sands.

Aims

- To investigate the effect of soil cover depths on the maximum available soil resistance to upheaval buckling in pipes, the corresponding mobilisation distance and the shape of the uplift force-displacement curve
- To investigate the scaling effects of the centrifuge, with particular respect to the effect of model pipe diameters and g-levels on the maximum available soil resistance to upheaval buckling in pipes, the corresponding mobilisation distance and the shape of the uplift force-displacement curve to explore whether the centrifuge provides a reliable estimate for the available uplift resistance and mobilisation distance.
- Compare the findings from this investigation to previous research and the current design practice.

2 LITERATURE REVIEW

2.1 Strategy for analysis of upheaval buckling movement

The upheaval buckling stability of a pipe is controlled by a force balance between the available downwards restraint and the axial compressive force (P). Analysis by Palmer et al., (1990) suggests a general solution that represents the structural equilibrium of the pipe. This takes the form:

$$\Phi_w = A \left(\frac{\pi}{\Phi_L} \right)^2 - B \left(\frac{\pi}{\Phi_L} \right)^4$$

Equation 2-1

Where:

$\Phi_w = R \frac{EI}{\Delta P^2}$ = dimensionless uplift resistance

$\Phi_L = L \left(\frac{P}{EI} \right)^4$ = dimensionless imperfection length

EI = flexural rigidity of the pipeline

P = thermally – generated axial compressive force

Δ = maximum height of the imperfection

L = half the total imperfection length

A and B are constants to be determined numerically

The solution for any particular section of pipeline depends on the initial imperfection profile, (Croll, 1997). Since Φ_w intrinsically depends on Δ , any additional upward movement of the pipe acts as feedback into calculation. Using numerical calculations, Palmer et al., (1990) suggested that the required soil resistance, R, can be related to the imperfection length, L and imperfection height, Δ , using the following solutions:

For $0 < \Phi_L < 4.49$	$\Phi_w = 0.0646$
For $4.49 < \Phi_L < 8.06$	$\Phi_w = 5.68\Phi_L^{-2} - 88.35\Phi_L^{-4}$
For $\Phi_L > 8.06$	$\Phi_w = 9.6\Phi_L^{-2} - 343\Phi_L^{-4}$

Equation 2-2

Figure 2-1 shows the dimensionless design chart equivalent to equation 2-2

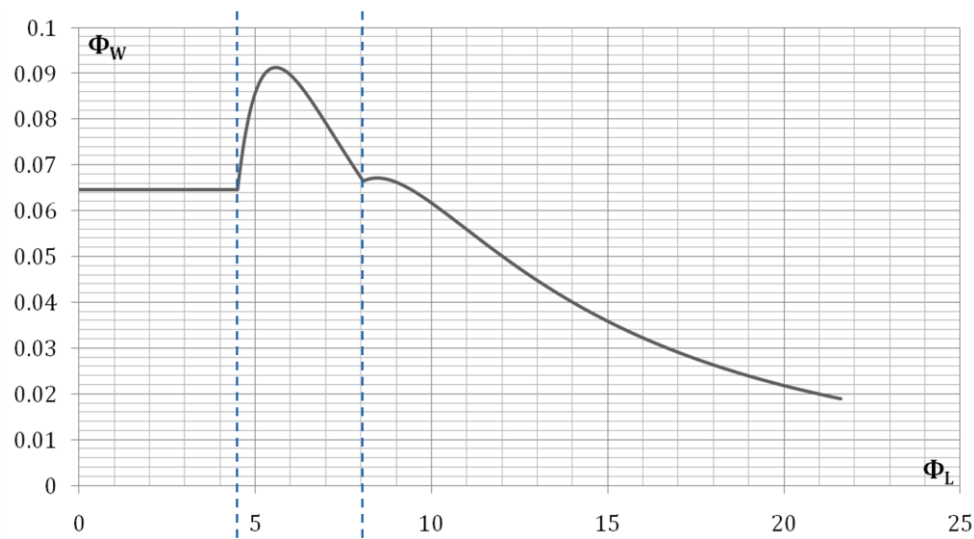


Figure 2-1 Dimensionless design chart for calculating required soil resistance, R
(Palmer et al., 1990)

Thus, the research by Palmer et al, (1990) links structural analysis with geotechnical principles.

2.2 Uplift Resistance in cohesionless soils

The uplift resistance should be sufficient to restrain the pipe from buckling vertically. As illustrated in Figure 2-1, a Vertical Slip Surface model, Pederson (1988) can be used to calculate the uplift resistance for pipes buried in cohesionless soils. The model considers both the total effective weight within the boundary of the two vertical slip surfaces and the shear from along the two vertical slip planes.

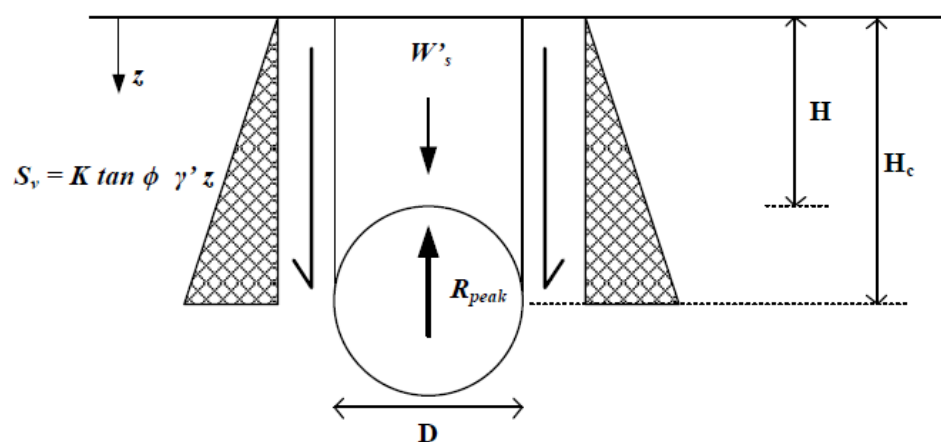


Figure 2-1 The Vertical Slip Surface Model

Resolving the vertical forces as illustrated in Figure 2-1, results in the dimensionless expression for R_{peak} .

$$\frac{R_{peak}}{\gamma' HDL} = 1 + \left(\frac{1}{2} - \frac{\pi}{8} \right) \frac{D}{H} + K \tan \phi \left[\frac{D}{H} \times \left(\frac{H}{D} + \frac{1}{2} \right)^2 \right]$$

Equation 2-3

The first term represents the effective weight of the soil rectangle above the crown of the pipe. The second term represents the effective weight of the soil between the soil rectangle and the pipe. The final term represents the contribution due to shear along the two vertical slip planes.

Since K and $\tan \phi$ depend on the soil material used, it is difficult to obtain an accurate value, hence $K \tan \phi$ is replaced with the constant f_p , the Pedersen uplift factor;

$$\frac{R_{peak}}{\gamma' HDL} = 1 + \left(\frac{1}{2} - \frac{\pi}{8} \right) \frac{D}{H} + f_p \left[\frac{D}{H} \times \left(\frac{H}{D} + \frac{1}{2} \right)^2 \right]$$

Equation 2-4

2.3 Current Design Practice

Offshore practices define the way that pipeline designers and engineers work. Appendix B of the Offshore Standard, DNV-OS-F110: Global Buckling of Submarine Pipelines – Structural Design due to High Temperature / High Pressure DNV, (2007) concentrates on soil resistance modelling and provides guidelines to ensure exposed pipelines are designed to buckle in a controlled manner and buried pipelines to stay in place. This implements the requirements outlined in the recommended practice, DNV-OS-F101 – Submarine Pipeline Systems.

2.3.1 Uplift resistance in cohesionless soils

The design approach currently adopted by the DNV-RP-F110 to predict R_{peak} , uses the vertical slip surface model (Equation 2-4). Equation 2-5 expresses an alternative version, which considers a simplified slip surface model, where the term, 1, represents the self weight and the H_c/D term represents the shear contribution:

$$\frac{R_{peak}}{\gamma' H_c DL} = 1 + f_p \frac{H_c}{D}$$

Equation 2-5

2.3.2 Tri-linear force displacement curve model for uplift

DNV-RP-F110, (2007) suggests that the non linear normalised force-displacement response of a buried pipe can be represented for design by a tri-linear curve. This curve is reproduced in Figure 2-2. Research by Trautmann et al (1985) verifies $\beta=0.2$ as a practical choice to locate the first kink in the tri linear force displacement curve. Within the limitations of the tri-linear soil resistance mobilisation curve, the modelling recommendations suggested are outlined in Table 2-1.

It is important to note that the uplift resistance, R_{peak} , is assumed to be fully mobilised at a vertical uplift displacement, δ_f . DNV-RP-F110 (2007) suggests that for sands this mobilisation distance, δ_f , is 0.5%-0.8% of the cover height H , and hence independent of the ratio H/D , as detailed in Table 2-1.

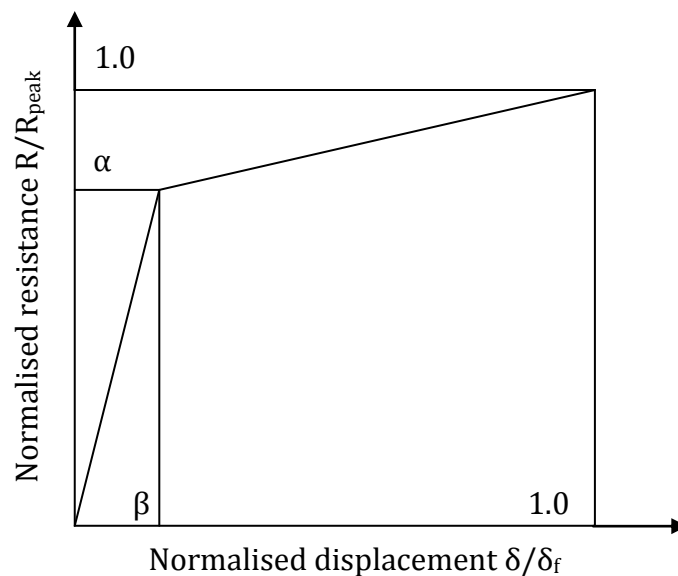


Figure 2-2: Tri-linear force displacement curve model for uplift

Characteristics	H/D Range	Parameter		Range
Medium/Dense Sand (pre-peak)	[2.0, 8.0]	f_p	ϵ	[0.4, 0.6]
		δ_f	ϵ	[0.5%, 0.8%] H
		α	ϵ	[0.65, 0.75]
		β	$=$	0.2

Table 2-1: Defined Ranges for the soil parameters

2.4 Centrifuge modelling as a physical modelling technique

Centrifuge modelling is a physical modelling technique, which comprises of a scaled version (the model) of an actual object or scenario (the prototype). Thus, centrifuge modelling allows information of a real design scenario to be obtained through study of the model in a more cost and time efficient manner. Soil models experience an inertial radial acceleration, which the soil sample feels as a gravitational acceleration field that is multiple times stronger than the Earth's gravity. In this modelling technique it is important that the same stress increase is experienced by the model as that of the prototype. There are two main issues associated with centrifuge modelling; scaling laws and scaling errors (Taylor, 1995).

2.4.1 Scaling Laws

A soil sample in a model container is stress free at the surface, but within the soil sample, the stress increases with depth as a function of the strength of the g-field and the density of the soil. If a similar stress history is replicated in the model soil sample as the prototype soil, then for a centrifuge model subjected to an inertial acceleration field of N times the Earth's gravity, the vertical stress at depth h_m will be identical to that of the corresponding prototype at depth h_p , where $h_p = N \times h_m$. Thus, in order to ensure that the model experiences that same stress as the corresponding prototype, this basic scaling law is used. Hence Table 2-2 details scaling factors relevant to pipeline upheaval buckling.

Prototype Quantity	Description	Dimension	Prototype:Model Scale factor
H	Cover	[L]	N
D	Pipe diameter	[L]	N
l	Pipe length	[L]	N
g	Acceleration due to gravity	[LT ⁻²]	1/N
R	Uplift force per unit pipe length	[MT ⁻²]	N
Δ	Uplift displacement	[L]	N
γ'	Saturated unit weight	[ML ⁻² T ⁻²]	1/N

Table 2-2 Scaling factors relevant to upheaval buckling

2.4.2 Sources of error in centrifuge modelling

As previously mentioned, centrifuge modelling is designed to give the same stress-field in the model as in the prototype. This should lead to an identical strain field and hence scaled results. This premise, however, relies on several assumptions:

- The gravity field is uniform and parallel throughout the model
- The soil behaves as a continuum

These assumptions have an associated uncertainty, which can lead to modelling errors.

1. Particle size effects

There is an error due to soil particle size since the particle size is not reduced in size by the factor N . The assumption that soil will behave identically independent of the model size will break down at a critical ratio between the model pipe diameter and the average grain diameter. Taylor (1995) suggests this limiting ratio to be less than 15 in shallow foundations.

2. Rotational acceleration field

There is an error due to the g -field not being parallel throughout the model. The centrifuge has an axis of rotation that is vertical. The vertical axis of the model is horizontal during rotation. Consequently, the model experiences a centrifugal acceleration of magnitude Nxg in the radial direction, as well as the gravitational pull from Earth in the vertical direction. The main centrifugal acceleration thus diverges from the surface to the base of the model. This error is minimised in the drum centrifuge due to the curved container used in the investigation.

The acceleration within the centrifuge model varies linearly with radius

$$a = \omega^2 r$$

Equation 2-6

Consequently the gravity at the surface of the model is less than the gravity at the bottom of the model. In this design scenario the minidrum centrifuge has a diameter of 0.5m. The maximum height occupied by sand in the centrifuge in the testing series reaches 0.42m. Thus the top of the sand experiencing a g -force that

is 84% (0.42/0.50) of that experienced at the bottom; hence the model is probably 10% under the expected g-level at the top of the model, and 10% above the expected g-level at the bottom, and this brings a source of error to the centrifuge modelling technique.

2.5 Previous research: Monotonic & Cyclic Uplift Resistance of Buried Pipelines in Cohesionless Soils, Wang (2012)

Wang's PhD research addresses the pipeline upheaval buckling problem, conducting full scale tests in loose saturated sand ($D_{50} = 0.14\text{mm}$, $I_D = 30\%$), dense saturated sand and dry rock, and centrifuge tests in loose and dense sand. The experimental tests focus on low H/D values.

2.5.1 Conclusions drawn from this research with respect to the pipeline uplift force-displacement relationship in cohesionless soils

- The experimental data accurately compliments the Pedersen Design Equation (Equation 2-4).
- Experimental data suggests a value of f_p , the Pedersen uplift factor, to be between 0.4 and 0.8 in medium/dense sand.
- The mobilisation distance at R_{peak} does not agree with the DNV-RP-F110, (2007) recommendation that $\delta_f \in [0.5\%H, 0.8\%H]$. When the mobilisation distance is normalised with H , δ_f/H , the design range proposed was between 1% and 8% for H/D between 0 and 6, and between 1.5% and 4.5% for H/D between 2 and 5.
- A relationship between mobilisation distance normalised with D , δ_f/D , and H/D is proposed as: $\frac{\delta_f}{D} = 0.02e^{\left(\frac{1}{2}\frac{H}{D}\right)}$. This hypothetical exponential relationship is derived from results from Wang, et al., (2010)

2.5.2 Conclusions drawn from this research with respect to the scaling effects of the centrifuge

- Modelling design scenarios at different g-levels does not significantly affect the normalised peak uplift force, provided that $D/D_{50} > 20$.
- Modelling design scenarios at increasing g-levels magnifies the interpreted values of the prototype scale mobilisation distance. This discrepancy is not due

to systematic errors, hence a hypothesis has been proposed stating that as the g-level increases, the number of grains of soil above the crown of the pipe reduces, limiting their ability to rearrange during uplift. This validity of this hypothesis will be investigated.

2.5.3 Analysis Plots

Wang's research comprises of experimental data for a loose saturated sand ($D_{50} = 0.18\text{mm}$, $I_D = 30\%$). Alongside the conclusions stated above, the research includes some interesting plots that can be used to investigate the particle size effect.

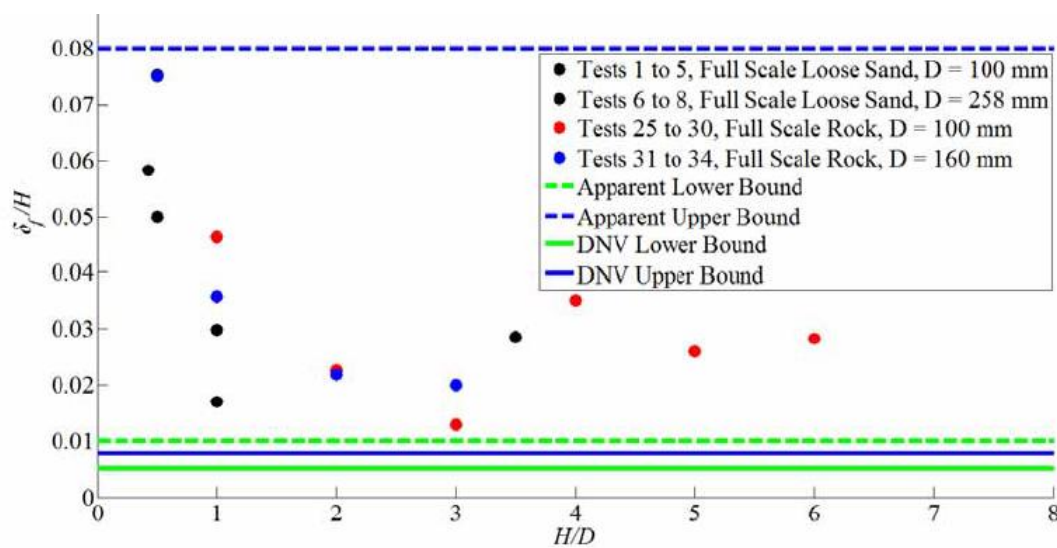


Figure 2-3 Plot of δ_f/H values against H/D ratios for all full scale tests, (Wang, 2012)

Figure 2-3 plots values of δ_f/H against H/D for all Wang's full scale tests. At H/D ratios greater than 2, the average value of δ_f/H can be taken as 2.5%. At H/D ratios less than 2, the δ_f/H value is not constant, and is much higher than 2.5%. H/D values greater than 2 will be considered in the scope of this project.

3 EXPERIMENTAL CONCEPT AND METHODOLOGY

3.1 Experimental Concept

In order that this study will broaden the research base within the field of pipeline upheaval buckling, the centrifuge testing should address the following questions:

1. Is the existing design equation, Equation 2-4, adequate in high H/D (>8) scenarios?
2. How could the force-displacement curve be predicted? In particular, how can the mobilisation distance be predicted at the peak uplift force?
3. How well does the centrifuge model predict full-scale behaviour? Does the particle size of the soil have an effect on the force-displacement curve?

In order to answer these questions, the centrifuge test series must:

- Use a sand backfill that is representative of that used offshore;
- Be performed in saturated conditions to replicate offshore conditions;
- Cover a practical range of H/D ratios;
- Use practical model pipe diameters;
- Facilitate accurate recording of force and displacement data.

Throughout the centrifuge modelling in this testing series, it will be assumed that there is a negligible effect due to the radial gravity field, but the effect of particle size will be investigated, particularly with respect to the conclusions from previous research as detailed in section 2.5.2.

3.2 Experimental Design

The sand used throughout the experiment is Hostun sand. This particular sand has $D_{50} = 0.47\text{mm}$, and a relative density, I_D , of 53%. These soil properties are typical of those of seabed sands. This sand is 2.6 times coarser than that used in previous research by Wang (2012), thus can be used to investigate the effect of particle size.

An Automatic Sand Pourer (ASP) (Madabhushi, et al, 2006) was used to prepare the sand backfill for some of the centrifuge tests. The advantage of using the automatic sand pourer is the consistency and controllability of the relative density of the backfill that it provides for the centrifuge model box. It provided negligible deviations of I_D at 53% and corresponding γ' of 9.25kN/m^3 , when the same ASP settings for nozzle size (7mm), drop height ($z=20\text{mm}$), velocity in the two horizontal axes and step width were used. Due to unavailability of the automatic sand pourer, some centrifuge model boxes were prepared by manually pouring sand. This method resulted in relative density values of $53\%\pm 3\%$. This method was possible due to the small size of the soil sample required. Using the ASP is particular advantageous for preparing large soil samples.

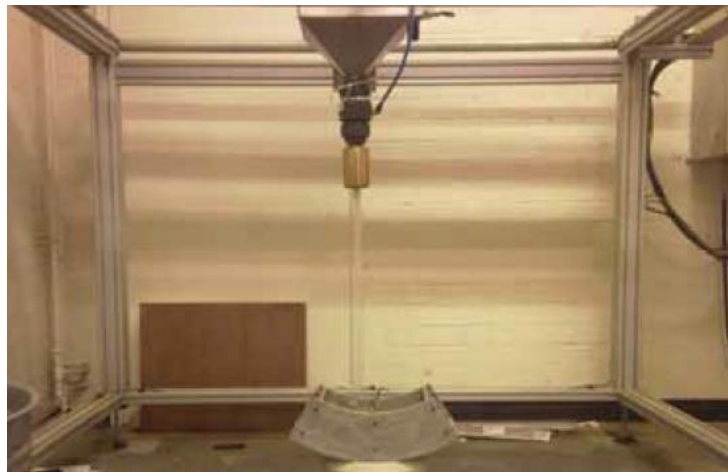


Figure 3-1 Automatic Sand Pourer (ASP) used to prepare backfill for centrifuge testing

The Mark II minidrum centrifuge in the Schofield Centre is suitable for the geotechnical physical modelling that is proposed in objectives in section 1.1. Figure 3-2 shows the centrifuge in operation. The maximum rotational speed of the minidrum centrifuge is 1067rpm which corresponds to 636g. A pivot on the minidrum enables the soil container to be fitted into the centrifuge channel in a convenient manner. This can then be rotated 90° on the pivot to the horizontal position for spinning. There is an inlet pipe to provide the water supply to the base of the ring channel in which the soil container is fixed. The water level increases and drains away within this ring channel through control of a standpipe, which is operated through an air motor. Further specifications of the minidrum centrifuge are outlined in Barker, (1998).



Figure 3-2 Mark II minidrum centrifuge

In order to facilitate the accurate recording of force and displacement data, the in-built computer on the centrifuge supplies up to 16 channels of data collection at up to 10kHz.

An actuator is fitted in order to enable radial movement. Its function is to provide the vertical uplift movement of the pipe throughout the investigation. It is fitted on the turntable in the centre of the minidrum centrifuge. The actuator operates at a constant speed of 0.1mm/s. The speed of the actuator itself can range from 0.002mm/s to 0.2mm/s. The stroke length is 120mm.

The design of the actuator assembly is unchanged from the setup of previous testing by Wang, (2012) but preliminary testing was carried out to ensure that a suitable setup was used. A linear variable differential transformer (LVDT) is connected to the actuator and is used to record the pipe displacement during the uplift process. The calibration factor of the LVDT is 15.52V/mm.



Figure 3-3 Actuator assembly fitted to the minidrum centrifuge (photo: Wang, 2012)

A load cell is attached to the actuator assembly and can easily be changed and/or relocated on the loading plate. The load cell used in the experiment is a tension-compression load cell, with a loading range rated $\pm 250\text{N}$. The load cell records the force exerted during uplift. Calibration measures were conducted using known hanging weights. The load cell showed a consistent calibration factor, with no hysteresis loops. The calibration data for a hang weight test is detailed in Table 3-1, with the trend line shown in Figure 3-4. The calibration factor for the load cell was 19.8N/V .

Loading step	Output Voltage (V)	Hang mass (kg)	Total Weight (N)
1	2.720	0	0
2	5.693	5.486	53.818
3	6.162	6.486	63.628
4	6.685	7.486	73.438
5	7.150	8.486	83.248
6	7.652	9.486	93.058
7	8.006	10.486	102.868
8	8.390	11.486	112.678
9	8.970	12.486	122.488
10	7.151	8.486	83.248
11	5.693	5.486	53.818

Table 3-1 Calibration data from hanging weights

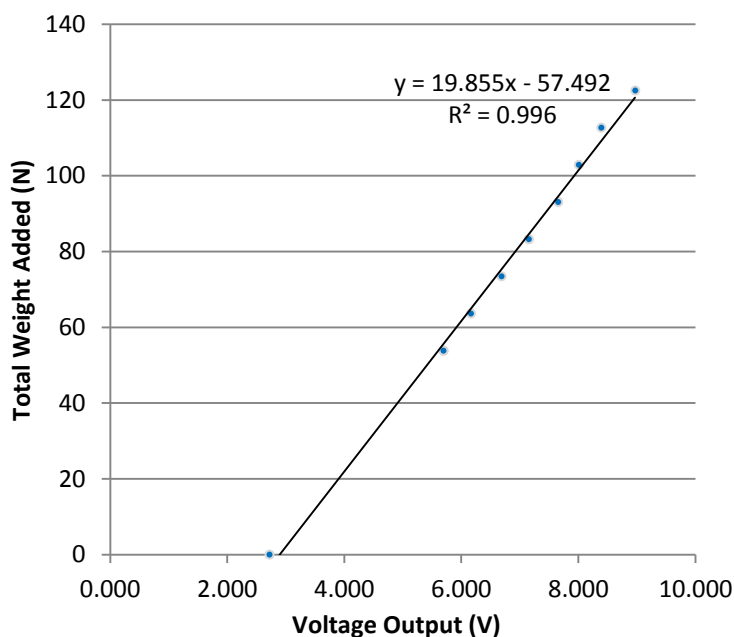


Figure 3-4 Calibration trend line

An observation from the preliminary testing is the potential source of error from the slip of the cables attached to the actuator. This error must not be ignored in analysis.

The design of the centrifuge container and pipe setup is similar to the setup of previous testing by Wang, (2012). The changes arise from differences in the investigation objectives, thus the setup for this experiment is detailed in Figure 3-5.

In order to investigate how well the centrifuge model predicts full-scale behaviour, model pipes of 6.3mm, 9.4mm, 12.7mm, 19.3mm, and 25.3mm are used. The 3mm pipe used for Wang's experiment is not used due to the associated D/D_{50} value of 6.4, which would not yield reliable results.

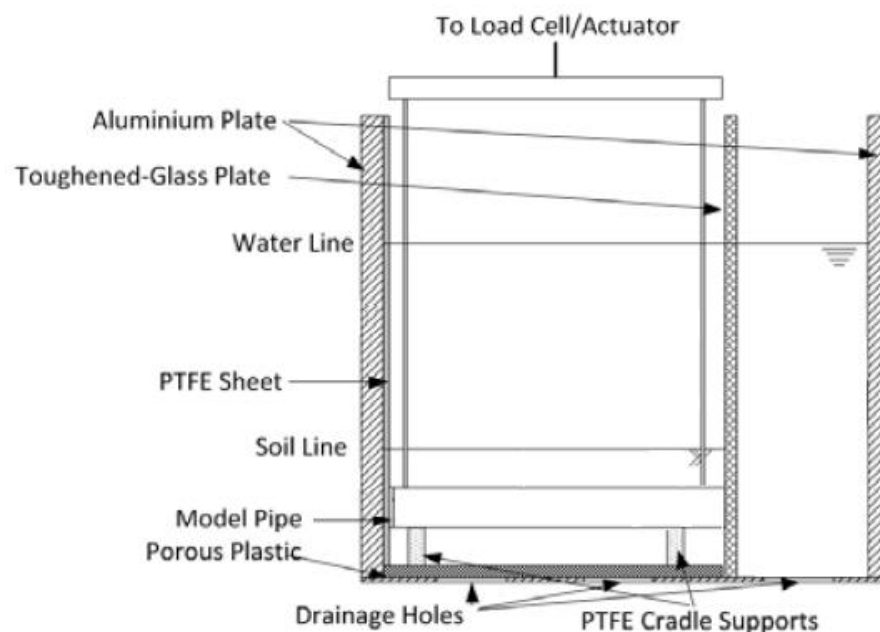


Figure 3-5 Cross sectional view of the centrifuge container set up (adapted from Wang (2012))

3.3 Experimental Setup

Figure 3-6 shows the testing apparatus design to perform small scale physical modelling in which to investigate the force displacement behaviour of buried pipelines under axial loading. The counterweight box must balance the submerged weight of the container, soil sample and model pipe in order to balance the centrifuge rotor. The model preparation and testing procedure is:

1. The load cell is calibrated. If the automated sand pourer is used, the nozzle size (7mm) and drop height ($z=20\text{mm}$) is fixed to achieve uniform relative density of 53% in the sand backfill. If the automated sand pourer is not used, the sand is poured manually from a height of 0.5m to achieve the same relative density.
2. Sand is poured up to the base of the cradle supports. The model pipe is placed on the supports, temporarily fixed in place using sticky aluminium tape.
3. Sand pouring continues until the desired cover is poured. The surface of the sand sample is wetted in order to induce a capillary suction inside the sandy backfill to hold the backfill in place prior to the centrifuge axis is rotated from horizontal to vertical
4. The model container and counterweight boxes are fixed into the centrifuge channel. The sticky aluminium tape is removed. The actuator is moved as necessary in order to attach the model assembly to the load cell on the loading plate.
5. All connections are checked to ensure the recording of force and displacement data is set up. A connection to the internal centrifuge computer is made.
6. The centrifuge is accelerated to 10g. Once the g-level has stabilised, water is added to the ring channel of the centrifuge until the water level is at least 10mm above the sand surface.

7. The centrifuge acceleration is increased to the desired g-level.
8. Once stabilised, data recording commences and the model pipe is pulled out at a constant rate of 0.1mm/s, as set by the actuator settings, until the model pipe is completely above the soil surface. This process is illustrated in Figure 3-7
9. On completion of the pipe displacement, the standpipe is lowered to drain the water at 30g. The centrifuge can then be stopped.

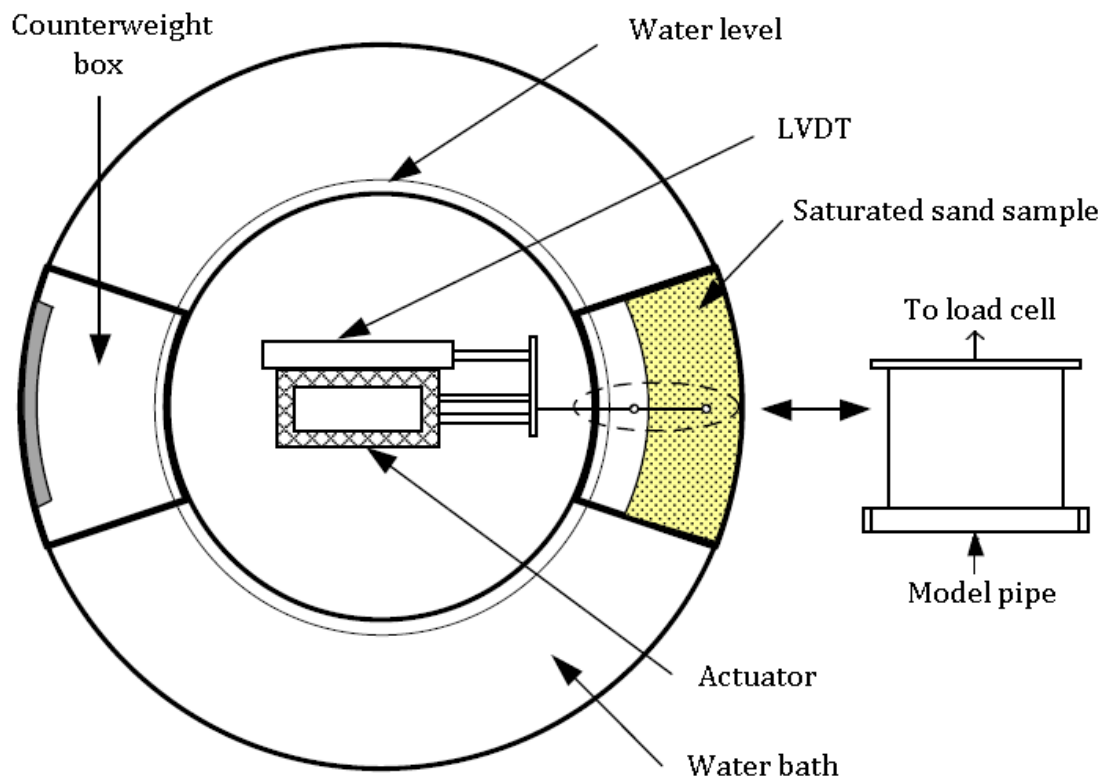


Figure 3-6 Schematic illustration of the centrifuge model setup (Wang, 2012)



(a)



(b)



(c)



(d)

Figure 3-7 The model pipe assembly in operation in the centrifuge (a) the model pipe assembly under stable g-level conditions, (b) and (c) the model pipe is just visible as it is pulled out of the sand at constant rate, (d) the pipe is completely above the soil surface.

3.4 Testing Program

The minidrum centrifuge test program is summarised in Table 3-2. 11 tests were conducted in the test series. Tests 01-06 investigate the effect of soil cover depth in saturated medium dense sand at 30g. An 8.6mm diameter **model** pipe is equivalent to a 258mm diameter pipe at **full scale**. This corresponds to a maximum **full scale** cover in the field of 2.58m at a H/D ratio equal to 10. Test 07-11 focus on the scaling effects of the centrifuge.

Test No.	Backfill	g-Level (g)	H/D	D _m (mm)
01	Hostun Sand (D ₅₀ =0.42, I _D =53%)	30	1.5	8.6
02			2	
03			4	
04			6	
05			8	
06			10	
07		41	2	6.3
08		30		8.6
09		20.4		12.7
10		13.4		19.3
11		10.2		25.3

Table 3-2 Testing Schedule

4 RESULTS AND DISCUSSION

4.1 Centrifuge monotonic uplift testing results in saturated sandy backfill

Salient values for the prototype scaled measured uplift force-displacement data for Tests 01-11 are detailed in Table 4-1.

Test No.	Backfill	G-Level	H/D	D_m (mm)	R_{peak} (kN/m)	Mobilisation distance δ_f (mm)
01	Hostun Sand ($D_{50}=0.42$, $I_D=52.7\%$)	30	1.5	8.6	1.10	30
02			2.0		4.3	35
03			4.0		8.30	50
04			5.8		9.80	180
05			8.1		33.50	130
06			9.8		43.50	280
07	Hostun Sand ($D_{50}=0.42$, $I_D=52.7\%$)	41	2.0	6.3	3.35	35.3
08		30	2.0	8.6	4.3	35
09		20.4	2.0	12.7	4.62	30
10		13.4	2.0	19.3	4.54	38
11		10.2	2.0	25.3	4.15	26

Table 4-1: Summary of R_{peak} and δ_f results from centrifuge monotonic uplift results

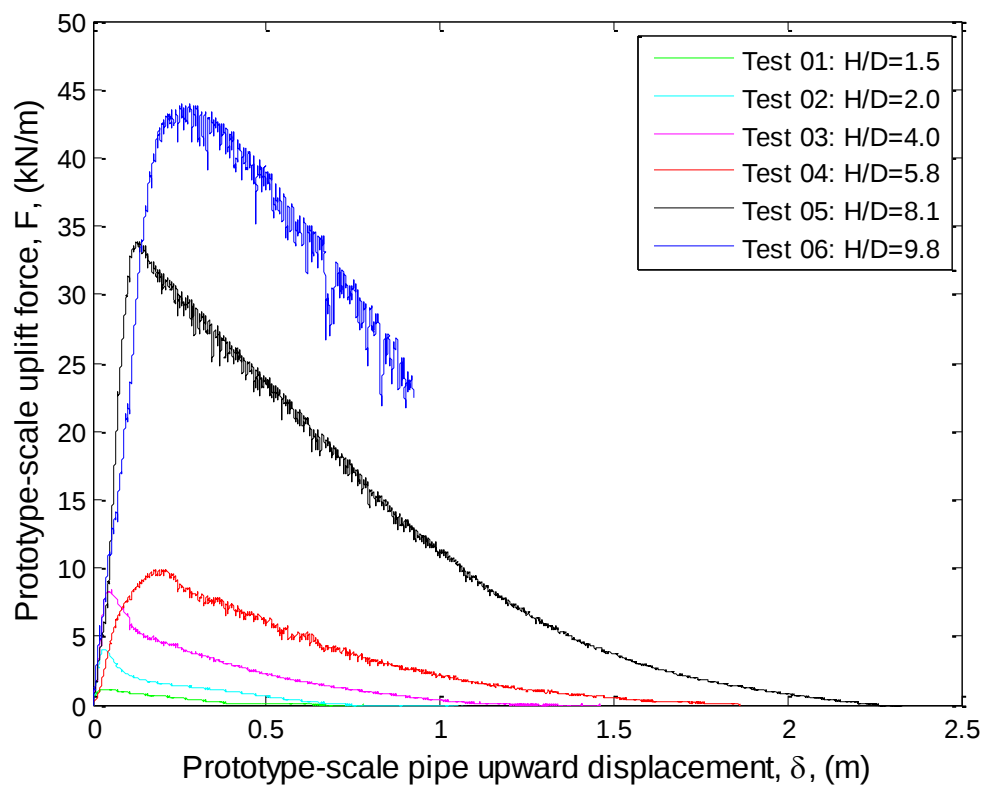


Figure 4-1: Prototype scale Force Displacement Curve at different H/D values at 30g

Centrifuge monotonic uplift tests at different H/D values at 30g (Test 01-06) are plotted in Figure 4-1.

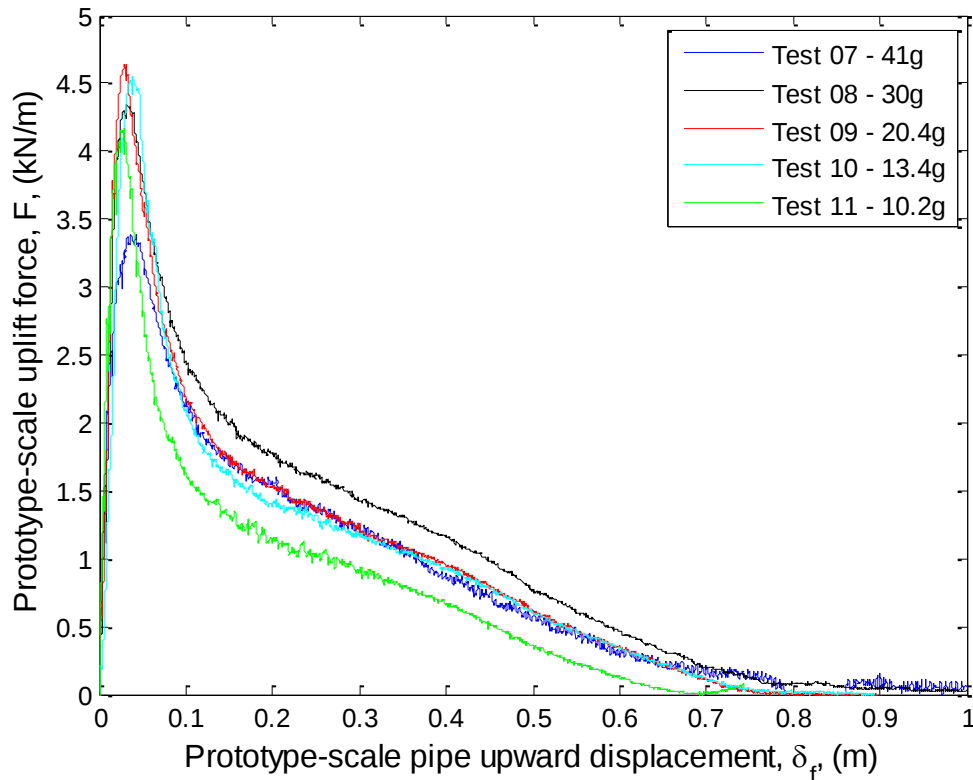


Figure 4-2 Prototype scale force displacement curve at different g-levels at H/D=2

Figure 4-2 shows the prototype scaled measured uplift force-displacement data for centrifuge tests for H/D=2 at different g-levels (Tests 07-11).

The data from tests 01-11 have been manipulated to account for the error due to cables in the actuator slipping as mentioned in section 3.2. Test 01 and 04 appear anomalous and would need to be repeated for a complete set of results. They have not been included in further analysis.

4.2 Soil Characteristics

Figure 4-3 shows the characteristics of Hostun sand with respect to the model of the tri-linear force-displacement curve. The experimental data is significantly softer, regarding mobilisation distance, than would normally be predicted for design. This highlights that the mobilisation distance is greater than the DNV codes predict, supporting research by Wang, as referenced in section 2.3, implying that the DNV designs are potentially unconservative, being based on excessive stiffness.

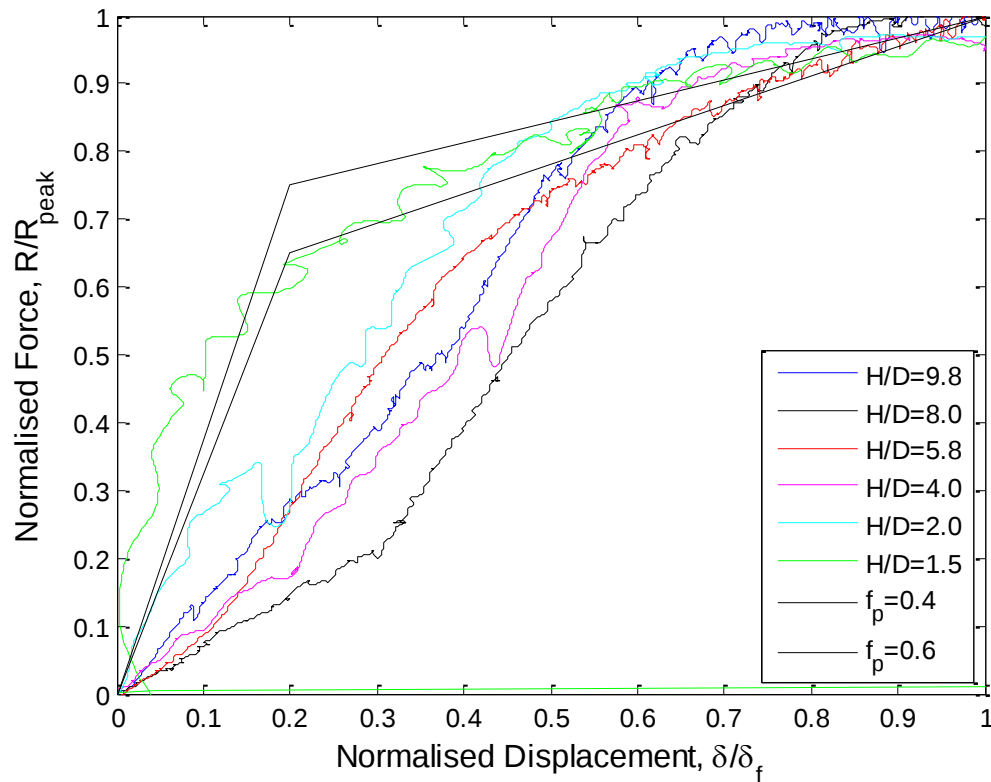


Figure 4-3 Experimental data following the tri-linear force-displacement curve

4.3 Prediction for R_{peak}

As detailed in Table 2-1 in section 2.3.2, the design code DNV-RP-F110 (2007) incorporates uncertainty. The current practice limits R_{peak} to the weight of soil column above the pipe rectangle for design based on H/D values between 2 and 8. The plot in figure 4-4 shows the trend lines corresponding to the minimum and maximum f_p , according to Equation 2-4 and the design range defined in the offshore design code (Table 2-1), and the average f_p from the experimental data. The salient values are detailed in Table 4-2.

H/D	f_p
2	0.7185
4	0.4255
8.1	0.5834
9.8	0.5352

Table 4-2 f_p values corresponding to experimental data at 30g

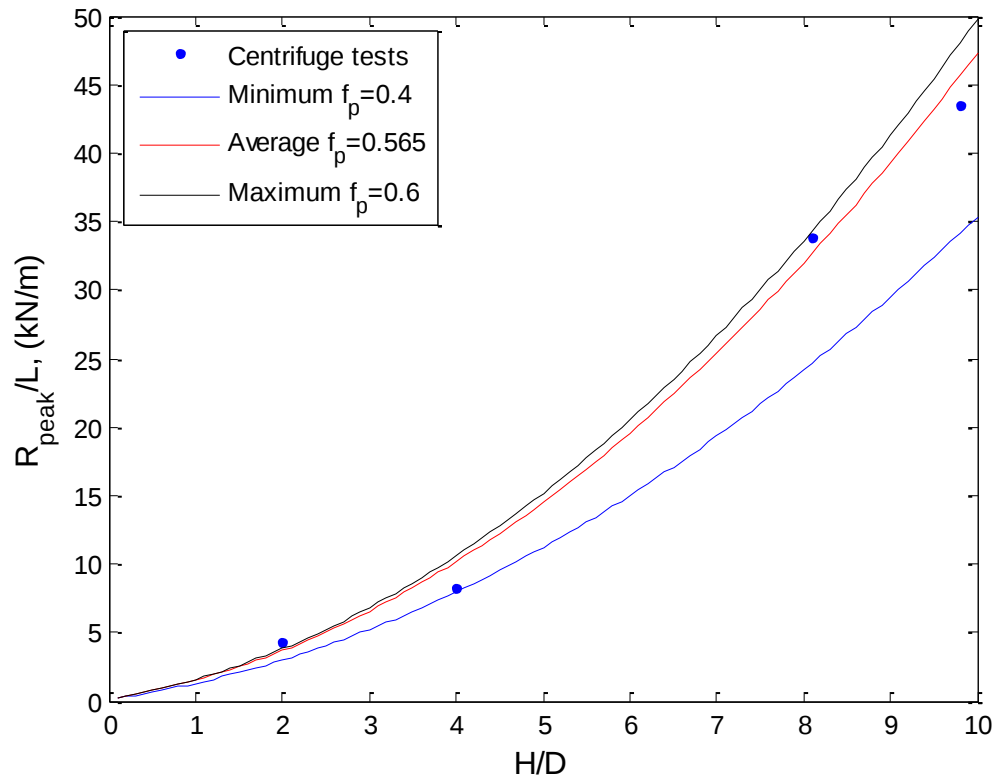


Figure 4-4 Experimental R_{peak} data at 30g compared with predictions from Equation 2-4

Table 4-2 and Figure 4-4 show that the experimental data does agree with the predicted trend from Equation 2-4. There is some scatter present in the data, but the data does suggest that a value for f_p , the Pedersen uplift factor, should be between 0.4 and 0.8 for medium/dense sand, as opposed to the DNV codes proposal defining a range of f_p between 0.4 and 0.6, as tabulated in section 2.3.2.

The experimental data was extended beyond the defined range of H/D proposed by DNV-RP-F110 of H/D between 2 and 8 for medium/dense sand. Test 06 investigated the effect of $H/D = 9.8$. The experimental data for Test 06 agrees with the trend proposed by the Pedersen design equation (equation 2-4). This agreement suggests that the mechanism for pipeline uplift does not change for H/D values up to 10.

4.4 Prediction for mobilisation distance

The current design practice DNV-RP-F110, (2007) details that the mobilisation distance, normalised with H , δ_f/H , should give values between 0.5% and 0.8%, and that the value should be independent of H/D . As described in section 2.3 the design code DNV-RP-F110 (2007) provides an unconservative prediction for the mobilisation

distance for a sand 2.6 times as fine as the sand in this investigation, $D_{50} = 0.18\text{mm}$ and $D_{50} = 0.47\text{mm}$ respectively.

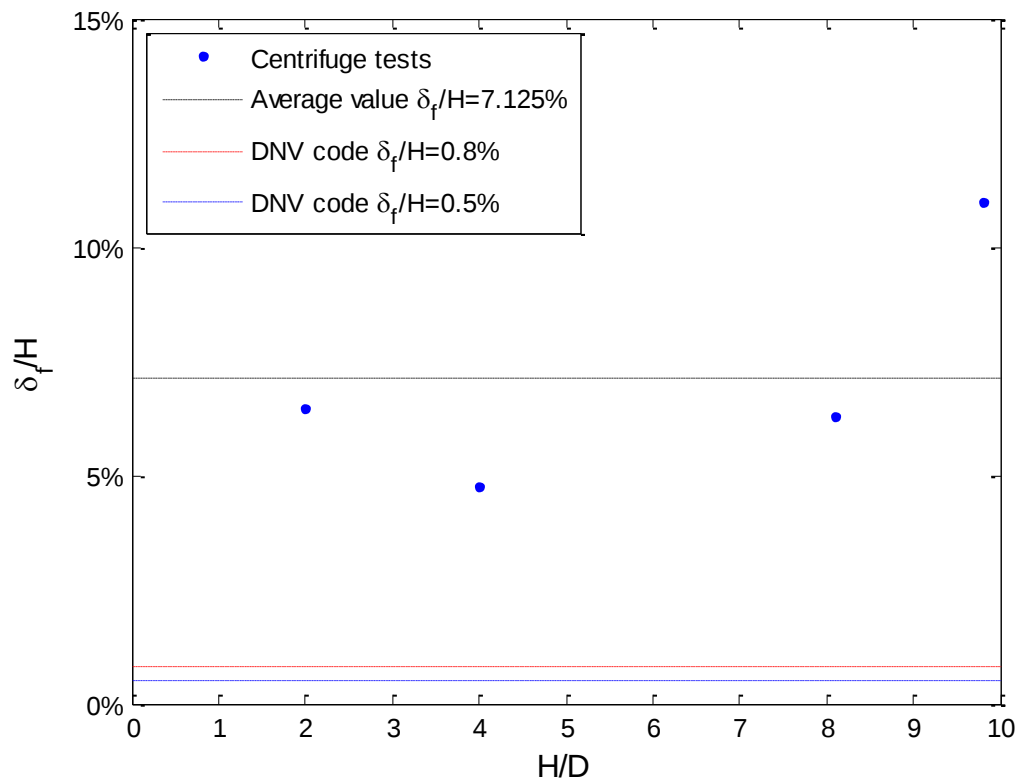


Figure 4-5 Plot of δ_f/H values against H/D for 30g scale tests

For a sand of $D_{50} = 0.18\text{mm}$, at full scale, the average value of δ_f/H is 2.5% (at H/D values that are relevant to this investigation), as illustrated by figure 2-3 in section 2.3.3. The experimental data from this particular soil under investigation, $D_{50} = 0.47\text{mm}$, lies above that expected from Wang's full scale data, with the average value of δ_f/H at 7.5%. Hence, the δ_f/H found for this centrifuge data is three times greater than the expected δ_f/H value from Wang's full scale data.

The hypothetical exponential relationship, $\frac{\delta_f}{D} = 0.02e^{\left(\frac{1}{2}\frac{H}{D}\right)}$, Wang, (2010) is derived from a limited number of physical model tests from previous published results. Given the scatter in the experimental data, figure 4-6 shows the data of physical models at 30g is broadly in agreement with this relationship proposed by Wang, which is based on the larger data set.

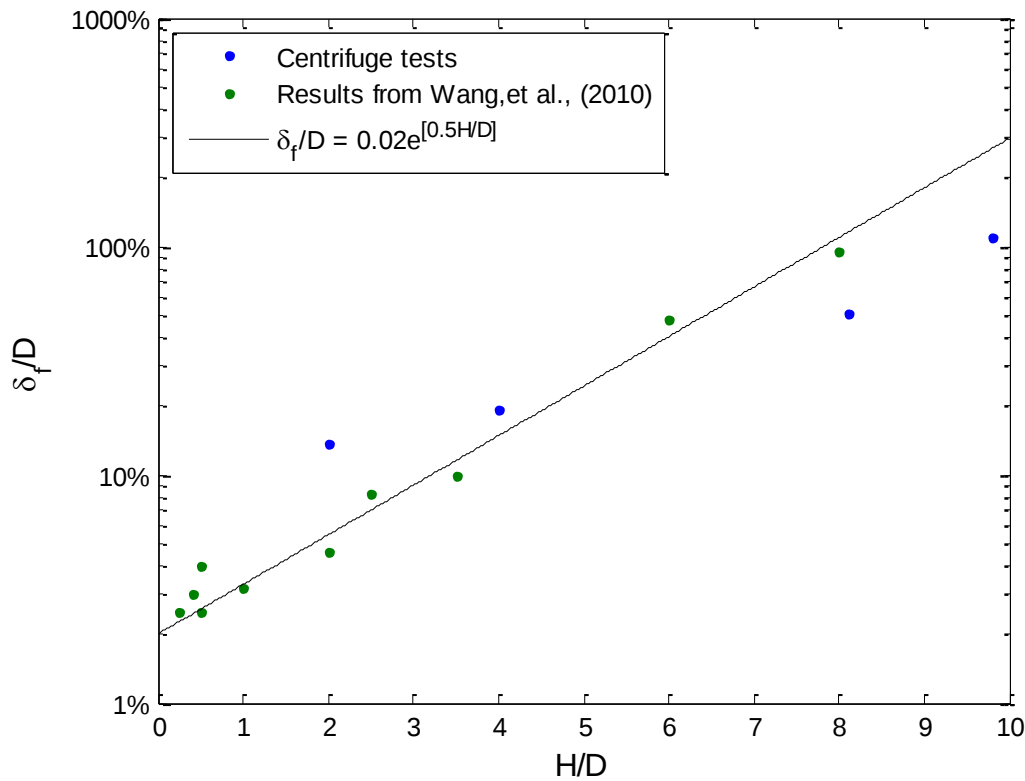


Figure 4-6 Plot of δ_f/D values against H/D for 30g scale tests in this investigation and results from Wang, et al. (2010). A trend line proposed on larger data set $\frac{\delta_f}{D} = 0.02e^{\left(\frac{1}{2}\frac{H}{D}\right)}$ proposed by Wang is also plotted.

Yet, a large proportion of the results from Wang, et al., (2010) is concentrated at H/D values between 0 and 4. The data from this experiment is consistent with the trend line but at high values of H/D , δ_f/D values fall below this trend line. Experimental error, due to slack in the actuator system, for example, is unlikely to reason this, as these errors would overestimate δ_f/D . This suggests that δ_f/D is starting to flatten off at high H/D values.

4.5 Modelling of physical models in uplift resistance tests in sands

Tests 07-11 simulate the same prototype design, i.e. a full scale, monotonic uplift scenario of $D = 258\text{mm}$, $H/D = 2$ in saturated Hostun sand with $I_D = 53\%$. This test series allows the ability of the centrifuge to predict full scale behaviour to be investigated.

4.5.1 Variation of R_{peak} across centrifuge g-levels

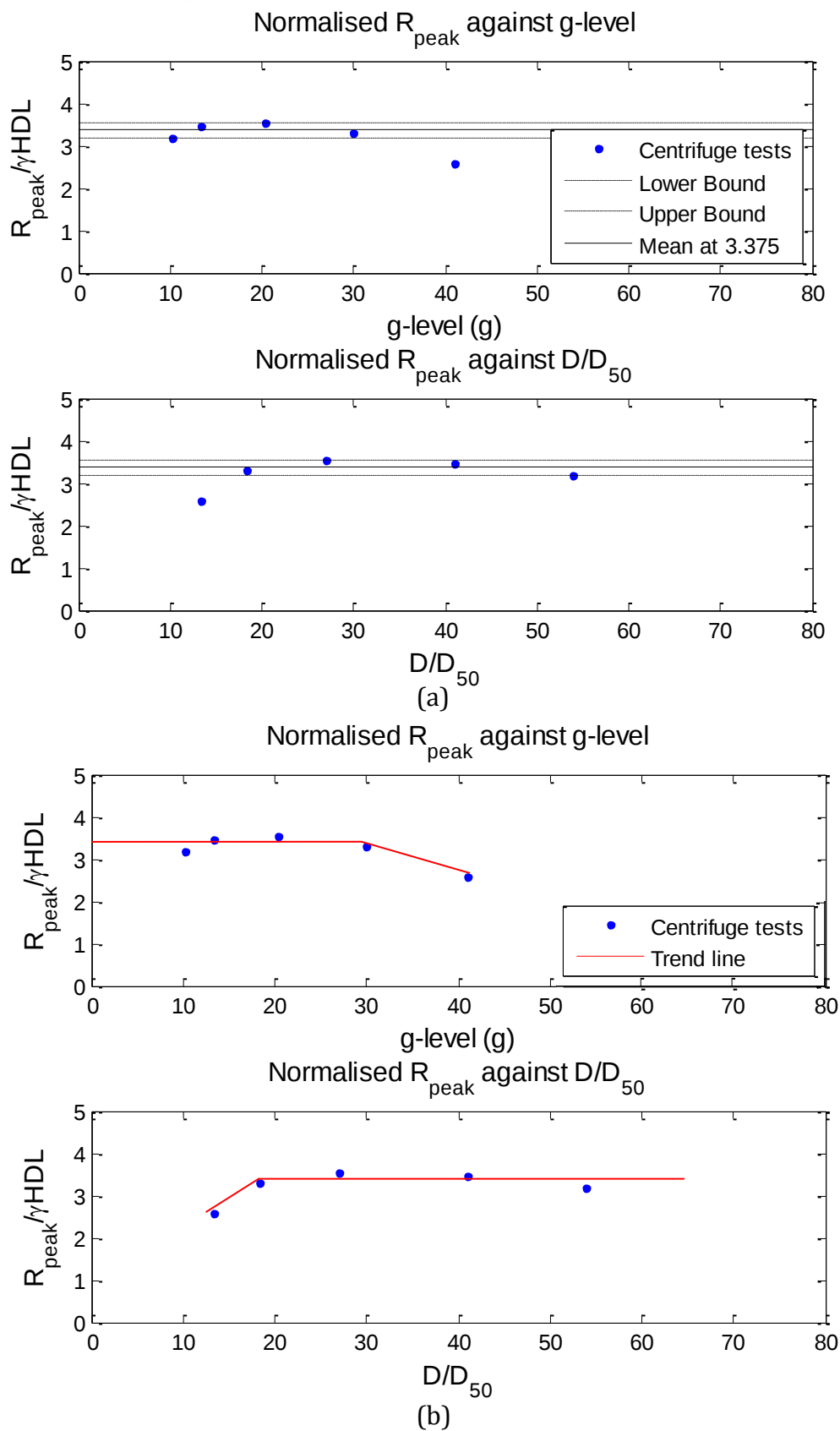


Figure 4-7 Plot of $\frac{R_{peak}}{\gamma'_{HDL}}$ versus g-level and versus $\frac{D}{D_{50}}$ for Tests 07-11 alongside (a) constant lines (b) a trend line to highlight the drop in $\frac{R_{peak}}{\gamma'_{HDL}}$

Figure 4-7(a) highlights that modelling design scenarios at different g-levels does not significantly affect the normalised peak uplift force, provided that $D/D_{50} > 18$. However, figure 4-7 (b) illustrates that, at $D/D_{50} < 18$, the value of the normalised peak uplift force falls. This agrees with previous work by Wang, (2012) stating the D/D_{50} value should be approximately 20. This is also consistent with work on shallow foundations by Ovesen (1979) that the ratio of foundation diameter to grain size should be more than 15. Further experimentation should take place at a higher g-level, say 40g, to confirm this falling trend.

4.5.2 Variation of δ_f across centrifuge g-levels

With the available peak uplift resistance not significantly affected by g-level, provided that $D/D_{50} > 18$, it would be interesting to see if this is applicable for δ_f . This is investigated in Figure 4-9 where the conventional interpretation of δ_f ($\delta_m \times N$) is plotted against the centrifuge g-level (N) and D/D_{50} respectively. The prototype scale mobilisation distance, δ_f , is normalised against the mobilisation distance at full scale $\delta_{f,prototype,1g}$. Since no full scale test was carried out in this investigation, the centrifuge data for Test 07-11 is normalised against an estimate of $\delta_{f,prototype,1g}$. The estimate is taken to be 25mm based on the full scale tests carried out by Wang (2012), as indicated in figure 2-3 in section 2.5.3. The trend line for the experimental data is plotted. The trend line for similar data for a sand of $D_{50} = 0.14\text{mm}$, Wang (2012) is also plotted.

There is scatter present in figure 4-9. As mentioned in section 4.5.1, values associated with $D/D_{50} < 18$ show deviation from the prototype value. Hence, the data point labelled (2) in figure 4-9, with an associated value of $D/D_{50} = 13.4$, is unreliable.

The value of D/D_{50} corresponding to data point (3) is 18.3. This value borders the ideal limit for sensible centrifuge modelling of $D/D_{50} = 18$. Although the normalised peak uplift force estimate for data point (3) is consistent with the rest of the experimental data set, there is reason to suggest that the normalised $\delta_{f,prototype}$ value for data point (3) is also an underestimate.

Data point (1) in figure 4-9 appears to be an overestimate. Looking at the force-displacement curve in figure 4-8 for this data point, contraflexure is observed.

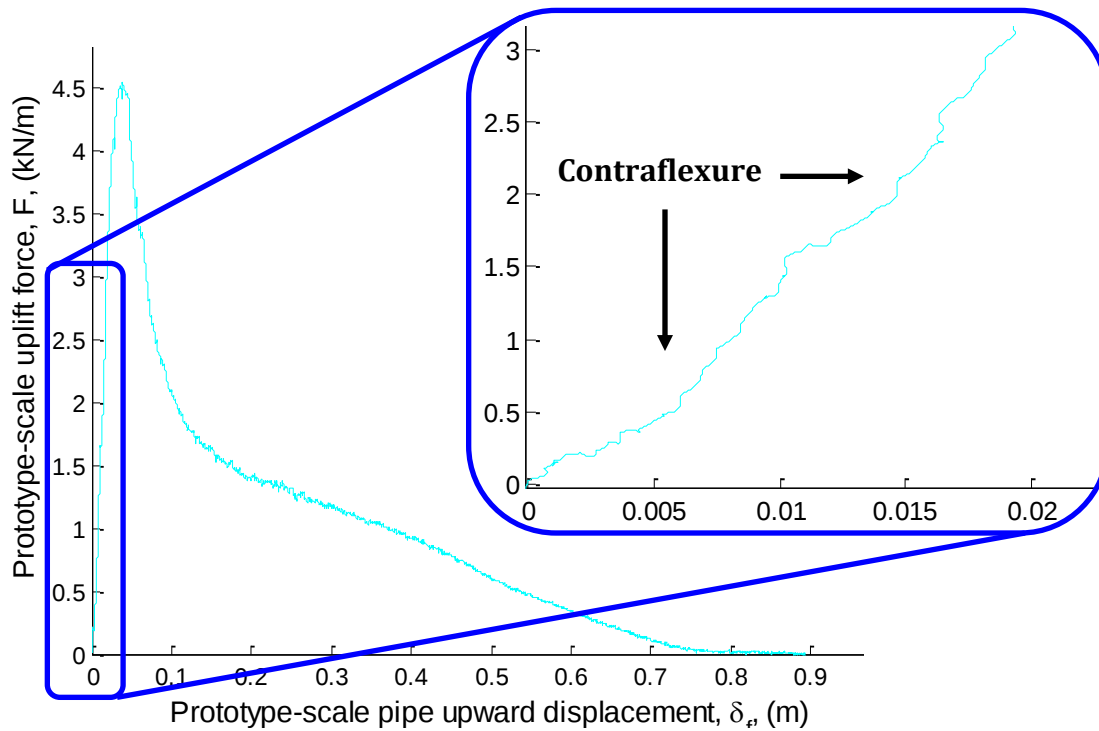


Figure 4-8 Contraflexure observed in the force displacement curve in Test 10 at 13.4g

If the curve was shifted to the left to make an allowance for the effect of contraflexure, the data value would be lowered, as indicated by the arrow on figure 4-9.

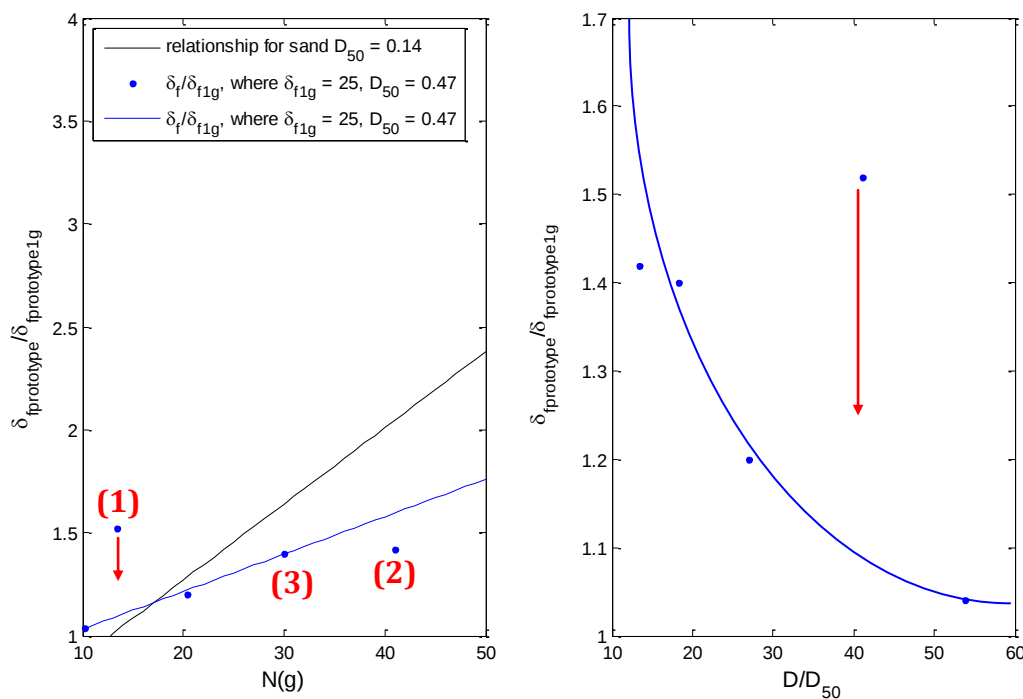


Figure 4-9 Variation of $\delta_{f,prototype}/\delta_{f,prototype,1g}$ values with g-level and D/D_{50} values, where $\delta_{f,prototype,1g} = 25\text{mm}$

Whilst also taking into consideration the unreliability of data points (1) and (2), it is possible to plot a potential trend line of the experimental data. It is important to note that the strength of the data is relatively weak. Further experimentation should be carried out to increase the reliability of the trend, as recommended in section 5.

The weak trend line plotted in figure 4-9 suggests that the experimental data has less of a scaling effect than the finer sand investigated by Wang (2012). It would be expected that a bigger sand particle size would result in a bigger scaling effect. A potential source of error is the assumption that $\delta_{f,prototype,1g}$ is 25mm, as based on full scale testing on loose sand of $D_{50}=0.14\text{mm}$, $I_D=30\%$.

Figure 4-10 shows the variation of $\delta_{f,prototype}/\delta_{f,prototype,1g}$, when different values of $\delta_{f,prototype,1g}$ are considered. It shows the effect of altering the value of $\delta_{f,prototype,1g}$, to try and fit the trend line of Wang (2012). An estimate of $\delta_{f,prototype,1g} = 20\text{mm}$ promotes a trend-line with a similar scaling effect to Wang's data over the 30g – 40g range. But no dramatic change in the slope gradient is observed by altering the value of $\delta_{f,prototype,1g}$. The experimental data doesn't agree with previous research by Wang (2012).

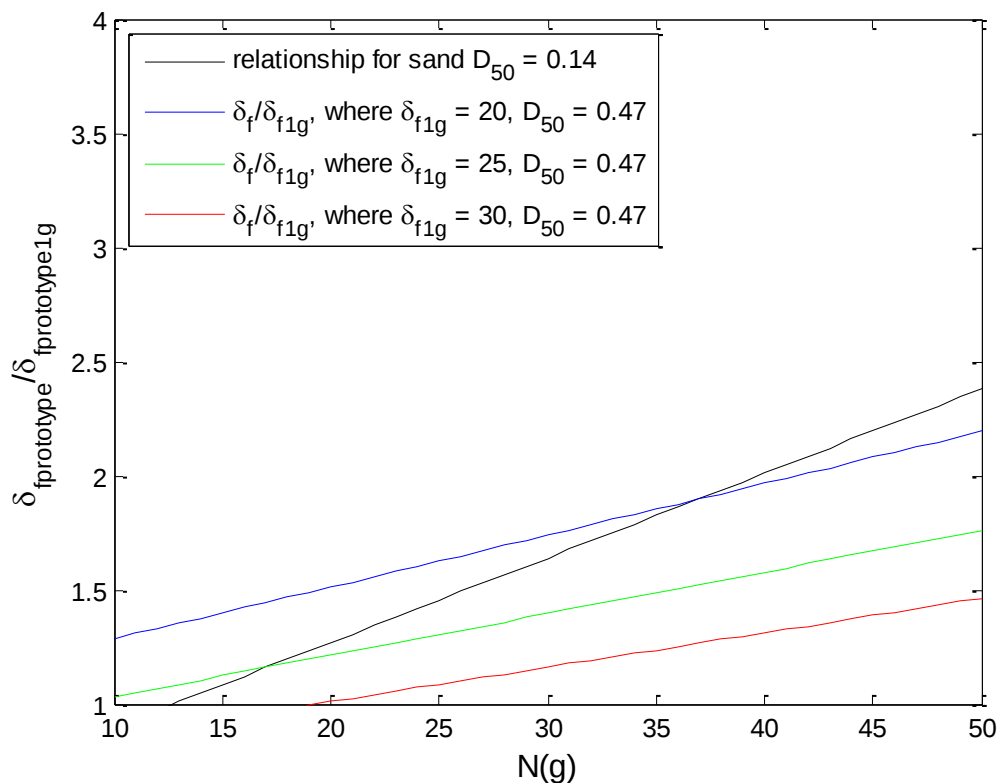


Figure 4-10 Comparison of $\delta_{f,prototype}/\delta_{f,prototype,1g}$ against g-level for a sand, $D_{50}=0.14\text{mm}$, and at various values of $\delta_{f,prototype,1g}$ for a sand $D_{50}=0.47\text{mm}$

It is, however, reasonable to conclude that the mobilisation distance does increase with increasing centrifuge g level.

The disparity between the gradient for the experimental data in this investigation, and the experimental data for Wang, (2012) might be the effect of differing relative density values, $I_D=50\%$ and $I_D=30\%$ respectively, or different sand types, Hostun sand and Fraction E sand respectively.

5 CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

5.1 Conclusions

Monotonic pipeline uplift force-displacement relationship in cohesionless soils

- The experimental data is significantly softer, regarding mobilisation distance, than would normally be predicted for design. This highlights that the DNV design is unconservative, being based on excessive stiffness.
- Experimental data from this investigation suggests that the current industry practice to predict the maximum uplift resistance is valid for a H/D ratio between 2 and 10. This suggests the mechanism for pipeline uplift does not change for H/D values up to 10.
- Data obtained from this investigation suggests that the value for f_p , the Pedersen uplift factor is between 0.4 and 0.8 in medium dense sand.
- If the mobilisation distance at R_{peak} , δ_f , is normalised with H, the resulting δ_f/H values range between 5% and 10% for H/D between 2 and 10, and 5% and 7% for H/D between 2 and 8. The experimental results do not support DNV-RP-F110 (2007)'s guidelines that $\delta_f \in [0.5\%H, 0.8\%H]$. The δ_f/H found for this centrifuge data is 2.5-3x greater than the expected δ_f/H value from Wang's full scale data. The soil in the centrifuge data is 2.5x coarser than the soil under investigation in Wang's research.

Modelling of physical models in monotonic pipeline uplift in cohesionless soils

- For $D/D_{50} > 18$, $\frac{R_{peak}}{\gamma'_{HDL}}$ does not vary significantly with N or D/D_{50} , hence centrifuge modelling can provide a reliable prediction for the maximum available uplift resistance, R_{peak} in the same model backfill as the prototype. At $D/D_{50} < 18$, the model underestimates the prototype estimate for R_{peak} .

5.2 Further Work

Continued research on monotonic pipeline UHB in cohesionless soils

- If δ_f is normalised with D , the experimental data is broadly in agreement with the hypothetical exponential relationship $\frac{\delta_f}{D} = 0.02e^{\left(\frac{1}{2}\frac{H}{D}\right)}$, proposed by Wang, (2010). The data does suggest that δ_f/D is starting to flatten off at high H/D values. Further experimentation at higher H/D values would be required to strengthen this hypothesis to provide a better model over the practical H/D range.
- More physical testing and analysis should take place to try to provide a more defined range of f_p values, or determine a reliable expression for f_p in terms of common geometric and soil mechanics parameters such as I_D , ϕ_{crit} , H/D , D/D_{50} .

Continued research on modelling physical models

- If $\delta_{f,prototype}$ is normalised with a predicted value of $\delta_{f,prototype,1g}$ a trend line is observed which highlights that centrifuge modelling does magnify the interpreted prototype-scale δ_f values. Based on the experimental data available, the trend line does not agree with research by Wang (2012). This disparity might be the effect of differing relative density values, $I_D=50\%$ and $I_D=30\%$ respectively, or different sand types, Hostun sand and Fraction E sand respectively. Hence, a much denser sand, say $I_D = 80\%$, should be investigated. Additionally, in order to strengthen the experimental trend line, an identical test at full scale should be carried out to find the value of $\delta_{f,prototype,1g}$ and further centrifuge tests should be carried out, where $D/D_{50} > 18$. This further experimentation will help draw stronger comparisons and thus attempt to form conclusions on the effect of particle size.
- In order to confirm the trend that $\frac{R_{peak}}{\gamma'_{HDL}}$ does not vary significantly with N for $D/D_{50} > 18$, a centrifuge test at a higher g -level, say 50g should take place.

6 REFERENCES

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7 APPENDIX A

7.1 Risk Assessment Retrospective

The initial risks highlighted at the beginning of the project were associated with mechanical and electrical equipment, primarily the automated sand pourer and the minidrum centrifuge. Appropriate training was given for equipment use. No additional hazards were encountered throughout the project and so the original risk assessment can be deemed adequate.