Inclined and Uplift Resistance of Pipelines Buried in Rock

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ABSTRACT

Offshore pipelines are often buried to provide (i) thermal insulation, (ii) protection from anchor dragging or trawling and (iii) protection from scour or hydrodynamic loading. Compressive forces in the pipeline associated with transportation of hot fluids tend to cause the pipeline to buckle, which is resisted by the overburden stress from the burial material. Quantifying both the magnitude of the resistance to buckling and the pipeline movement to mobilise this resistance are important for design. Much of the effort in this area has focused on understanding this behaviour for upheaval buckling, where the pipeline moves vertically –less attention has been given to the scenario where the pipeline movement is lateral or inclined.
This paper reports results from a program of tests in which pipeline sections buried in trapezoidal rock berms were pulled out at different load inclinations. The tests considered a 0.2 m diameter pipe buried up to 1.2 m deep in rock, with variations in the (rock) cover widths, cover heights and load inclinations.
Results show that the resistance during inclined pullout is significantly greater than during vertical pullout. The resistance is also enhanced by higher and wider rock cover. The results allow part of a failure envelope, in vertical-horizontal load space to be assessed, quantifying this influence of pullout direction.

Keywords: offshore pipelines, model testing, centrifuge, rock berms, load inclination

INTRODUCTION

Offshore pipelines may be buried in rock to provide: (a) scour protection, (b) impact protection from dropped objects, (c) secondary stabilisation from local environment loading, and (d) restraint to pipeline buckling associated with thermal expansion. The latter aspect is the subject of this paper. Much attention has been given to the uplift resistance provided by rock berms when the direction of uplift is vertical (e.g. DNVGL 2019). However, a pipeline may tend to breakout under an inclined direction, depending on the distance from the pipeline to the free-surface of the berm, which will be controlled by the level of pipeline cover and the berm geometry. Limited studies have aimed to quantify the level of resistance afforded by the rock berm for conditions other than pure vertical loading, and have relied primarily on numerical modelling (Eiksund 2015, Ballard et al. 2014). In addition, uplift resistance – and the pipe displacement associated with mobilisation of this resistance – is typically quantified by dimensionless groups that use pipe embedment, H, and pipe diameter, D, in the normalisation (Williams et al. 2015). Confidence that these dimensionless groups – which are mainly established from reduced scale model testing at low stress levels – may be applied at full scale and to rock rather than sand, requires an assessment of the potential for scale effects to influence the results. This paper considers both uncertainties through a series of centrifuge tests where the pipe was buried in rock berms of different geometries and subjected to loading in different directions. In addition, parallel large scale tests were conducted in a new test rig. Comparison of these two test programs allows scale effects to be examined.

EXPERIMENTAL DETAILS

Overview

The centrifuge tests were conducted at The National Geotechnical Centrifuge Facility located at The University of Western Australia. The experiments were performed at 1:15 reduced scale of a particular prototype pipeline design, with the rock gravel sizes and grading chosen to achieve a close match with a rock grading curve used in practice. These centrifuge experiments formed part of a larger testing campaign that also involved half-scale pipe tests (at single-gravity). Whilst the focus of this paper is reporting of the centrifuge results, a comparison of the centrifuge and large scale test data is included later in the paper.

A schematic of the test scenario is provided in Fig. 1. In the actual tests, the side slope of the berm away from the direction of pipe movement was omitted (shown by the dotted box in Fig. 1) to optimize the testing volume available within the sample container. The parameter variations were the: (i) rock berm height above top of pipe (H = 0.6, 1.0, 1.2 m at full scale ('prototype')) and (ii) loading direction (α = 10°, 30°, 60° and 90° (vertical)).

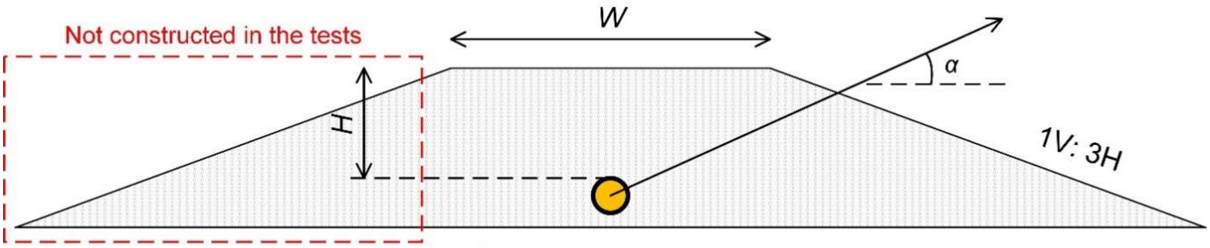


Fig. 1. Schematic of test scenario (not to scale, prototype pipe dimensions).

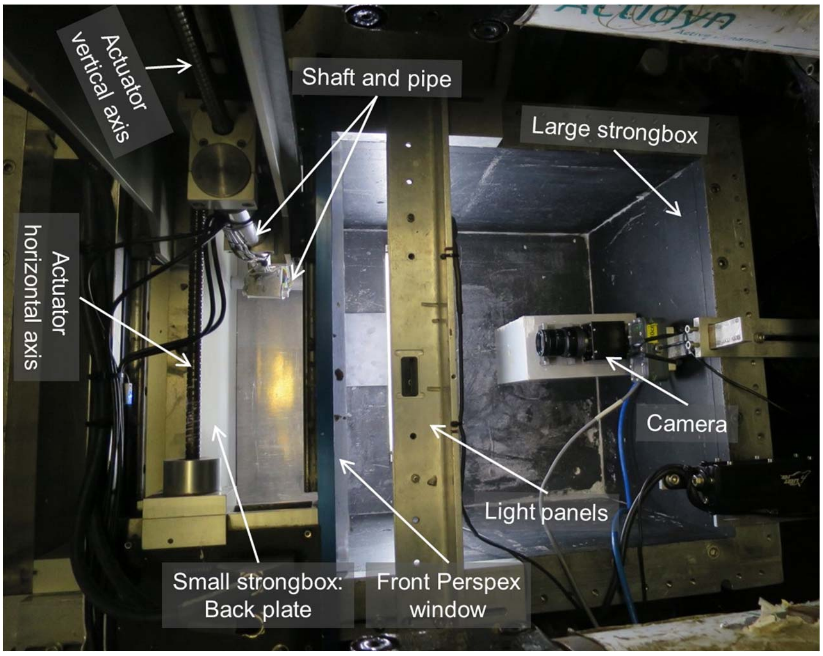
The centrifuge experiments were conducted at 15g using the National Geotechnical Centrifuge Facility's 40 g-tonne, 3.6 m diameter fixed beam centrifuge. As shown in Fig. 2, the centrifuge tests were carried out in a sample container (or 'strongbox') that was located at one extremity of a larger strongbox, with the other extremity used to locate a five-megapixel resolution machine vision camera and lighting, both controlled using in-house software (Stanier & White, 2013). The smaller strongbox was partitioned to create a space for the model with internal dimensions of 338 mm by 100 mm in plan and 299 mm in depth. The vertical end walls had transparent viewing windows, which allowed observation of movements in the rock.

The model pipe fabricated for the centrifuge testing (shown in Fig. 3) has a diameter, D = 15 mm and an assembled length, L = 99 mm. The length is slightly less than the test container width of 100 mm, which allows some clearance between the pipe ends and the side plates and thus avoids side friction during testing. The model represents a prototype pipe, 0.225 m in diameter under the testing acceleration level of 15g and a length to diameter ratio of larger than 6. The pipe was sand blasted to achieve a surface mean roughness of $R_a \approx 4.0$ µm.

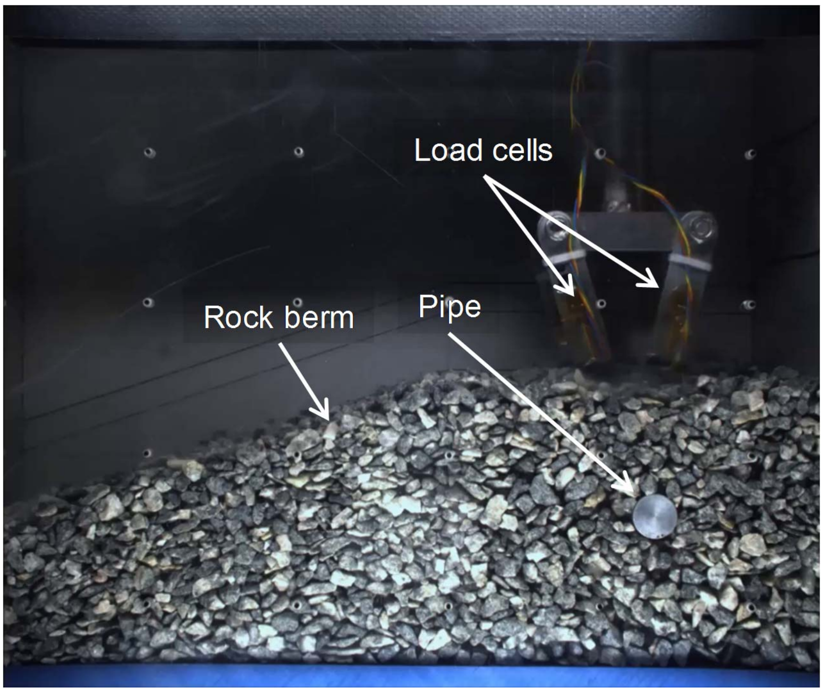
To measure both horizontal and vertical resistance forces when the pipe is moving out of the rock, four custom-designed plate load cells were fabricated (see Fig. 3), each with a strain gauge output capacity of 2 kN. These load cells were assembled together with the pipe arranged in a 'V'-shaped frame (Fig. 3b). As such, each plate experienced only tensile or compressive forces during testing. The resultant horizontal and vertical forces acting on the pipe, F_x and F_y, can be estimated based on a simple geometric relationship:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} \sin(\theta/2) & 0 \\ 0 & \cos(\theta/2) \end{bmatrix} \begin{bmatrix} -1 & 1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \tag{1}$$

where $\theta = 30^{\circ}$ is the intersection angle of the frame at the location of the pipe. F_1, F_2, F_3 and F_4 are compressive or tensile forces experienced in the four plates respectively, with positive direction in tension. As the load cells were subjected to locked-in loads during assembly of the frame, the frame was calibrated after assembly by applying forces on the centre of the pipe in different directions, rather than calibration of the plate load cells individually.



(a)



(b)

Fig. 2. Experimental arrangement for the centrifuge tests: (a) top view, (b) front view

The frame (and hence the model pipe) was manipulated using an electro-mechanical actuator that was mounted on the large strongbox. The actuator controls movement independently along vertical and horizontal axes. Driving these axes at different velocities allowed different directions of motion to be imposed on the pipe.

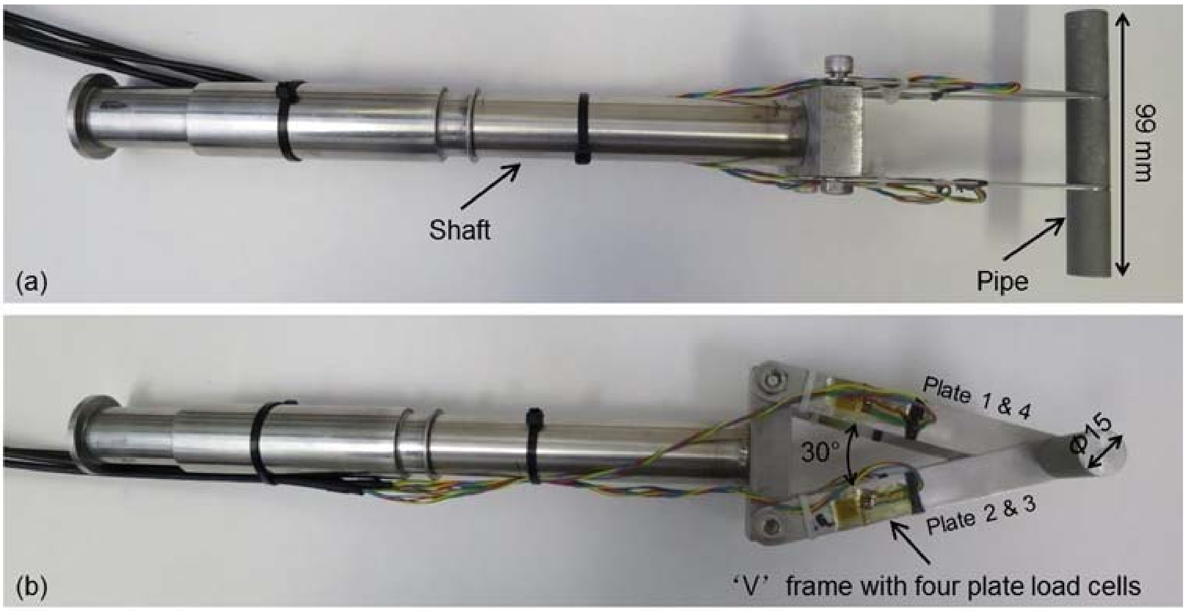


Fig. 3. Centrifuge model pipe and instrumentation: (a) top view (b) side view

Rock material

The rock material used for the centrifuge experiments was a scaled version of rock typically used for pipeline protection. The target and scaled grading curves are provided in Fig. 4, with engineering properties summarised in Table 1.

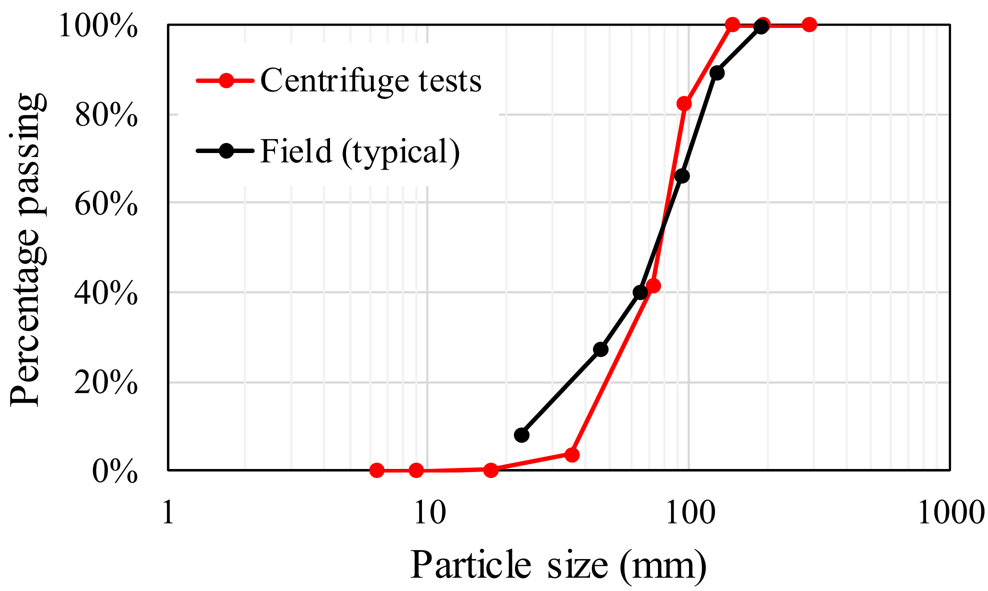


Fig. 4. Comparison of rock grading curves: centrifuge (scaled by 15) and field

Experimental procedures and programme

Each sample was prepared with the model pipe in place, before dumping the rock from a height selected to achieve the densities reported in Table 1. The surface profile of the rock was created to match the target profile drawn on the side wall of the testing container. The experimental programme comprised 24 large scale single gravity tests and 12 centrifuge tests. Variations on all test parameters were included in the large scale test program, while only cases with berm width of W = 1 m were included in the centrifuge test program (Table 2).

Table 1. Rock properties

Parameter	Value
Density of solid rock (t/m^3)	2.48
Bulk dry density (t/m^3)	1.47
Bulk dry unit weight (derived from above, in prototype scale units, kN/m^3)	14.44
Porosity (derived from above)	0.43
Void ratio (derived from above)	0.74
Friction angle* (°)	36
Pipe-rock interface friction angle† (°)	23

* Estimated from the slope of a volume of rock that was dumped against a wall
† Obtained by pulling the pipe axially at constant velocity over a level rock bed, whilst measuring the pulling resistance using a load cell

Table 2. Experimental programme

Test ID	Test conditions		
	H (m)	W (m)	α (°)
C_H40W134D10	0.6	1.0	10
C_H40W134D30	0.6	1.0	30
C_H40W134D60	0.6	1.0	60
C_H40W134D90	0.6	1.0	90
C_H67W134D10	1.0	1.0	10
C_H67W134D30	1.0	1.0	30
C_H67W134D60	1.0	1.0	60
C_H67W134D90	1.0	1.0	90
C_H80W134D10	1.2	1.0	10

RESULTS AND DISCUSSSION

Centrifuge tests

Typical results from the centrifuge experiments are provided in Fig. 5, showing cases with a rock cover height, H = 1.2 m and at all four load inclinations. Resistances are expressed in prototype scale, as forces per unit length of pipe, as the resultant force, F, and the component of this resultant force that acted in the direction of loading, R. Pipe displacement, δ, is the resultant of the vertical and horizontal displacements and is normalised by the pipe diameter, D. The response is characterised by increasing load to a peak value before decreasing due to the reducing embedment and shallower failure mechanism in the rock.

Fig. 5 shows that both the pipe resistance and the displacement needed to mobilise this peak resistance increase as the load inclination becomes progressively more lateral. This is made clearer by Fig. 6, which plots the variation in peak resistance, F_{peak}, and the normalised peak displacement, $(\delta/D)_{peak}$, against load inclination, α. The increase in pipe resistance as the load inclination reduces from α = 90° to 10° is about 5 for this and the intermediate pipe embedment depths, and about 4 the shallowest pipe embedment depth. Mobilisation displacements increase by a factor of about 4 at the highest pipe embedment, by 5 at the intermediate pipe embedment and by 6 at the shallowest pipe embedment.

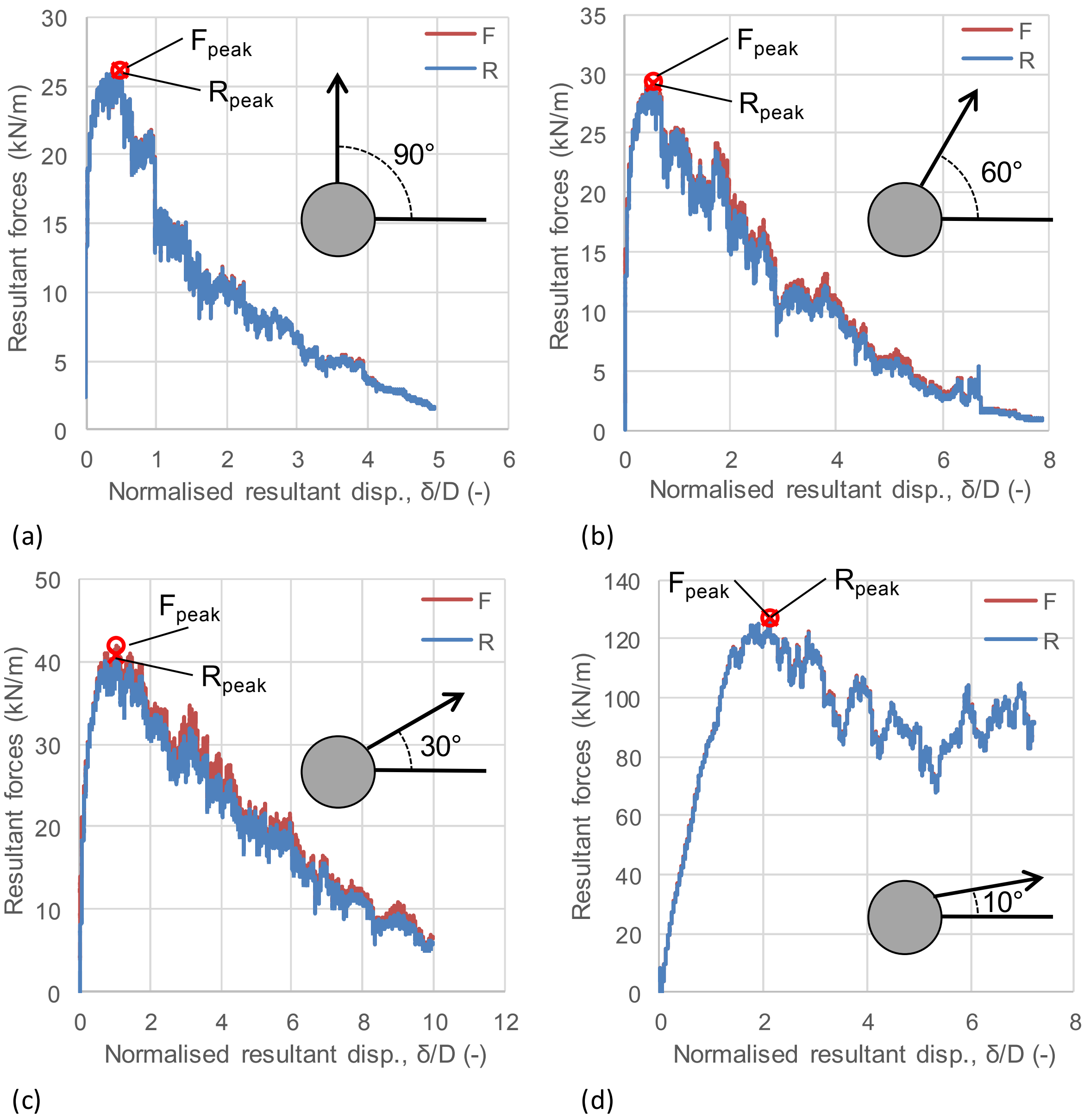
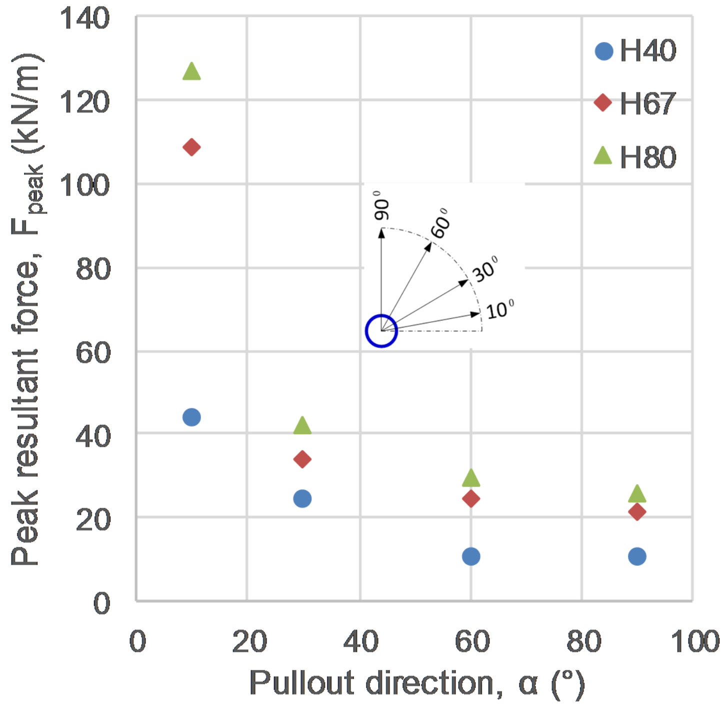
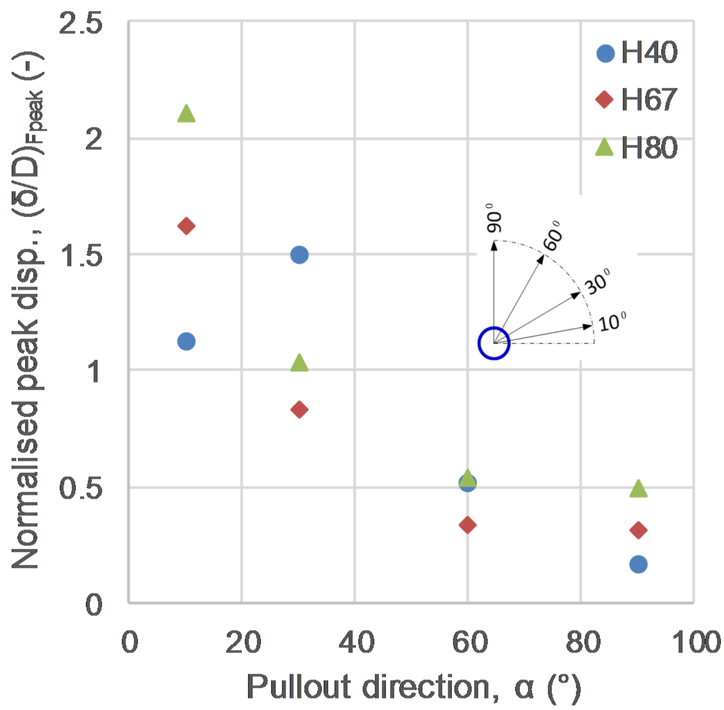


Fig. 5. Example centrifuge test results for a rock berm height of 1.2 m and at different load inclinations: (a) α = 90° (C_H80W134D90), (b) α = 60° (C_H80W134D60), (c) α = 30° (C_H80W134D30), (d) α = 10° (C_H80W134D10) (F – resultant force; R – resultant force along direction of loading)



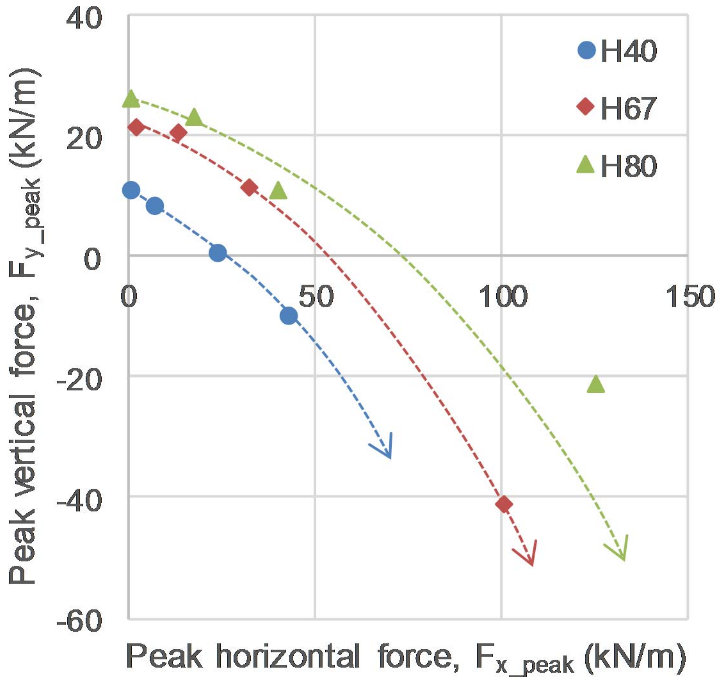
(a)



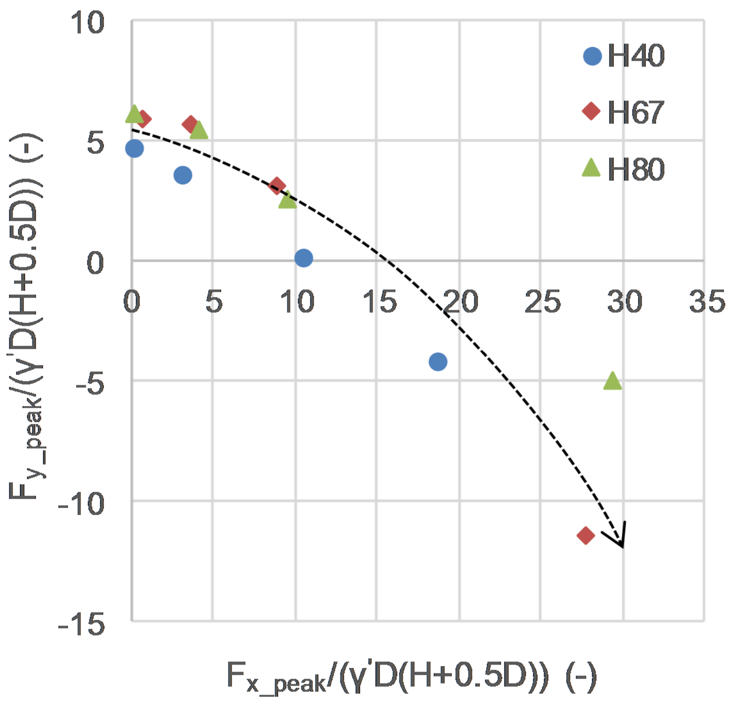
(b)

Fig. 6. Summary of centrifuge test results: (a) peak forces, (b) mobilisation displacements

Fig. 7a shows that the combined horizontal and vertical peak forces fall on a failure envelope that expands with berm height. It is noted that some values of F_y become negative (or compressive) at a load inclination, α = 10°. However, there is no requirement for the direction of motion and the resultant force to be collinear apart from the pure vertical uplift case, where symmetry applies. Therefore, it is possible for movements to be diagonally upwards but the resultant force (by the pipe on the underlying soil) to be diagonally downwards. Normalised peak forces are also shown in Fig. 7 (Fig. 7b), which are relatively insensitive to berm height, because the pipe embedment (H+0.5D) is used for normalisation. With this normalisation, it is possible to use a unique failure envelope to satisfactorily describe all the combinations of horizontal and vertical forces.



(a)



(b)

Fig. 7. Interaction of vertical and horizontal peak forces: (a) measured, (b) normalised

Comparison between large scale tests and centrifuge tests

As noted earlier in the paper, large scale tests were also conducted to provide a basis for checking the consistency of the test data at different scales. These experiments were conducted in the custom built testing chamber shown in Fig. 8, and utilised a pipe of diameter, D = 100 mm, assembled length, L = 0.98 m and with a sand-blasted surface with a surface mean roughness $R_a \approx 13.28$ μm. Control of the load inclination was achieved using a pair of adjustable guide rails, with rollers at the pipe ends permitting free movement along the rails[1]. Two pulleys were attached at the end of the guide rails, with the pipe movement controlled by pulling a pair of wires that connect the pipe via the pulleys to an electric actuator above the chamber (see Fig. 8b). The resistance experienced by the pipe was measured by two load cells fitted to the end of each pulling wire at the connection point to the actuator, with pipe displacement measured by a string potentiometer mounted on the actuator frame and connected to the moving crossbeam of the actuator.

Fig. 8. Large scale pipe tests: (a) general arrangement showing actuator located over test chamber, (b) pipe and supporting frame

Tests with a berm width, W = 1 m (in prototype scale) were performed in both the large scale and centrifuge testing programmes, so it is possible to compare results from the two test series. This permits a check on the appropriateness of the dimensionless groups used to express resistance. As noted earlier in the paper, these groups have mainly been derived from reduced scale tests, where the rock material was modelled using sand or gravel. Fig. 9 compares the resultant forces normalised by ($\gamma' D(H+0.5D)$). Good agreement across the testing scales is evident, with the exception of the $\alpha = 10°$ data (with prototype berm height of 1.0 and 1.2 m respectively). In this case the centrifuge data are around 1.4 to 2.2 times higher than the corresponding large scale test results. This difference can be explained by the visual observations for the two corresponding tests from the large scale and centrifuge test programmes (i.e. test H0.6W1.0D10 versus H80W134D10) as illustrated in Fig. 10. In this centrifuge test, with the highest berm and lowest load inclination, the 'V' frame was significantly buried in the rock and acted jointly with the pipe, so that a larger volume of rock was mobilised, which contributed to the much higher resistance. For the other cases, the peak uplift resistances agree to within typically <10%.

CONCLUDING REMARKS

Reduced scale model tests at 1:15 in a centrifuge and 1:2 at single gravity have been undertaken to assess the uplift resistance of pipes buried within trapezoidal rock berms. The

[1] System friction was between 0.4% and 3% of the lowest measured pipe resistance for any given loading direction, as assessed from tests where the pipe was moved in air (i.e. with no rock covering the pipe)

tests considered variations in the berm geometry and pipe embedment within the berm, and also the load inclination of the pipe. In this latter respect the testing addresses a gap in the current state-of-knowledge on uplift resistance of pipes buried in rock.

The test data are consistent across the two testing scales considered, with minor differences at low load inclinations originating from the different loading apparatuses used. Collectively the data demonstrate a strong dependence of uplift resistance on load inclination, with lower (i.e. more horizontal) load inclinations leading to resistances that are typically five times that when the load is vertical. The data also show that pipe resistance is enhanced by higher and wider rock cover. The experimental arrangement in the centrifuge tests provided measurement of both horizontal and vertical resistance components, allowing part of a failure envelope, in vertical-horizontal load space to be assessed, quantifying the influence of load inclination.

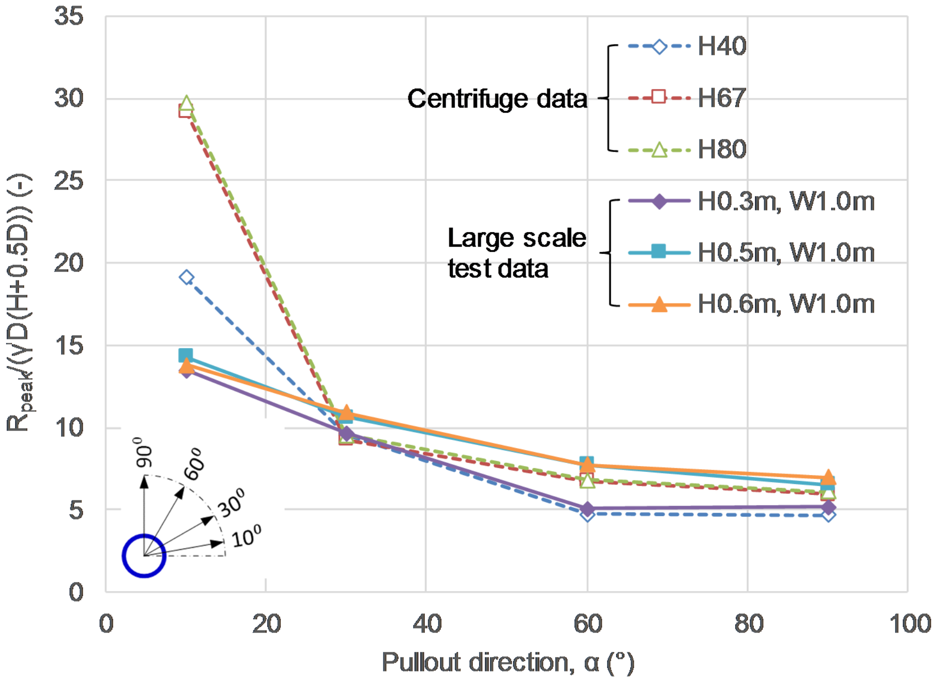


Fig. 9. Comparison between large scale and centrifuge test results

Fig. 10. Comparison of rock movement between large scale test SG_H0.6W1.0D10 and centrifuge test C_H80W134D10 at four diameters pipe displacement (δ/D = 4)

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