Submarine Debris Flow Impact on Pipelines: Recent Advances in the State-of-the-Art and Future Outlook

Arash Zakeri
C-CORE, St. John's, Newfoundland and Labrador, Canada

ABSTRACT
Estimating the impact drag forces exerted by a submarine debris flow on a pipeline is a challenge. The conventional geotechnical based methods available to estimate drag forces on buried pipelines in unstable slopes are not applicable to a debris flow impact situation as they ignore or significantly underestimate the shear rate effects in the soil-structure interaction. The results of recent investigations indicate that a fluid dynamics approach in conjunction with rheological principles of non-Newtonian fluids provides a more appropriate way in the study of soil-pipe interaction for submarine debris flow impact situations. To that extent, this paper presents a method for estimating the drag forces on suspended (free-span) and laid-on-seafloor pipelines (longitudinal and normal to the pipe axis) caused by clay-rich submarine debris flow impact. The method covers various angles of impact. Further, it brefily discusses two conceptual measures to mitigate and control the impact drag forces. The method is based on experimental flume tests and Computational Fluid Dynamics (CFD) numerical analyses. Finally, recommendations for future research and development to advance the state-of-the-art are presented.

RÉSUMÉ
L'estimation des forces d'impact exercées par l'écoulement de débris sous-marin sur un oléoduc/gazoduc est un défi contemporain. Les méthodes disponibles de la géotechnique sont habituellement basées sur l'évaluation de la force de traînée sur les oléoducs enterrés dans les pentes instables. Ces méthodes ne sont pas applicables à une situation d'impact de l'écoulement sous-marin assidue car ils ignorent ou sous-estiment de façon significative les effets de taux de tondage impliqué par l'interaction entre le sol et la structure. Les résultats d'enquêtes récentes indiquent qu'une approche de dynamiques des fluides en conjonction avec les principes rhéologiques de liquides non-Newtoniennes fournit une voie plus appropriée dans l'étude des interactions oléoduc-sol pour les situations d'impact d'écoulement sous-marin. À cette mesure, ce papier présente une méthode pour estimer les charges traînées sur un oléoduc suspendu (travée libre) et disposé-au-fond (longitudinal et normal à l'axe) provoqué par les impacts d'écoulement de débris sous-marins riches en argileux. La méthode couvre des angles d'impact différents. De plus, il présente deux mesures conceptuelles pour atténuer et contrôler les forces de traînées causées par l'impact. La méthode est fondée sur des épreuves de bassin d'essai à circulation expérimentales et la modélisation numérique et dynamique des fluides (MDF). Finalement, les recommandations pour la recherche future et le développement pour avancer l'état de l'art sont présentées.

1 INTRODUCTION

Submarine landslides and debris flows are amongst the most destructive geohazards, economically and environmentally, for installations on the seafloor. Estimating the drag forces caused by these geohazards is an important design consideration in offshore engineering. Failure of a hydrocarbon pipeline may be economically and environmentally devastating. With offshore oil and gas activities pushing into deeper water, there is a need to better assess and quantify the risk associated with geohazards. Research in the area was inspired in the wake of the 1969 Hurricane Camille in the Gulf of Mexico, during which three offshore platforms and the associated network of pipelines suffered significant damage. Subsequent studies concluded that the damage was mainly due to wave induced mass movement at the seafloor and not the wind and surface wave action alone (Coleman and Prior 1978; Schapery and Dunlap 1978).

A moving failed mass from a submarine landslide undergoes a series of complex processes from initial disintegration to glide blocks to fast moving fluid-like debris flows and turbidity currents. It is this complex process that has led to considerable confusion of nomenclature in the literature and inappropriate use of the methods in assessing soil-structure interaction forces. For example, geotechnical-based methods that were developed for the case of fully or partially buried pipeline in an unstable slope are sometimes applied to the problem of debris flow impact. Mulder et al. (2001) provide a clear and simple classification system for sedimentary density flows based on their physical flow properties and grain support mechanisms encompassing both cohesive and cohesionless soils. Clay-rich submarine debris flows are often fully remoulded and in a fluid state of pseudoplastic type.

This paper briefly describes the methods developed between the mid 1970's and late 1980's to assess the drag forces arising from soil-pipeline and soil–pile interaction in submarine landslide situations. It presents a recently developed method to estimate the drag forces on laid-on-seafloor and suspended (free-span) pipelines arising from clay-rich debris flow impact. Further, it briefly discusses to conceptual mitigation and control measures to protect submarine pipelines against debris flows and finally, provides recommendations for future research in this area.

2 PREVIOUS METHODS

The problem of submarine landslides and their interactions with seafloor installations such as pipelines and piles has been mainly investigated from two perspectives: a geotechnical approach and a fluid dynamics approach. In the former, the drag forces are directly linked to the soil shear strength either linearly or through a power-law relationship including the rate of shear. Whereas, the latter approach considers the soil fully fluidized and applies fluid mechanics principles.

Zakeri (2009a) summarizes and compares the highlights of the these methods. The methods, mainly developed between the late 1970's and mid 1980's, are limited in terms of the potential applications and predict very different results. In general, critical information such as model scaling, parameters pertaining to the soil and other materials used in the experiments are missing or poorly described in much of the literature. The methods mainly address the issue of submarine piles and buried pipelines in unstable zones as opposed to an impact situation caused whether by a glide block or debris flow from a landslide. They must be applied to prototype situations with caution and within their range of validity. The literature cites where the methods have been erroneously applied and hence, erroneous results were obtained. For buried pipelines in cohesive slowly moving unstable slopes, the available methods seem to provide more or less similar estimates for the drag force normal to the pipe axis. However, this is not the case for estimates of the drag force parallel to the pipe axis. Dependency of the drag force on the rate of shear in cohesive soils has been overlooked by many researchers or poorly addressed in these methods. With one or two exceptions, the methods should not be applied to the case debris flow impact analysis. For cohesionless soils, the methods available are even far more limited and less reliable compared to those available for cohesive soils. In summary, there is a significant potential and need for improving the state-of-the-art to estimate impact drag forces on submarine pipelines and piles caused by debris flows. A brief description of the methods is as follows.

2.1 Geotechnical Approach

This approach directly relates the drag forces exerted on a structure to the shear strength of the sliding soil mass. A typical equation for the drag force, F_D, on a structure in a mudslide has the form of:

$$F_D = k \cdot s_u \cdot A \tag{1}$$

where, s_u is the undrained soil shear strength and A is the projected frontal area in the flow direction. The k-parameter in Eq. (1) has been determined experimentally or based on field data by several authors. Some authors have selected a constant value for the k-parameter based on an analogy similar to that of the conventional foundation bearing capacity analysis – here referred to as the 'conventional approach'. Others have expressed it as a power-law function reflecting the strain-rate effects on the undrained shear strength of the moving soil, and this method is referred to as the 'strain-rate dependent approach'. The conventional approach was mainly developed for structures built in unstable slopes (e.g. buried pipelines) as opposed to debris flow impact.

Demars (1978), Swanson and Jones (1982), Bea and Aurora (1982), Audibert et al. (Audibert and Nyman 1979; Audibert et al. 1984), and Summers and Nyman (1985) all adopted the conventional approach to study drag forces on buried pipelines in an unstable clay-rich slope. Their k-parameter is a constant ranging between 7.5 and 10. Georgiadis (1991) investigated the strain-rate dependency of the drag force on a pipeline embedded in a moving clay-rich soil mass and modified the conventional geotechnical approach. The relative velocities in his experiments ranged between 1 to 90 mm/min. Calvetti et al. (2004) adopted the conventional approach for pipelines in unstable sand-rich slopes. They proposed the method put forth by Audibert and Nyman (1984) for estimating the horizontal component of the drag force and described the soil failure locus being a function of the pipe burial depth, and the horizontal and vertical components of the drag force. Their paper is fairly detailed and comprehensive.

For piles, Wieghard (1975) and Towhata and Al-Hussaini (1988) used the conventional geotechnical approach whereas Schapery and Dunlap (1978) and Vivtrat and Chen (1985) adopted the strain-rate dependent geotechnical approach. Wieghadt (1975) experimented with granular flow around vertical rods (circular, semi-circular, rectangular and slit in cross section) of various dimensions and immersion depths and concluded that the drag force is strongly rate dependent. The k-parameter put forth by Towhata and Al-Hussaini (1988) is a constant for cohesive soils whereas the one recommended by Schapery and Dunlap (1978) and Vivtrat and Chen (1985) is only a constant at the reference shear rate (i.e. the rate of shear corresponding to a standard vane test) and increases with the strain rate. Vivtrat and Chen (1985) found a marked similarity between the constant in their k-parameter and the bearing capacity factor, N_c, value proposed by the others. However, it was concluded that this similarity is purely coincidental.

2.2 Fluid Dynamics Approach

Drag forces exerted by non-Newtonian fluid flow around objects based on fluid dynamics and rheology principles were first investigated by Pazwash and Robertson (1975). In the fluid dynamics approach, the drag force is estimated from the equation:

$$F_D = \frac{1}{2} \rho \cdot C_D \cdot U_\infty^2 \cdot A \tag{2}$$

where, ρ is the fluid density, C_D is drag coefficient, and U_∞ is the free upstream velocity. They experimented with flat plate, ellipsoid, sphere and disc shaped objects immersed in kaolin clay solutions of different concentrations. Pazwash and Robertson (1975) determined that the drag coefficient for an object immersed in a Bingham fluid is a function of the corresponding drag coefficient in a Newtonian fluid, a shape factor and the dimensionless Reynolds and Hedstrom numbers. As such, they established a shape factor for each object tested based on the drag force measured. A Bingham fluid is a fluid that its rheological behaviour could be expressed mathematically by Eq. (3) (Coussot 1997):

$$\tau = \tau_o + \mu_B \cdot \dot{\gamma} \tag{3}$$

where, τ is shear stress, τ_o is the yield stress, μ_B is the dynamic viscosity, and $\dot{\gamma}$ is shear strain rate. A Bingham fluid flows when the applied shear stress is greater than its yield stress. Pazwash and Robertson (1975) concluded that the drag coefficient is related to the body surface area and the ratio of body length over diameter. Although a shape factor for a circular cylinder was never determined, the authors state that the shape factor may be interpolated for other simple body shapes.

Chehata et al. (2003) experimented with a fixed horizontal cylinder immersed in a dense uniform quasi 2D granular flow and presented the drag force results in dimensionless form using the drag coefficient in Eq. (2). They used glass pellets to model the granular material. The velocities ranged between 0.015 and 0.470 m/s. Wassgren et al. (2003) complemented the work done by Chehata et al. (2003) through a series of two-dimensional Discrete Element Method (DEM) numerical simulations of dilute granular flows around an immersed cylinder in a confined rectangular setting. They concluded that a cylinder immersed in a dilute granular flow has many similarities to that of rarefied gas flow. The drag coefficient for the cylinder strongly depends on the flow Knudsen number with a secondary dependence on the upstream Mach number. With respect to independency of the drag force on the upstream velocity, it was concluded by Chehata et al. (2003), that more studies are required to investigate the drag force transition from the velocity squared dependence for dilute granular flows to the velocity independence for dense granular flows.

For piles, Pfeiff and Hopfinger (1986) studied the drag force exerted on a vertical cylinder (18 mm in diameter) moving in dense suspensions of polystyrene beads (0.45 mm mean diameter). The volumetric solids contents, C_v, ranged from 10% to 62%, and the rod velocities varied from 0.015 to 0.42 m/s. The corresponding shear rates ranged between 0.8 and 23.3 s^{-1} in the experiments. The beads had a specific gravity close to water. The rheological properties of the suspensions were determined experimentally, and the Reynolds number (Re) in each run was estimated using the definition of the apparent viscosity. The dependency of C_D on the Re was sought. The authors concluded that when C_v < 50%, the estimated drag coefficient values are very close to those of Newtonian fluids. However, for more dense suspensions, the experimental results suggest that the drag coefficients are systematically higher than the corresponding values in Newtonian fluids. The authors found it difficult to explain this increase in drag coefficient and stated that this may be due to the experimental setup or the experimental inaccuracy. The observations indicated that in denser suspensions ($C_v \approx 55\%$), the flow around the cylinder moving with moderate velocity of 0.05 m/s, is clearly laminar.

3 RECENT DEVELOPMENTS

Zakeri et al. (2008a) adopted the fluid dynamics approach and developed a method for estimating impact drag forces from a clay-rich submarine debris flow on suspended and laid-on-seafloor pipelines. The method is based on an experimental program consisting of physical flume experiments (Zakeri et al. 2008a) complemented by numerical analyses using the Computational Fluid Dynamics (CFD) method (Zakeri 2009b; Zakeri et al. 2009a; Zakeri et al. 2009b). For the case of suspended pipelines, the method covers various angles of incidence making it possible to estimate the impact drag forces parallel and normal to pipe axis. Further, Zakeri et al. (2008b; 2009c) introduced two conceptual measures to mitigate and control the debris flow impact forces on suspended and laid-on-seafloor pipelines. Brief descriptions of the experimental program, the method developed and the conceptual mitigative and control measures are given below.

3.1 Experimental Program

3.1.1 Flume Experiments

The physical flume experiments involved subaqueous gravity flow of various clay-rich slurries impacting a model pipe in a direction normal to its axis. The slurries were a mixture of kaolin clay, sand and water. A total of 50 experiments were carried out in a 0.20 m wide and 9.5 m long flume suspended inside a 0.6 m wide tank (Fig. 1). The flume slope was adjustable (3 and 6 degrees) and the bed was rough. The instrumentation consisted of:

- 2 Canon GL2 cameras for measuring the slurry head velocities near the gate and 5.9 m downstream - 720W x 480H pixels frame size at 30 fps,
- 2 high-speed EPIX cameras covering the area immediately upstream and downstream of the pipe to investigate the impact and flow characteristics in the wake - 1,280W x 1,024H pixels frame size at 30 fps and 550W x 600H pixels at 96 fps,
- 4 load cells to measure the drag and vertical forces - sampling rate of 1,000 Hz, and
- 1 submersible sonar to measure slurry flow and overriding turbidity heights. Transducer: A301S-SU, Olympus NDT and pulser/receiver: DPR300, JSR Ultrasonics.

Each time, 190 liters of slurry was prepared in the mixing tank located some 6 m above the flume and conveyed into the head tank. Two copper model pipe sizes, 22.2 mm and 28.6 mm O.D., were used. The high frequency sonar system consisted of a stationary 500 kHz submersible transceiver just below the mean water surface oriented normal to the sloping bed surface, approximately 0.62 m above the bed surface. The data collection protocol involved two sampling periods: the first period at 50 Hz for 60 second and the second period at 6 Hz for the next 30 minutes. For each ping, the system sampled backscatter at a rate of 8 MHz for 10,000 samples (1.25 milliseconds). The plexiglass flume walls are smooth and the shear stress induced on the slurries was assumed to be negligible (Crowe et al. 2001). The experiments attempt to model about 2 seconds of continuous flow, ideally under constant head condition.

Prior to the flume experiments, an extensive rheological study using laboratory rheometers was carried out to determine the slurry properties and suitable mix design. Table 1 presents the different slurry compositions and material properties.

The Brookfield DV-III Ultra vane-in-cup rheometer was used to determine the rheological properties of the slurries. The slurry preparation and rheology experiments were carried out in accordance with the ASTM (D2196-05) procedures. The results of the rheological experiments and mathematical models are presented on Fig. 2. All the results of the rheological experiments were repeatable within ± 5%. Both the Herschel-Bulkley and Power-Law models had a confidence of fit of 98% or greater.

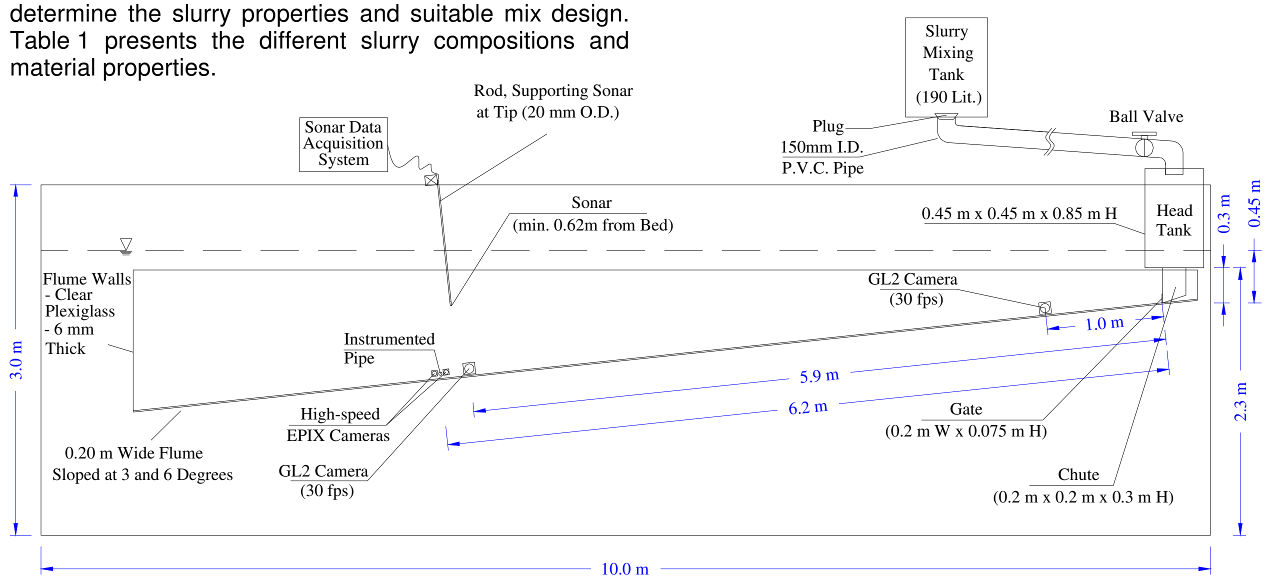


Figure 1. Experimental setup for flume experiments

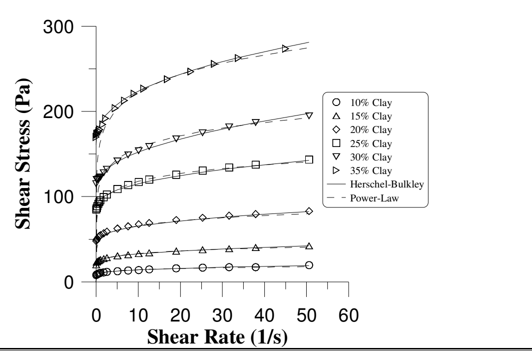
Table 1. Slurry composition and material properties

Slurry Percent Clay	Percentage Material by Mass			Density (kg/m3)	Sand Gradation	
					Mesh Size (mm)	% Passing
	Clay	Water	Sand		0.425	100
10	10	35	55	1,681.0	0.300	99.5
15	15	35	50	1,685.7	0.212	95.5
20	20	35	45	1,687.7	0.150	77.5
25	25	35	40	1,689.6	0.106	33.5
30	30	35	35	1,691.6	0.075	8.5
35	35	35	30	1,694.0	0.053	0.5

Notes:

1- Sand properties: Specific Gravity = 2.65, Uniformity coefficient (Cu) = 1.7 defined as the ratio of the maximum particle size of the smallest 60 percent (d_{60}) over that of the smallest 10 percent (d_{10}) of the granular sample. Cu = 1 for a single-sized soil, Cu < 3 a fairly uniform grading and Cu > 5 a well-graded (Whitlow 2001).

2- About 5% of the mass of sand was replaced by black diamond coal slag for visual purposes. The black diamond slag had the same specific gravity and grain size distribution as the sand.



Slurry	Rheological Models	
	Power-law	Herschel-Bulkley
10%Clay	$\tau = 10.3\dot{\gamma}^{0.14}$	$\tau = 7.3 + 3\dot{\gamma}^{0.35}$
15%Clay	$\tau = 25\dot{\gamma}^{0.125}$	$\tau = 20.5 + 5.5\dot{\gamma}^{0.35}$
20%Clay	$\tau = 50\dot{\gamma}^{0.12}$	$\tau = 43 + 10\dot{\gamma}^{0.35}$
25%Clay	$\tau = 91.5\dot{\gamma}^{0.11}$	$\tau = 85 + 12\dot{\gamma}^{0.4}$
30%Clay	$\tau = 118\dot{\gamma}^{0.125}$	$\tau = 110 + 15\dot{\gamma}^{0.45}$
35%Clay	$\tau = 165\dot{\gamma}^{0.13}$	$\tau = 161 + 25\dot{\gamma}^{0.4}$

Figure 2. Results of the rheological experiments (top) and Herschel-Bulkley and Power-Law mathematical model fits (bottom). The shear stresses are in Pascal.

Examples of the images taken by high-speed camera in the flume experiments are illustrated on Fig. 3.

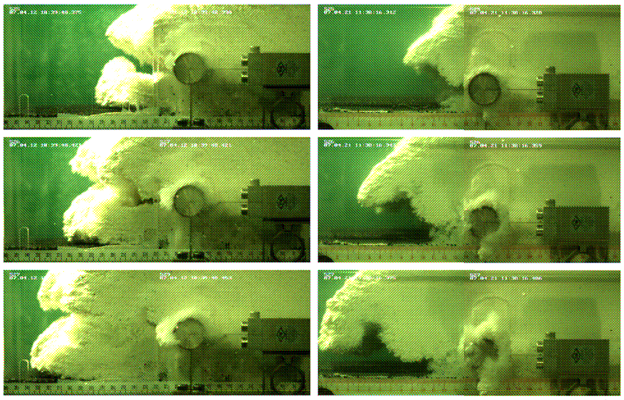


Figure 3. Typical impact, 20% clay slurry: (left) suspended pipe model, 1.09 m/s head velocity, (right) pipe-on-seafloor model, 1.13 m/s head velocity — consecutive images taken at a rate of 30 frames per second.

3.1.2 Numerical Analyses

The situations tested in the experiments were numerically analyzed using Computational Fluid Dynamics (CFD) method. The analyses were carried out using the CFD software, ANSYS CFX 11.0, which is based on the Finite Volume (FV) method for unstructured grids. The FV method uses the integral form of the conservation equations. With tetrahedra or hexahedra Control Volumes (CVs), unstructured girds are best adapted to the FV approach for complex 3D geometries (Ferziger and Perić 2002). The flume experiments constitute an incompressible two-phase, water and slurry, flow regime. The inhomogeneous two-phase separated Eulerian–Eulerian multiphase flow model of the CFX program was used to simulate the experiments.

The computational procedures consisted of first setting up and calibrating a numerical model to simulate the flume experiments using the rheological models given in Fig. 2. The numerical analyses were quite successful in closely simulating the subaqueous slurry flow characteristics (e.g. slurry head velocities, hydroplaning, slurry flow and overriding turbidity heights) as well as calculating the impact forces (normal drag and vertical) on the pipe models. Further, the flow parameters such as slurry velocity and shear rate profiles (upstream and around the pipe) computed in the CFD numerical analyses together with the high-speed camera images indicated that the experimental setup for suspended pipeline appropriately modelled the prototype situation. The model was then used to complement the flume data by running additional simulations with different slurry velocities and pipe diameters for both the suspended and laid-on-seafloor cases. Later, the numerical model was extended to cover all angles of incidence for the suspended pipeline case. As a result, both the normal and longitudinal (with respect to the pipe axis) impact drag forces on a suspended pipeline were investigated.

3.2 Method Developed to Estimate the Impact Drag Forces

The drag forces measured in the physical experiments and calculated in the simulations were correlated to the slurry head velocities measured upstream of the model pipe within a distance between 5 to 10 times the pipe diameter. It was observed in the experiments that in this range, the slurry flow is not affected by the presence of the pipe and therefore, the slurry head velocities could be considered as the free upstream flow velocity, U_∞. The fluid flow characteristics around an object of a given shape strongly depend on parameters such as the object size and orientation, relative velocity between object and fluid, and fluid properties. For the drag force, it is customary to use the inertia type of definition (White 2006), and define it by using a drag coefficient, C_D, through dimensional analysis by Eq. (4):

$$C_D = \frac{F_D}{\frac{1}{2}\rho \cdot U_\infty^2 \cdot A} \tag{4}$$

where, F_D and A are the total drag force and the projected slurry-pipe contact area (i.e. pipe diameter times the contact length), respectively, and ρ is fluid density. For the normal drag force, $F_{D\text{-}90}$, A is the pipe cross-sectional area projected onto the plane normal to the flow direction and for the longitudinal drag force, $F_{D\text{-}0}$, onto the plane parallel to the flow direction. C_D is a function of both the Froude number (Fr) and the Reynolds number (Re), which are the most important dimensionless parameters for studying incompressible fluid flow around an object. For many flows the gravitational effects are unimportant such as for the flow around a body or an airfoil where gravity waves are not generated. In that case, the Froude number is irrelevant and the drag coefficient becomes only a function of the Reynolds number (Kundu and Cohen 2004). The classical definition of the Reynolds number for a Newtonian fluid is:

$$\mathrm{Re}_{Newtonian} = \frac{\rho U_\infty D}{\mu} \tag{5}$$

where, μ is the absolute (dynamic) viscosity, and D is the length characteristic - here, the pipe diameter. This definition is not directly applicable to the problem of non-Newtonian fluid flow past a circular cylinder. Hence, an ad hoc Reynolds number was proposed for shear-thinning, non-Newtonian fluids described by the Power-law or Herschel-Bulkley rheological models. It was based on the apparent viscosity as opposed to the absolute viscosity. The apparent viscosity is defined as the ratio of shear stress to the rate of shear of a non-Newtonian fluid. The apparent viscosity changes with changing rates of shear and must, therefore, be reported as the value at a given shear rate. Here, for the impact situations the shear strain rate immediately outside the boundary layer is defined as:

$$\dot{\gamma} = \frac{U_\infty}{D} \tag{6}$$

where, U_∞ is the approaching debris head velocity. The pipe diameter is taken as the length scale. In shear-thinning fluids of the Power-law or Herschel-Bulkley models, the apparent viscosity, μ_{app}, is defined as:

$$\text{Power-law: } \tau = a \cdot \dot{\gamma}^{n} \text{ thus } \mu_{app} = a \cdot \dot{\gamma}^{n-1} \tag{7}$$

$$\text{Herschel-Bulkley: } \tau = \tau_C + K \cdot \dot{\gamma}^{n} \text{ thus } \mu_{app} = a \cdot \dot{\gamma}^{n-1} \tag{8}$$

In the above equations, τ and τ_C are the fluid shear stress and fluid yield stress, respectively, and the parameters a, n and K are model parameters which are determined from rheology testing. The Bingham model is a special case of the Herschel-Bulkley model where the fluid parameter, n, is equal to unity and the consistency, K, is the same as the Bingham viscosity, μ_B. The behaviour of most clay-rich debris flows can be described by the Herschel-Bulkley model (Locat 1997). The results of the numerical analyses indicated that Eq. (6) provides a reasonable approximation for the rate of shear induced on the slurry upon impact with the pipe as the magnitude of the shear rate induced on the slurry drops significantly away from the pipe surface - an order of magnitude within about a millimeter away from the pipe surface and two orders of magnitude within about 3 mm. This relatively small distance from the pipe surface basically constitutes the boundary layer thickness. Hence, the use of Eq. (6) is also appropriate for the field situation of submarine debris flow impact on pipelines. Using the shear rate defined by Eq. (6) and the apparent viscosity, defined by Eqs. (7) or (8), the following form of the Reynolds number is proposed for the problem of debris flow impact on pipelines:

$$\mathrm{Re}_{Newtonian} = \frac{\rho \cdot U_\infty^2}{\mu \cdot \dot{\gamma}} \text{ thus: } \mathrm{Re}_{non-Newtonian} = \frac{\rho \cdot U_\infty^2}{\mu_{app} \cdot \dot{\gamma}} = \frac{\rho \cdot U_\infty^2}{\tau} \tag{9}$$

The drag coefficient, C_D, was obtained using the total drag force (i.e. the sum of the viscous and inertia forces) measured from the experiments and calculated in the simulations using Eq. (4), and its dependency on the Reynolds number defined by Eq. (9) was then investigated. Ultimately, the following relationships were proposed for estimating the normal drag force on a pipeline for design purposes:

$$\text{Suspended Pipeline: } C_{D-90} = 1.4 + \frac{17.5}{\mathrm{Re}_{non-Newtonian}^{1.25}} \tag{10}$$

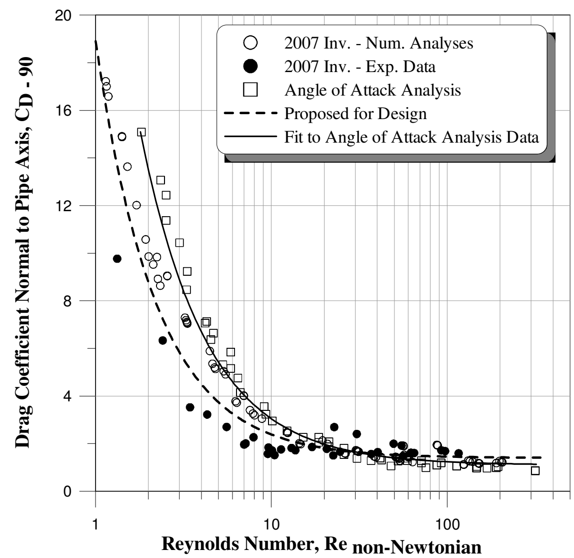
$$\text{Laid-on-seafloor Pipeline: } C_{D-90} = 1.25 + \frac{11.0}{\mathrm{Re}_{non-Newtonian}^{1.15}} \tag{11}$$

The above proposed relationships (dashed line for Eq. (10) and bold solid line for Eq. (11)) are shown on Fig. 4 along with the results of the physical and numerical experiments.

For the longitudinal drag force, the following C_{D-0}-Re relationship was proposed:

$$\text{Suspended Pipeline: } C_{D-0} = 0.08 + \frac{9.2}{\mathrm{Re}_{non-Newtonian}^{1.1}} \tag{12}$$

The above relationship which is based on CFD numerical analysis is shown on Fig. 5. The drag force normal to pipe axis is developed as a result of both dynamic pressures and viscous forces around the pipe whereas, the longitudinal drag force is due to the shear stress on the pipe surface. As such, the drag coefficients (i.e. C_{D-0}) computed from the CFD model are believed to be representative of the prototype.



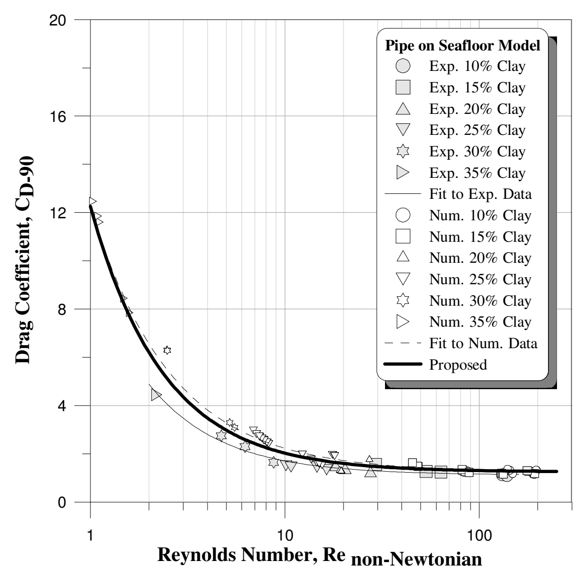


Figure 4. Drag coefficient versus Reynolds number curves: (top) suspended pipe model and (bottom) pipe on seafloor model. The angle of attack is normal to the pipe axis.

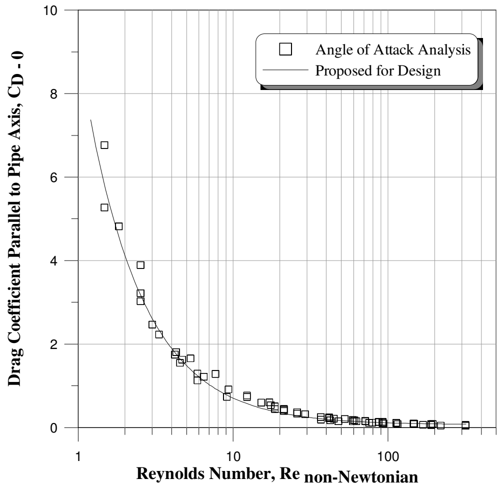


Figure 5. Drag coefficient versus Reynolds number: suspended pipeline, longitudinal impact drag force

3.3 Conceptual Mitigation and Control Measures

3.3.1 Berm-Protected Laid-on-Seafloor Pipeline

Designing a pipeline against failure or significant damage caused by debris flow impact is a key challenge. Berms constructed with gabion mats (wire mesh baskets filled with rockfill) stacked on top of each other may be considered as the protective structure for section of a pipeline (Fig. 6). Similar systems using highly durable (minimum 20-25 year of life) bituminous mattresses and Cross-Linked Polyethylene (XLPE) coated gabions have successfully been used offshore Turkey and Italy to protect the pipelines where burial or post-trenching was unfeasible (e.g. Vicari and Branzanti 2002).

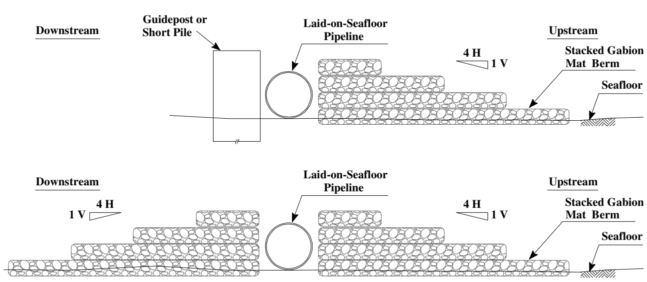


Figure 6. Conceptual design, berm-protected laid-on-seafloor pipeline: (top) upstream berm and guidepost system and (bottom) upstream and downstream berm protection system.

As part of the flume experiments (Fig. 1), one test was carried out to investigate the influence of an upstream berm on reducing the drag force on the laid-on-seafloor model pipe. A mock-up berm with trapezoidal cross section was constructed out of wood and fastened to the flume bed upstream of the test pipe. The flume experiment results showed that there is a possibility to protect a pipeline provided that the protective structure can withstand the basal shear forces induced by the debris flow on its surface. Later, Zakeri et al. (2009c) complemented the flume experiment by a series of CFD numerical simulations and presented a method for preliminary design of such protective structures. The berm-protected laid-on-seafloor pipeline concept is mainly suitable for shallow waters such as fjords, bay and river crossings were pipeline burial may be impractical for reasons such as rocky bed or economics.

3.3.2 Cable-Controlled Pipeline System

Demars (1978), Swanson and Jones (1982) investigated the failure of buried pipelines in the Gulf of Mexico and concluded that the failure mechanism is that of a tensile force generated at an upstream point in the line outside the slide zone. An unrestrained pipeline is structurally slender and exhibits a cable-like behaviour upon contact with a moving soil mass transforming the exerted drag forces into that of tension under which, it ultimately may fail. Pipelines are made up of sections of pipes and therefore, the rupture would most likely take place at or near the joint(s).

Figure 7 illustrates a cable-pipeline system through which the impact drag forces are transformed into tension and then transferred as lateral forces onto the suction caissons. The impact drag force may be estimated using the method discussed in the previous section from which the total tension force can be calculated assuming a cable-like behaviour of the pipeline. The number and size of the cables or strands can then be determined. The guide hoops have two major functions: 1) facilitate proper and uniform distribution of the cables around the pipeline, and 2) maintain this circumferential cable distribution after the impact and restrain the pipeline inside the cable-bundled system. The guide hoops can be designed to accommodate various cable / strand arrangements and can be installed at various intervals.

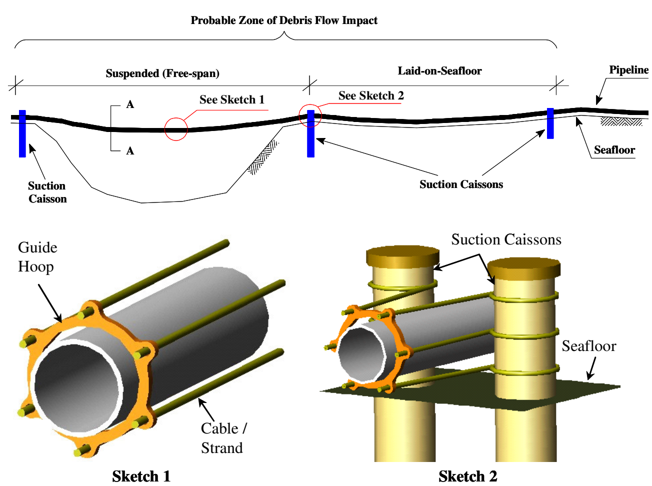


Figure 7. Conceptual design – cable-controlled system

Such cable-pipeline systems may be installed in shallow and moderately deep waters where the seabed is soft enough for suction caisson installation. There are well established design guidelines for suction caissons against lateral loading. Zakeri et al. (2009c) provided guidelines and numerical examples for the preliminary design of a such measure. The above is just a conceptual representation of the measure. Other arrangements may be devised. Additional investigation is required to study the feasibility and design issues such as vortex shedding force for such a system.

4 FUTURE OUTLOOK

Submarine landslides occur frequently on both passive and active continental margins releasing sediment volumes that may travel distances as long as hundreds of kilometres on gentle slopes (0.5 to 3 degrees) over the course of less than an hour to several days (Nadim and Locat 2005). The demand for hydrocarbon drives the oil and gas activities into the deep and ultra-deep waters exposing the facilities to a far greater geohazards, particularly those arising from submarine landslides, debris flows and turbidity currents. Hence, development of safe, cost-effective and reliable engineering solutions to protect the seafloor infrastructure has become a key challenge for the industry and a requirement for sanctioning deep and ultra-deep water developments.

There is a significant potential and need for improving the state-of-the-art to estimate impact drag forces on submarine pipelines and piles caused by debris flows. Towards this goal, the fluid dynamics approach combined with the principles of rheology for debris flows should be studied further given the capability for modeling a wide range of flow velocities and shear rates. Further experimental investigations inform of laboratory model tests and complementary numerical analyses are required. The investigations must take into account the rheology of debris flow materials as well as the rate of shearing (i.e. velocity effects) for the soil-structure interaction study in an impact situation.

The outcome of the recent investigations is a leap forward in the state of the art with respect to submarine debris flow impact on pipelines. It brings together and draws from the fields of geotechnical engineering, fluid dynamics, science of rheology and numerical analysis techniques. However, much work remains to be done. For example, the method should be extended to cover the impact of sand-rich debris flows on pipeline at various attack angles. Further, the methods should include piles, suction caissons and mooring systems. Finally, mitigation and control measures should be investigated to protect the seafloor installation.

5 CONCLUDING REMARKS

A combined experimental and numerical approach was used to develop a simple method for estimating the drag forces on suspended and laid-on-seafloor pipelines caused by a clay-rich debris flow impact. The method was based on fluid dynamics principles where the drag force is presented in the non-dimensional form – drag coefficient. An ad-hoc Reynolds number was defined to describe flow characteristics of clay-rich debris flows of shear-thinning non-Newtonian fluid behaviour described by Bingham or Herschel-Buckley rheological models. Drag coefficients were calculated for situation where the impact causes drag forces both normal and longitudinal to the pipe axes.

The experimental setup, instrumentation and testing procedures in the flume as well as the CFD simulations worked very satisfactorily. In practice, submarine pipe diameters range between 0.1 m to 1.0 m. Assuming a debris flow velocity between 1 m/s to 10 m/s, density of 1,600 kg/m^3 and shear stress between 0.5 kPa and 2.0 kPa, the shear rate upon the impact with a pipe would be in the range of 1 s^{-1} and 100 s^{-1}, and one would find the corresponding Reynolds number to be between 0.8 and 320. The experiments covered the Reynolds numbers between about 2 and 320 (i.e. more than two log cycles), and therefore, are considered appropriate for practical purposes.

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