Centrifuge modeling of subaqueous and subaerial landslides impact on suspended pipelines

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ABSTRACT
Subaqueous and subaerial landslides pose a significant threat to pipelines. This paper discusses the drag forces resulting from the impact of a portion of an intact submarine and subaerial landslide on a pipeline. Ten geotechnical centrifuge experiment tests were conducted. Eight of which simulated a submarine glide or out-runner block impact on pipeline, and two modelled that of subaerial. At 30 times of Earth's gravity, the prototype scale of the clay blocks used in the tests measured about 4.5 m high and 12.0 m long. The undrained shear strengths ranged from 4 to 7 kPa for the submarine tests and 9 to 13 kPa for the subaerial. The clay blocks impacted the model pipes, normal to its axis, at velocities ranged from 0.1 to 1.3 m/s. The shear strain rates (defined as the ratio of velocity over pipe diameter) in the experiments ranged from 10 to 137 reciprocal second. A method is presented to estimate the drag forces on a suspended pipeline caused by a glide or out-runner block in submarine scenario.

RÉSUMÉ
Les glissements de terrain subaquatique et subaériens constituent une menace importante sur les pipelines. Cet article discute les forces de traînée résultant de l'impact d'une partie d'un sous-marin intact et des glissements de terrain subaériens sur un pipeline. Dix essais expérimentaux géotechniques centrifuges ont été effectués. Dont huit qui simulait un glissement sous-marin ou un impact d'un bloc sur le pipeline, et deux tests représentent ce qui se passe dans l'air. À 30 fois la gravité terrestre, les prototypes des blocs d'argile utilisée dans les tests mesuraient environ 4,5 m de haut et 12,0 m de long. Les résistances au cisaillement non drainé variait de 4 à 7 kPa pour les essais sous-marins et de 9 à 13 kPa pour les subaériens. Les blocs d'argile ont touchés le tuyau modèle, normal pour son axe, à une vitesse variant de 0,1 à 1,3 m / s. Le taux de cisaillement (défini comme le rapport entre la vitesse et le diamètre du tuyau) dans les expériences variait de 10 à 137 1/s. Une méthode est présentée pour estimer les forces de traînée sur un pipeline en suspension provoquée par glissement dans le scénario sous-marin.

1 INTRODUCTION

Subaerial landslides and their consequences are well documented compared to their subaqueous counterpart. With the offshore oil and gas moving into deeper waters, offshore geohazards and their consequences have become subjects of research. Understand the drag forces generated from a submarine landslide onto a pipeline has gained interest in the recent years.

Zakeri et al. (2011) have conducted physical experiments to simulated submarine landslides impacting onto a suspended pipeline. Based on physical modelling using geotechnical centrifuge, Zakeri et al. (2011) have shown that the drag force of an intact glide or out-runner block (portion of the slide) can be estimated by using a dimensionless parameter, *k*. By knowing the undrained shear strength (s_u), velocity of a moving glide block (U_∞), and the pipe diameter (D), the horizontal drag force (normal to the pipe axis) per unit length can be calculated by the following equation.

$$F_D = k \cdot s_u \cdot D \qquad [1]$$

The value for the *k* parameter, which is very similar to the bearing capacity factor (N_c) in shallow foundation design, varies widely as noted by many researchers including Georgiadis (1991) and more recently by Zakeri (2009). One of the reasons for this is the inconsistency in the shear rates simulated and in some cases ignored by various authors. Zakeri et al. (2011) proposed the shear strain rate to relate the *k* value, where the shear strain rate was defined by the following equation.

$$\dot{\gamma} = \frac{U_\infty}{D} \qquad [2]$$

This paper is a continuation of the work done by Zakeri et al. (2011). It contains additional subaqueous experiments and new tests simulating subaerial scenario. All experiments simulated impact normal to the pipe axis.

2 CENTRIFUGE MODELING

2.1 Scaling Factor

The C-CORE geotechnical centrifuge located in St. John's, Newfoundland and Labrador, Canada, has a radial arm of 5.5 m and a 650 kg capacity at 200g. Geotechnical centrifuge (or centrifuge) is used to correct the scaling effect between the reduced model and full scale model. Centrifuge is used to generate centrifugal acceleration to simulate gravity and allows for correspondence of stress fields between the reduced model and full scale model. Procedures for centrifuge modelling and the appropriate scaling laws have been given by Taylor (1995) and Garnier et al. (2007). Table 1 summarizes the general scaling factors used for the centrifuge tests conducted for this paper.

Table 1. General Scaling Factors for Centrifuge Tests

Physical property	Units	Model scale
Gravitational acceleration	LT^{-2}	N
Dimension – length and diameter	L	1/N
Stress	$ML^{-1}T^{-2}$	1
Force	MLT^{-2}	$1/N^2$
Force per unit length	MT^{-2}	1/N
Velocity	LT^{-1}	1
Strain	-	1
Shear strain rate	T^{-1}	N
Model parameter, *k*	-	1

3 EXPERIMENTAL OVERVIEW

The aim of this experiment setup was to contain the clay sample (clay block) used to model the glide block while it is spinning in the centrifuge, and to collect the drag force generated from impacting the mid height of the clay block onto the model pipe. In addition, the speed and the sheared strengths of the clay blocks were also required. For more detail description, please refer to Arash et al. (2011).

3.1 Soil preparation

The glide block was modeled by using 100% kaolin clay. There are two consolidation phases; on the lab floor and centrifuge flight consolidation. Consolidation on the lab floor was done by mixing slurry of clay at 120% of its liquid limit under vacuum, and transferred it into a consolidation box. Vertical loads were applied in steps until it has reached the desired effective stress. The applied effective stress on the lab floor ranged from 40 to 120 kPa. Two clay blocks can be obtained from each floor consolidation. One clay block was cut into a 400 mm long, 200 mm wide, and approximately 150 mm high block and transferred to the aluminum cart (or cart) used for the test, while the other block remained inside the consolidation box with plates surrounding its sides. Additional, an 80 mm length, 200 mm high, and 80 mm aluminum tube was inserted into the consolidated clay to collect clay used in monitoring centrifuge flight. Excess space was filled with sand. For the subaerial scenario, a layer of approximately 1 mm thick Vaseline was applied to the clay to avoid from drying during the centrifuge flight.

3.2 Experiment setup

Figure 1 illustrates the experimental setup. The experiments were conducted inside an aluminum strong box. Two Plexiglass walls, one Plexiglass gate and the back of the cart were used to retain the clay block while it was consolidating during the centrifuge flight. A string potentiometer was connected to the back of the cart; it was used to measure the distance traveled. After consolidation, T-bar test was conducted and then the gate was lifted. The T-bar apparatus and the gate were connected to two actuators that were located above. A servo-motor located on top of the strong box was used to move the cart at varies speeds towards the suspended model pipe and allowed the clay block to impact.

Two solid stainless steel rods of 6.35 and 9.52 mm in diameter were used to model a 0.19 and 0.29 m suspended pipeline, respectively. Both ends of the pipe were connected to horizontal and vertical load cells by 3 mm diameter solid aluminum rods, forming a flex-link. Verification was done to ensure the flex-links caused no cross-communication between the horizontal and vertical load cells.

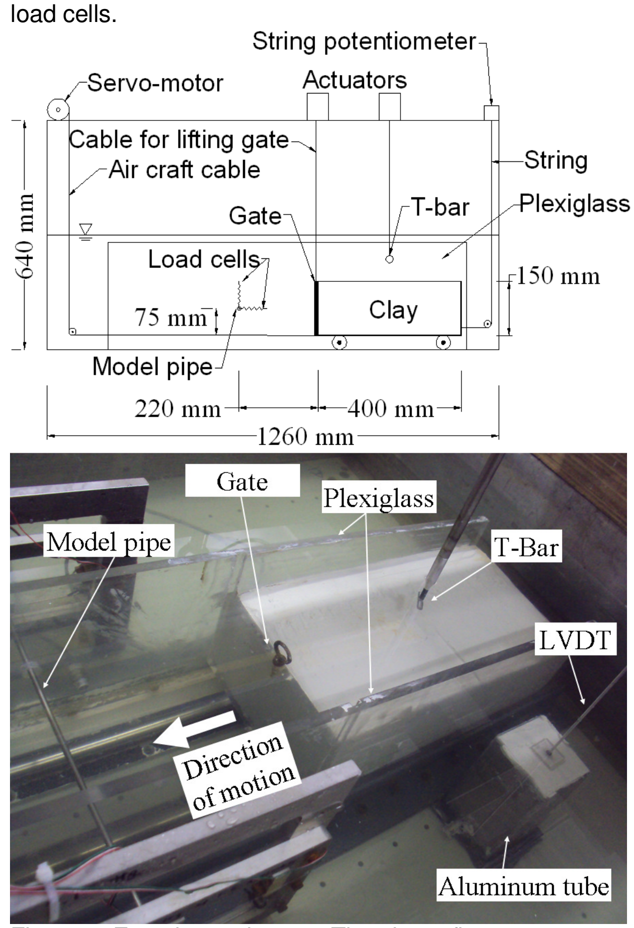

Figure 1. Experimental setup. The above figure presents a section view with dimensions and locations of the experiment components. The below photo presents a isometric view of the clay block and its surrounding experiment components.

3.3 Instrumentation

The following are the instruments used to determine several parameters during the experiment.

- T-bar: It was attached to an actuator and used to determine the undrained and remoulded shear strength of the clay block. It consisted of a long hollow aluminum rod attached to a solid aluminum bar of 7.5 mm in diameter and 30 mm long. A load cell was attached near the junction of the two rod and bar, to measure the load as it penetrates into the clay at 3 mm/s. Seven cyclic penetrations were conducted (only test number 1 had four cyclic penetrations). Frequency used to record was 40 Hz.
- String Potentiometer: It was attached to the back of the cart to determine the displacement. Frequency used varied from 400 to 2,000 Hz. Velocity can be back calculated by knowing the frequency used to record and the displacement traveled.
- Linear Variable Differential Transformer (LVDT): It was used to measure the surface movement of the clay; to monitor the progress of centrifuge flight consolidation. The measuring shaft was laid on top of a 20 mm x 20 mm square Plexiglass.

4 EXPERIMENTAL RESULTS, ANALYSIS AND DISCUSSION

A total of 10 tests were conducted for this paper. Test numbers 1 to 8 were conducted to simulate a submarine landslide scenario, and test numbers 9 and 10 were conducted to simulate the subaerial scenario. All tests were conducted at 30g. The test results and analysis are presented in the following sections

4.1 Summary of experimental results

Table 2 provides a summary of test conditions and results in model scale. The 6.35 mm diameter rod was used in test numbers 1 to 3, 8 and 9, while the 9.52 mm diameter rod was used in test numbers 4 to 7, and 10.

Table 2. Summary of the test conditions and results.

Test No	h/D* ratio	S_u** (kPa)	Speed (m/s)	$F_{D,Horizontal}$ (N/m)	$\dot{\gamma}$ (1/s)	k
1	12.8	4.3	0.16	327.5	24.5	12.0
2	10.6	4.7	0.21	333.2	32.8	11.2
3	10.9	4.3	0.10	297.2	16.5	10.8
4	8.9	4.1***	0.10	385.4	10.8	9.9
5	8.9	4.1***	0.20	383.0	21.3	9.8
6	6.8	4.3	1.30	609.0	136.6	14.7
7	7.1	6.0	0.77	728.5	81.4	12.8
8	10.9	6.7	0.30	483.7	47.8	11.3
9	10.7	12.1	0.10	598.0	15.9	7.8
10	7.6	9.9	0.70	1063.5	73.6	11.3

*h/D is the ratio of the height measured from the pipe center to the top of clay over the pipe diameter
** undrained shear strength near the center of the pipe
*** values estimated from test number 1

4.2 Undrained shear strength

The undrained shear strength, s_u, was determined by penetrating a T-bar apparatus into the clay block at the end of centrifuge flight consolidation. The s_u was calculated by using the following equation.

$$s_u = \frac{P}{N_b \cdot d} \qquad [3]$$

Where P is the resistance force per unit length, d is the diameter of the T-bar, and N_b is the T-bar factor. The value of N_b used in this study was 10.5 (Stewart and Randolph 1994). Figure 2 shows the estimated initial undrained shear strength of the clay blocks in model terms based on T-bar test results.

Remoulded shear strengths were determined by the final cyclic penetration of the T-bar test at the depth of the pipe. The remoulded shear strength ranged from 30 to 50% of the initial undrained shear strength (except for test numbers 4, 5 and 8. See below for explanation).

Due to technical problems, T-bar test results for test numbers 4 and 5 were not recorded and assumed to have the same s_u value as of test number 1 as they had the same consolidation history. For test number 8, the voltage was shifted after the initial penetration.

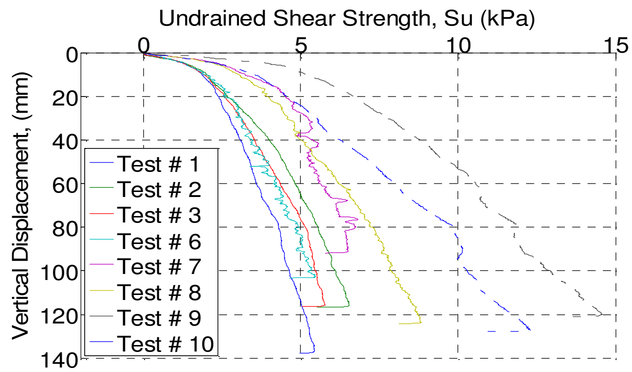

Figure 2. Initial s_u profile of the clay blocks

Moisture contents at the end of the tests were gathered from the undisturbed clay, which was located in the aluminum tube used to monitor centrifuge consolidation. The moisture content ranged from 55 to 75% for the submarine scenario and 55 to 63% for the subaerial scenario.

4.3 Horizontal drag force

Figure 3 illustrates the horizontal drag forces per unit length over the interaction course of roughly 0.35 m in model terms. Except test number 10, all tests reached the steady state conditions where the maximum drag force was measured.

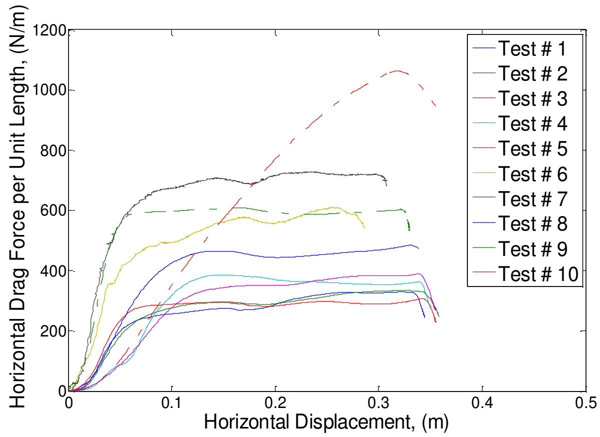

Figure 3. Development of horizontal drag forces. Units are in model terms.

To relate the horizontal drag force and the impact velocity, Eq. 2 and 3 were used to calculate the values for *k* and $\dot{\gamma}$. Figure 4 illustrates the relationship between the *k* parameter and shear strain rate for both submarine and subaerial scenario. The shear strain rates from the tests ranged from 10 to 137 reciprocal second. The proposed relationship for the submarine scenario is

$$k_{submarine} = 6.97 \cdot \dot{\gamma}^{0.14} \qquad [4]$$

The subaerial impact tests seem to have a similar trend as those of the subaqueous experiments. In the subaqueous tests, water is entrapped in the wake behind the pipe. This is not the case for subaerial tests. Figure 5 illustrates the wake from test number 10, a subaerial scenario. One would expect the *k* values in the subaerial test to be larger than those measured in subaqueous experiments. However, the data shows the *k* value to be the same or even lower. No definitive conclusion can be made for the subaerial cases at this time. This is a matter of further research.

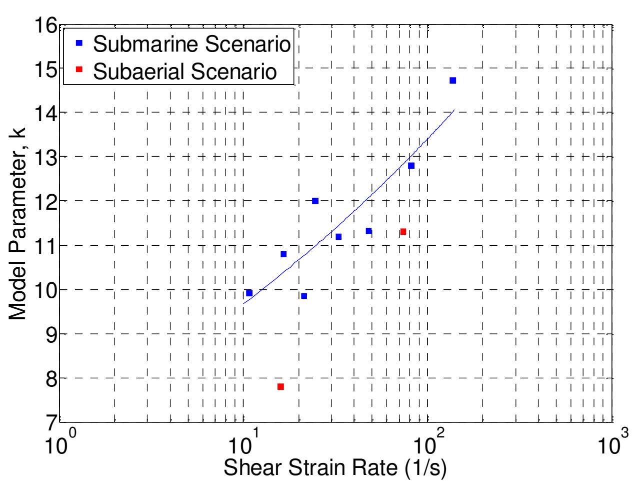

Figure 4. *k* parameter versus shear strain rate, $\dot{\gamma}$, for model and prototype terms

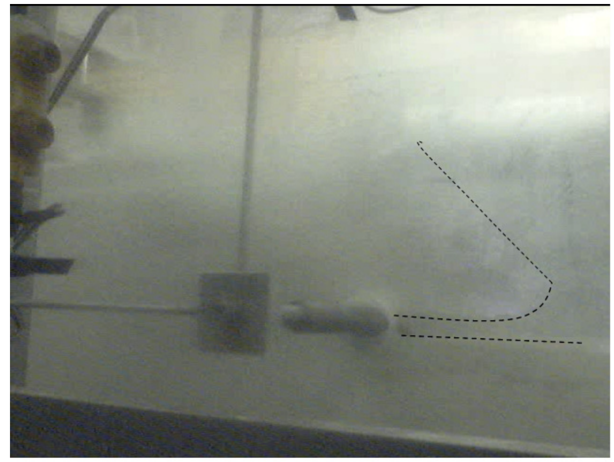

Figure 5. Wake generated from a moving clay block through a pipe.

4.4 Vertical drag force

At the initial stage of the impact, the clay block generates a small upward vertical force onto the pipe. The force ranged from 4 to 14 % of the horizontal drag force. Due to the large h/D ratio, this vertical force diminished quickly as the clay block continues to flow around the rod. Relatively insignificant vertical force was also observed by Oliveira et al. (2010) when the h/D ratio was greater than 1.0. This vertical uplift force was assumed to be generated by the clay block's front, which it was failed (approximately 45° from the vertical) when the Plexiglass gate was lifted prior to moving the clay block. However, this does not have a significant effect on horizontal drag force.

5 CONCLUSION

Ten tests were conducted in the C-CORE centrifuge facility in St. John's, Newfoundland and Labrador, Canada, to simulate a submarine and subaerial scenario of an intact portion of a landslide, glide or out-runner block, impacting a suspended pipeline normal to its axis. The size of the clay blocks were approximately 4.5 m high and 12.0 m long, and the undrained shear strengths ranged from 4 to 7 kPa for the submarine tests and 9 to 13 kPa for the subaerial. The clay blocks impacted the model pipes, normal to its axis, at velocities ranged from 0.1 to 1.3 m/s. The shear strain rates of the experiments ranged from 10 to 137 reciprocal second.

It was shown that the model parameter, *k*, was not significantly different in the submarine and subaerial scenario, at least when only two subaerial tests were compared with eight submarine cases. One important aspect in the submarine scenario is the wake of entrapped water as the clay flows around the pipe.

Only two tests were conducted so far for the subaerial scenario. Additional tests have been planned to develop a better relationships for the drag forces both for submarine and subaerial scenarios and also to show the similarities and differences between them.

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