Centrifuge testing of lateral pipeline-soil interaction buried in very loose sand

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ABSTRACT
This paper presents the results of a series of small-scale centrifuge testing program conducted at C-CORE to explore the lateral response of pipelines to large deformations in dry sand. The model pipes were buried inside dry sand at different depths to investigate the load-displacement response to lateral displacement. Pipe diameter effect was also investigated by adjusting centrifuge acceleration. The results showed that the lateral resistance and the load-displacement response of the pipeline is significantly affected by burial depth, pipe diameter, relative density, and soil friction angle. The results were subsequently compared against the corresponding full-scale experiments, and a fairly acceptable agreement was observed. It was found that a smaller displacement is required in centrifuge to develop the peak resistance in comparison with the full-scale tests.

ABSTRAIT
Cet article présente les résultats d'une série de programmes de tests de centrifugation à petite échelle menés à C-CORE pour explorer la réponse latérale des pipelines à de grandes déformations dans le sable sec. Les tuyaux du modèle ont été enterrés à l'intérieur de sable sec à différentes profondeurs afin d'étudier la réaction de déplacement de la charge au déplacement latéral. L'effet du diamètre du tuyau a également été étudié en ajustant l'accélération de la centrifugeuse. Les résultats ont montré que la résistance latérale et la réponse en charge-déplacement de la canalisation sont significativement affectées par la profondeur de l'enfouissement, le diamètre du tuyau, la densité relative et l'angle de frottement du sol. Les résultats ont ensuite été comparés aux expériences en vraie grandeur correspondantes, et un accord assez acceptable a été observé. Il a été constaté qu'un déplacement plus petit est nécessaire dans la centrifugeuse pour développer la résistance maximale en comparaison avec les essais en vraie grandeur.

1 INTRODUCTION

Pipelines used for water or hydrocarbon transportation are exposed to environmental, geophysical, and operational risks. The risks include pipeline movements induced by internal pressure and temperature, ice gouging, fault activities, landslides, a range of field activity interference, anchors, environmental erosion, etc. In order to mitigate the risks, a common solution widely used in industry is to bury the pipeline. The buried pipelines are confined and protected by the surrounding soil. Any factors which may cause a relative displacement between soil and pipeline are considered in the framework of pipe-soil interaction. In this framework, pipeline design engineers evaluate the estimated loads and deformations, using existing guidelines against ultimate and serviceability limit states.

There are numerous analytical, numerical, and experimental studies that have been performed in the past to investigate pipe-soil interaction. These studies are categorized into axial, lateral, oblique, and uplift pipeline–soil interactions. Some of the physical models which have been executed in granular testbeds are summarized here: Audibert and Nyman (1977) presented the results of tests using three different model pipelines with diameters of 25 mm, 60 mm, and 111mm in loose and dense sand with a cover depth ratio ranging from 1 to 24.

Trautmann and O'Rourke (1985) conducted 30 lateral pipeline-soil interaction tests using pipelines with 102 mm and 324 mm diameters buried in dry sand at various burial ratios of 1.5, 3.5, 5.5, 8, and 11. The investigated testbed densities were 14.8, 16.4, and 17.7 kN/m^3 representing loose, medium and dense sand. Hsu (1993) performed approximately 120 lateral pipe-soil interaction tests to investigate the effects of sand density, pipe diameter, pipe burial depth, and relative interaction velocity on pipe lateral soil restraint. Pipe diameters ranging from 38.1 mm to 228.6 mm were used and the pipe displacement rate ranged from 0.001 to 0.1 pipe diameters per second. The burial depth ratio varied from 0.5 to 20 and embedment ratio varied from 1 to 20.5. In this study, the embedment depth ratio was used rather than the centerline depth, which was defined as the depth from pipe bottom to soil surface.

Burnett (2015) conducted a series of large-scale tests at Queen's University. Pipeline-soil interaction was investigated through lateral imposed displacement. Two pipeline pieces of 914 mm length with various diameters were used in a test program under plane strain condition. Transparent windows mounted on both sides of the container, along with an image-capture system, enabled a detailed investigation of the failure mechanisms, soil deflections and pipe trajectory path. The pipe diameter (D), burial depth (H), and sand density (γ) were the variable parameters studied throughout the testing program. The pipes (914 mm long with diameters 254 mm and 610 mm at burial depth ratios of 1, 3, and 7) were tested in both loose and dense sands.

Debnath (2016) studied the axial, lateral, and oblique behavior of pipe–soil interaction using centrifuge small scale modelling.

Karimian et al. (2006) conducted three lateral pipe–soil interaction tests in Fraser River sand with diameters of 324 and 457 at burial depth ratios 2.75 and 1.92, respectively. The relative density of the sand was considered to be around 70%.

In the present test program, the lateral pipeline-soil interaction was investigated through a series of centrifuge tests in both granular and cohesive testbeds. However, this paper only covers the dry sand tests. The experiments were conducted in a plane strain strongbox using small scale centrifuge model, reproducing the pipe diameters studied by Burnett (2015). The tests performed in sand were intended to investigate the failure mechanisms, lateral resistance, and load–displacement response of buried pipelines to large displacements in granular material.

2 TESTING SETUP AND PROCEDURE

The testing program consisted of three series of tests engaging the pipeline-soil interaction in sand through large lateral displacements. The buried pipes were pulled in opposite directions over a large course of displacements (2.5 to 3.0D). In tests with deferent G-levels, the pipes were pulled in two individual stages. Sand was placed inside the box without any densification process. However, there would have been some slight levels of densification during loading of box onto the platform and during centrifuge running.

Two model pipes were pulled in opposite directions and tested in each run resulting in six sand tests in total. The instrumentation of pipe-2 was not ready at the time of testing, therefore, the results of pipe-2 were not measured during the experiments. The assumed uniform lateral distributed force due to pipe-soil interaction was obtained using two shear strain gauges which were installed at two sections of the pipe. These two strain gauges measured all the shear force developed between the locations of the strain gauges. The schematic view of test-1 is shown in Figure 1. The internal dimensions of the testing box were 0.9 m by 0.3 m wide by 0.4 m high. The testing box was designed to simulate plane strain conditions, as an infinitely long buried pipeline would experience similar conditions in the field. Both pipe and sand are restrained at two sides of the box and during lateral movement of the pipe, sand cannot flow out of the plane.

Pipe diameter effect was investigated by changing the centrifuge acceleration in second and third tests. The interactive soil deformation mechanisms were directly monitored through an observation window. One digital camera was installed in front of the observation window for the purpose of post-processing and Digital Image Correlation (DIC) analysis. Two vertical drivers were located on the strong box in order to pull the cables through the pulleys at the level of buried pipe. This configuration is designed to pull the pipes laterally in opposite directions with predetermined moving rates where pipes are free to move vertically. The test setup is designed to conduct two independent tests at the same time, therefore, sufficient margins and appropriate boundary conditions were incorporated to ensure that the interference between the soil failure zones in each test is prevented. Some of the dimensions shown in Figure 1 were compared with pipe diameters to facilitate easier review of the boundary margins. More details about the test setup and comprehensive test program are discussed in Kianian et al. (2018).

The initial and post-test locations of the pipes and the trajectory of pipes are also incorporated in Figure 1. As the pulling lateral distances in the current study were up to 3 times the diameter of the pipe, the vertical displacement of the pipes also become a considerable value, generating an unrealistic vertical component which was introduced unintentionally to the system. This could be considered a limitation of the test setup where the pulling cable was not able to adjust itself with the vertical elevation of the pipe with the result that only a pure lateral force was produced. However, the vertical component was negligible. For example, at the end of test-1 (as shown in Figure 1), the final angle was 4° in T1P1, which imposed 4.7 kN/m extra vertical force in the prototype-scale at the end of the pulling distance. The downward vertical component has slight increasing impact on the resistance of soil. The pipeline tendency to move upward during lateral pipe-soil interaction originates from the nature of the buried pipeline in terms of slip surface development toward the soil surface. The testbed was prepared using silica sand. The sand particle size analysis shows that the sand is poorly graded, having D_{50} = 0.19 mm and coefficient of uniformity C_u = 1.96.

The current experiments are designed with the purpose of investigating the behavior of the soil during large lateral deformations in comparison with the full-scale tests which has been done by Burnett (2015). The scales were selected in such a way to mimic the full-scale tests. The tests were designed to (a) investigate lateral pipe-soil interaction in a plane strain condition, (b) find more accurate analytical solutions for ultimate resistance, (c) reveal the failure mechanisms at different depths and scales, (d) determine the load-displacement (P-y) curves, and (e) assess the influence of depth, embedment ratio, and pipe diameter by changing the scale. Table 1 summarizes the testing program. Burial depth ratio (H/D) is defined as the distance from the soil surface to the pipe centerline over the pipe diameter D. In test 2 and test 3 two various G-levels have been considered. Therefore the centrifuge conducted the tests in two stages with different accelerations.

Table 1. Summary of the testing program

Test	Pipe	Test ID	Scale	Model pipe diam (mm)	Prototype pipe diam (mm)	Prototype depth (m)	Burial ratio, H/D	Υ (kN/m3)	Confining pressure (kPa)	Resistance (kN/m)	Normalized resistance
Test 1	Pipe 1	T1P1	19.06	31.75	605.2	1.20	2.0	13.5	16.24	63.93	6.50
	Pipe 2	T1P2	19.06	31.75	605.2	1.20	2.0	13.5	16.24	-	-
Test 2	Pipe 1	T2P1	19.06	31.75	605.2	0.60	1.0	13.5	8.15	33.69	6.83
	Pipe 2	T2P2	7.95	31.75	252.4	0.25	1.0	13.5	3.40	-	-
Test 3	Pipe 1	T3P1	7.95	31.75	252.4	0.72	2.8	13.5	9.66	20.03	8.21
	Pipe 2	T3P2	19.06	31.75	605.2	1.72	2.8	13.5	23.16	-	-

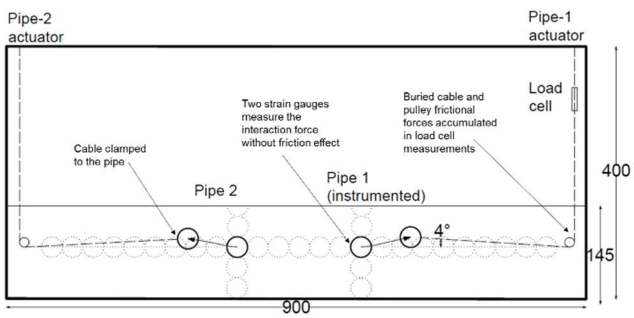

Figure 1. Schematic view of test 1; initial and post-test location of pipe; all dimensions are in mm

3 FORCE-DISPLACEMENT AND LATERAL RESISTANCE

This section presents a brief review of the force-displacement response obtained from the testing program. Prototype-scale force-displacement data was obtained by applying the appropriate scaling factors to model-scale data. The figures presented in this paper are all provided in prototype-scale. It was observed in granular material testbed that the lateral response of the pipeline could be significantly affected by several key parameters, mainly from pipe diameter, burial depth, and relative density.

Lateral load-displacement relationships are commonly expressed with the dimensionless load, $N_{qh} = F/(\gamma HDL)$, and dimensionless lateral displacement y/D in which F is the force acting on the test pipe, γ is the test soil density, H is the distance from the soil surface to the pipe centerline, D is the pipe diameter, L is the pipe length (0.3 m in current test), and y is the lateral pipe displacement. Figure 2 is the lateral load-displacement curves after normalization in order to illustrate the influence of normalization on the appearance of p-y curves. It was observed that increasing burial ratio or pipe diameter leads to increases in the lateral resistance applied to the pipeline. For a given pipe diameter at T1P1 and T2P1, pipelines tested at larger burial depth ratio experience larger lateral soil resistances and require a large displacement to mobilize peak lateral soil force. Pipelines with a larger diameter experience larger lateral soil forces and require a large displacement to reach the mobilization distance. As shown in Figure 3, for the same pipe diameter in T1P1 and T2P1, the higher burial depth ratio (T1P1) experiences less upward movement.

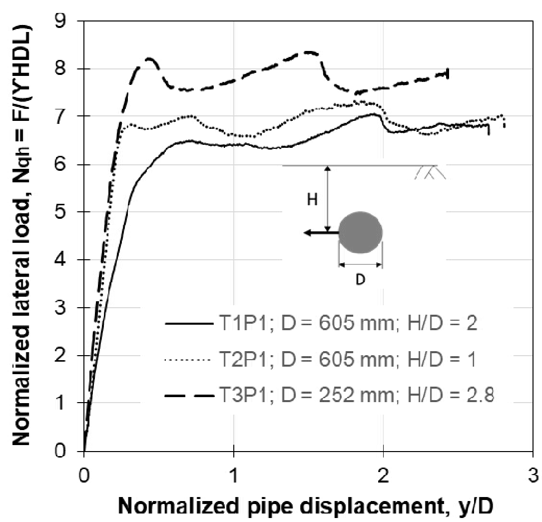

Figure 2. Force-displacement responses before and after

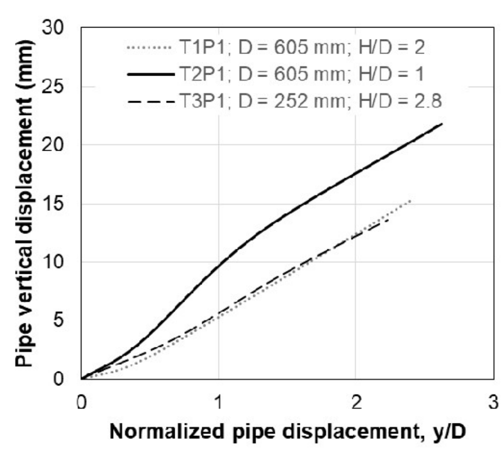

Figure 3. Pipe trajectories

4 COMPARISON WITH PUBLISHED STUDIES

Figure 4 compares the test data with some other experimental studies and guidelines including, ALA (2005), PRCI (2009) and Rajah et al. (2014). All the data presented in this figure are selected from the previous experiments executed in loose sand testbeds. ALA (2005) predicts closer results to the present experiments. There are many sources of discrepancies, including friction angles, sand types, sand densities, and experimental procedures associated with test setups and their side effects on the produced results. Table 2 describes some of the differences in the sand type, friction angle, scaling, pipe diameter, burial ratio, and relative density conditions.

The results of the current study are comparable with the results of the full-scale experiments conducted by Burnett (2015). There were several differences between the current study and Burnett (2015) including small scale modelling using centrifuge, as well as the sand type and relative density. Figure 5 shows the force–displacement curves of the current study in comparison with the corresponding full-scale experiments performed in olivine loose sand (Burnett 2015). All results show a favorable agreement. There are no major deviations in the trends seen in the load–displacement behavior, mobilization distances, or the maximum lateral soil forces. The load-displacement curves of both experiments show that increases in the burial ratio or pipe diameter lead to increases in the lateral resistance applied to the pipeline. The other conclusion is that for a given pipe diameter, pipeline tested at larger burial depth ratios, showed larger lateral soil resistance, which means that a larger displacement is required to mobilize ultimate lateral soil resistance. The displacement associated with the maximum resistance is defined as $0.04\left(H+\frac{D}{2}\right)$ which should not be taken more than 0.01D to 0.15D (ALA 2005 and PRCI 2009). This guideline is in accordance with the fact that both depth and diameter of the pipe have direct relationship with mobilization distance.

There are three main discrepancies in the results of full-scale (Burnett 2015) and centrifuge small-scale tests (current study) including: (a) Full-scale experiments due to the higher level of relative density and, consequently, the friction angle, led to higher levels of ultimate resistance. (b) Full-scale tests due to higher relative density showed greater initial stiffness. (c) Mobilization distance seems to be shorter in centrifuge small-scale tests with respect to the full-scale tests. This might be because of the scale effect in centrifuge.

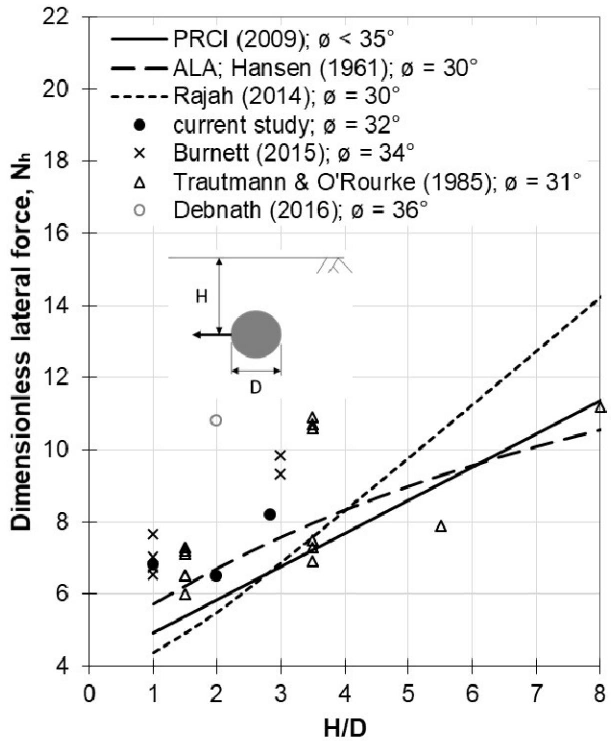

Figure 4. Comparison of the normalized resistance with several published test results and guidelines for loose sand

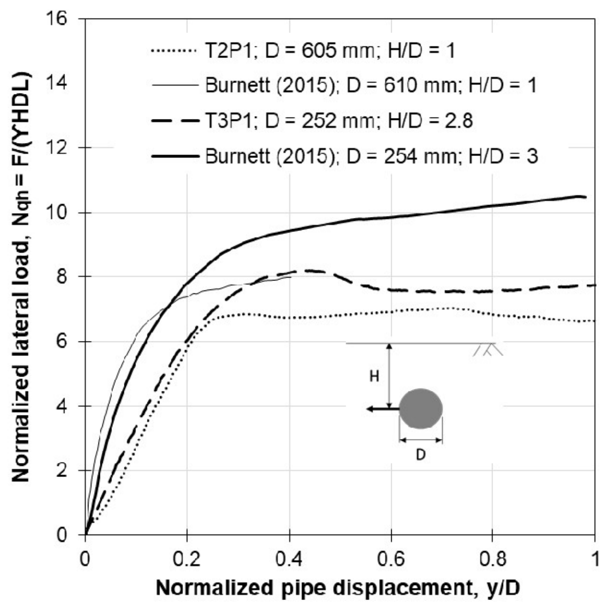

Figure 5. Comparison of the present study (very loose sand) with Burnett (2015) (full-scale loose sand)

Table 2. Lateral pipe–soil interaction experimental studies in sand

Experimental study	Sand type	Relative density condition	H/D	Pipe diameter (mm)	scale	Friction angle
Current study	Dry silica sand	Loose	1, 2, 3	252 & 605 prototype	7.95 & 19.06	32
Debnath (2016)	Dry silica sand	Dense and loose	2	609 prototype	13.25	32
Burnett (2015)	Dry synthetic olivine sand	Loose and dense	1, 3, 7	254 & 610	1	32.7 - 35.4
Karimian et al. (2006)	Moist & dry Fraser River	Medium dense	2.75, 1.92	324 & 457	1	32 - 34
Trautmann and O'Rourke (1985)	Dry Cornell filter sand	Loose to dense	1.5, 3.5, 5.5, 8, 11	102 & 325	1	31, 36, 44
Audibert and Nyman (1977)	Carver sand	Loose to dense	1 to 24	25, 63.5, 114.3, 228.6	1	35

5 CONCLUSION

A comprehensive understanding of pipe-soil interaction is necessary for the design of pipelines to minimize the risk from environmental, geophysical, and operational events. The response to large lateral displacement of the pipeline, regardless of the cause of the event, is crucial to the current understanding of pipeline-soil interaction.
This paper presents the results of a centrifuge experimental study of lateral pipeline-soil interaction induced by relative large horizontal movement of buried pipeline in silica sand under a plane strain condition. The present experimental program has focused primarily on the ultimate resistance against pulling the pipeline horizontally and the force-displacement relationships associated with the progressive mechanisms of failures which were observed through the window. The current results of buried pipeline in pure granular soil without trench are then comparable with the results of the cohesive testbed and granular backfill (Kianian et al. 2018).
The results of the current small-scale centrifuge study are comparable with the results of the full-scale experiments conducted by Burnett (2015). There are three main discrepancies in the results including: (a) the full-scale experiments due to higher level of relative density and consequently the friction angle, showed higher level of ultimate resistance. (b) Full-scale tests due to higher relative density showed greater initial stiffness. (c) Mobilization distance seems to be shorter in centrifuge tests with respect to the full-scale tests. This might be because of the lower relative density in centrifuge tests.
Initial observations of the conducted testing program can be summarized as follows:

- ALA (2005) predict closer to the results of the present experiments.
- Between the assessed guidelines, ALA (2005) showed closer prediction for the lateral bearing factor (normalized lateral force)
- All test results agree with previously published literature. There is no major deviation in the trends. Overall, centrifuge tests under estimate the ultimate resistance of soil in comparison with associated full-scale tests.
- There is no specific criteria to select the mobilization distance in loose sand therefore the choice of the distance required to develop maximum load in loose sand from the experimental data is somewhat subjective. And there is high variability in this parameter.
- An increase in pipe diameter leads to higher lateral soil resistances and, therefore, greater ultimate values. Larger pipe diameter results in more upward movement during pure lateral actuation.
- Deeper burial depths result in greater required displacement to develop ultimate resistance (mobilization distance)

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