Drag force investigation in the collision between sub-aqueous mudflows and pipeline

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Abstract— **This paper describes an investigation of the events when sub-sea pipeline is impacted by submarine slide. Investigations are carried out by developing the model in the laboratory in the form of a collision between sub-aqueous mudflow with a pipe stem. Gravity flow concepts of fluid mechanics principles and lock-exchange system are adopted to build the laboratory experiment. It is implemented into a set of equipment of rectangular channel to generate the simulation of mudflow in water ambient. A crosswise pipe stem positioned at certain run-out distance is collided by mudflow. Mud model used is slurry of kaolin clay-water mixtures. The collision attributes of the collision event is including velocity, Reynolds number, maximum drag force exerted by mudflow, and drag force coefficient. All are observed based on percentage of kaolin clay content. The series of experiments is representing the estimation of drag forces exerted by muddy submarine slide on pipeline in the prototype condition.**

Keywords-drag force; gravity flow; lock-exchange; mudflow; drag force coefficient

INTRODUCTION

The rapid development of oil and gas industry, which is moving to depth over 1000 m along or in propinquity of the continental slope [1] has consequences that pipelines installation are subjected to geologically hazardous condition of submarine slide. Mudflows is one type of submarine slide, originating from unconsolidated clays (the main material of seabed sediment deposits) which after collapse transform into a finely mixture of clay and water. Several studies revealed that the submarine slide involved cohesive fine-grained material, i.e. clays and silts [2]. In different studies, muddy material in terrigenous clastic sediment dominated the schematic of sediment deposits [3]. Furthermore, kaolin was the most predominant clay mineral contained in seafloor sediment [4-6].

In the scope of the seabed geo-hazard study, the major concern is facilities and infrastructure damages caused by the underwater flow of submarine mudslides, especially pipelines. In this case, the interaction between mudflow and pipeline generates drag force. This force is exerted by mudflow and is a destructive force against the pipelines. As proposed in predecessor researches of mass flow-pipe interaction, drag coefficient has been determined experimentally through geotechnical and fluid dynamics approaches [7-8].

Previous experiments used granular material (sand and gravel) in their debris model in order to imitate the contexture of submarine sediment deposit [9-13]. While clay (in mud form) was predominant deposit, then its essential movement (and/or its flow) is very necessary to be initially observed as basic representative mode of submarine sediment transport. Hence, this experiment is limited to use mud only (without other granular material, such as sand and gravel).

The aim of this research is to investigate the drag force exerted by mudflow in the collision against pipe stem in the course of laboratory simulation. The determination of drag force and drag coefficient is referring to rheological properties of mud model. The current experimental work is carried out in view of providing the basis for developing methods for prediction of the mudflow impact forces on pipe stem.

BACKGROUND

Fluid dynamics approach implemented using gravity flow concept has been widely used in research on fluid flow with two phases of different fluid density. This method is applied in the calculation and analysis of impact force of mudflow on pipe stem in the current study. It accommodates the additional effect of flow plasticity on the drag force related to the dynamic pressure which is proportional to mud density and the squared flow velocity. Therefore, drag force generated by mudflow on pipe stem can be expressed by traditional fluid dynamic force and rheology properties of non-Newtonian fluid flow as the following equation [14].

$$F_d = \frac{1}{2} \cdot \rho_f \cdot C_d \cdot A \cdot u^2 \tag{1}$$

where F_d is the drag force components perpendicular to pipe axis, ρ_f is the mud density, C_d is the drag coefficient, A is area of pipe stem which is facing opposite to mudflow direction, and u is flow front velocity of mudflow. As seen in (1), drag force analysis of this interaction is determined by mudflow's properties of density and velocity together with pipe's physical attribute of outside diameter (OD) and surface area.

EXPERIMENTAL PROGRAM

Laboratory experiments are implemented by development the main equipment of a rectangular channel of 8.53 m length, 0.25 width, and heights of 0.7 m and 1.30 m at the beginning and end point respectively. It is designed and assembled at Hydrology Laboratory of Universiti Teknologi PETRONAS, Malaysia. In this experiment, the slope angle used is 3 degrees. It is according to field observation data that set down as the highest frequency density distribution of the average angle of the slope at failure for the seafloor slope failures to be in the range of 3 to 4 degrees [2]. As shown in Fig. 1(a), the laboratory experiment is basically simulate a slump of mud, sliding into a pool of water then flowing over the surface of

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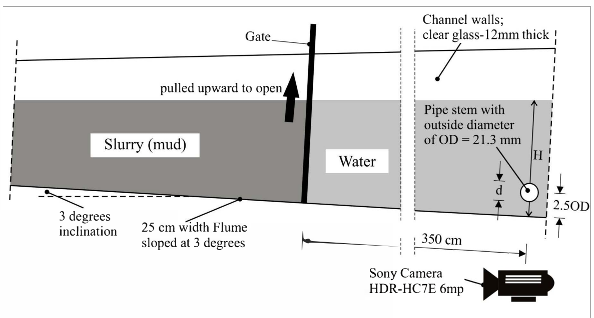
channel base and eventually colliding with the pipe stem at certain run-out distance.

Detail of assembly of pipe model (21.3 mm OD) connected to load cell apparatus is shown in Fig. 1(b). The current setup is using load cell type of DDEN-250N-RS485 with environmental protection of IP68 to 10 m depth. A data logger device of 'Smart Dynamic Strain Recorder' SDSR of DC-204R series is used to record the force responses of the load cell, which represents the force generated by mudflow during collision between mudflow and pipe model.

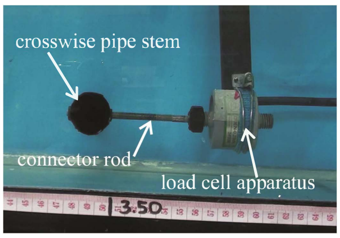
Mud model in this experiments was prepared as mixtures of refined kaolin and water with percentage variations of kaolin clay content (abbreviated as KCC) in range 10% to 35% (weight based), with 5% increment. The rheology properties of mud was obtained by using Brookfield Digital Viscometer DV-I+ equipment, according to ASTM D2196 [15]. The test was revealed the values of dynamic viscosity (μ) of each mud model at certain applied shear rate ($\dot{\gamma}$). Furthermore, results addressed by test were used to characterize type of mud in term of shear rate-shear stress relation. In the current study, Herschel–Bulkley model (abbreviated as *H-B* model) is adopted to characterize the mud rheological behavior and is expressed as in the following equation.

$$(\tau - \tau_c) = K \cdot \dot{\gamma}^n \qquad (2)$$

where, τ is shear strength, τ_c is the yield strength, K is equivalent to the dynamic viscosity, and n is positive parameters of model factor. Even though the linear viscoplastic Bingham model is the most commonly used to describe rheology of debris or mudflow, the *H–B* model has been found to be more appropriate for describing the nonlinear viscoplastic behavior of debris flows [16-17].



(a)



(b)

Figure 1. Laboratory equipment; (a) scheme of laboratory experiment setup; (b) load cell apparatus connected to pipe model.

TABLE I. MUD PROPERTIES BASED ON KCC AND *H-B* MODELS

KCC *(%)*	**Density (ρ_f)**		**Specific Gravity** *(GS)*	***H-B* model**
	(lbs/gal)	*(kg/m³)*		
10	8.79	1054	1.07	$\tau = 0.6 + 0.73\,\dot{\gamma}^{0.3}$
15	9.10	1092	1.10	$\tau = 1.71 + 1.63\,\dot{\gamma}^{0.27}$
20	9.45	1134	1.13	$\tau = 3.4 + 4.73\,\dot{\gamma}^{0.32}$
25	9.60	1152	1.20	$\tau = 3.57 + 8.88\,\dot{\gamma}^{0.4}$
30	10.3	1236	1.23	$\tau = 5.7 + 12.68\,\dot{\gamma}^{0.42}$
35	10.55	1266	1.27	$\tau = 9 + 20.36\,\dot{\gamma}^{0.5}$

Rheology test results summarized in Table I denotes the propagation of density, specific gravity, and *H-B* model based on percentage of KCC. Mud densities are in the range of 1054 kg/m^3 to 1266 kg/m^3 with increment of yield strength, τ_c, in the range of 0.6 Pa to 9.0 Pa.

RESULT AND DISCUSSION

Experiments were performed repeatedly three times for each percentage of KCC in order to obtain the typical flow behavior for a given percentage of KCC. Data used in analysis were the average data of those three experiments. The measurement and analysis of physical data obtained from the movement during flow consisted of velocity, u, at certain run-out distance, l, and drag force, F_d. The velocity of the mudflow as a function of flow-time and run-out distance is the main data obtained from laboratory experiment, so in the result analysis, it is the reference point for the elaboration and examination of the impact force on pipe stem exerted by mudflow. The flow also generated very small wave in water surface, however, this phenomenon was not observed further since the water surface was definitely free surface condition.

The total 18 executions of laboratory experiments for all percentage of KCC addressed velocity measurements with a pattern of acceleration and deceleration of the flow. Flow velocities were calculated by dividing the run-out distance with time. The distance was determined the distance based on two sequential images (captured by camera). The most front part of mudflow was point to identify the position. Observation reference points (ORP) were made at every 0.25 m interval along the flume to assist the mudflow measurement. Each mud models of 10% to 30% KCC had a relative small fluctuation of flow front velocity in the range of 0.237 m/s to 0.289 m/s at run-out distance of 3.5 m (i.e. at pipe position), whereas 35% KCC underwent a rapid deceleration and stopped at around 2.3 m of run-out distance. The propagations of velocities are shown in Fig. 2. Based on the velocity values, Reynolds number, *Re*, is calculated using the following equation.

$$Re = \frac{\rho_f \cdot u^2}{\tau} \qquad (3)$$

The value of the shear stress (τ) occurred during test is determined based on actual flow velocity in Fig. 2. It shows that all flows result the velocity (u) in the range of 0.164 m/s to 0.439 m/s after 0.5 m of run-out.

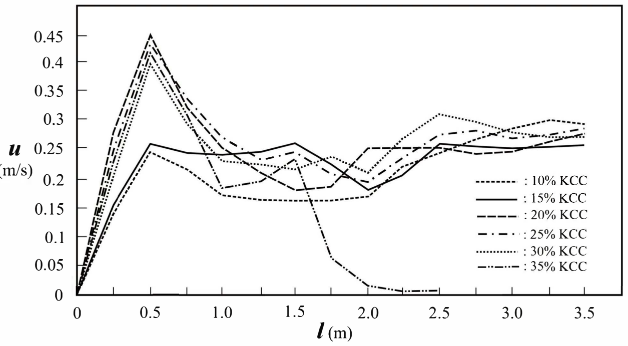


Figure 2. Mudflow velocities as a function of run-out distance in range of 0 to 3.5 m.

With reference to Brookfield rheology test, the velocity with that range has values of shear rate ($\dot{\gamma}$) from 7 to 34 s^{-1}. Thus, referring to (2) and Table I, the mudflows in this current experiment are described as generating the minimum shear stress (τ_{min}) of 4.47 Pa and maximum (τ_{max}) of 127.72 Pa. The maximum shear stress (τ_{max}) was occurred at around ORP of 0.5 where the flows developed the highest acceleration as seen in Fig. 2. Values of $\dot{\gamma}$ produced by these flows are higher than 3 s^{-1}, which are appropriate with the range of interest for the flume experiments as stated in [13].

Based on data of velocities and shear stress determined above, this current experiments address value of *Re* ranged from 1.34 to 40.14, where the lowest % KCC produced the lowest value of *Re* and vice versa. In further, mudflows with this range of *Re* are considered as laminar flow as small value of *Re* and viscous forces are dominating to inertial forces. This inference is in line with the selection method that fluid mechanics principles approach is more appropriate than the geotechnical.

Implementation of the collision experiments is obtaining sequential images captured by camera device. Fig. 3 shows the consecutive mudflows images captured of 15% KCC mud during collision against suspended pipe stem with *H*/*d* ratio of 18.3. The collisions generate drag force (F_d) exerted by mudflows on pipe stem. Measurement data of impact force magnitude are obtained from signal response provided by load cell, which is connected to pipe stem (see Fig.1 (b)). Load cell apparatus provides responses of the impact force in signal form, which is converted by data logger into force unit of Newton (N) as shown in Fig. 4. As a signal form, it was very difficult to determine the actual drag force occurred during collision. Even more, it is most likely involving the noise signal during generating responses of load cell. These two conditions cause inaccurate force magnitude read. Therefore, signal processing is implemented to get a precise read of data logger output. Tool of Fast Fourier Transform (FFT) was employed to analyze the data logger output. Measured data produced by data logger is time series of drag force (i.e. time domain data). In principle, FFT algorithm implements the discrete Fourier-transform to transform data from time domain into the frequency domain. It can be developed through computational programming of MATLAB.

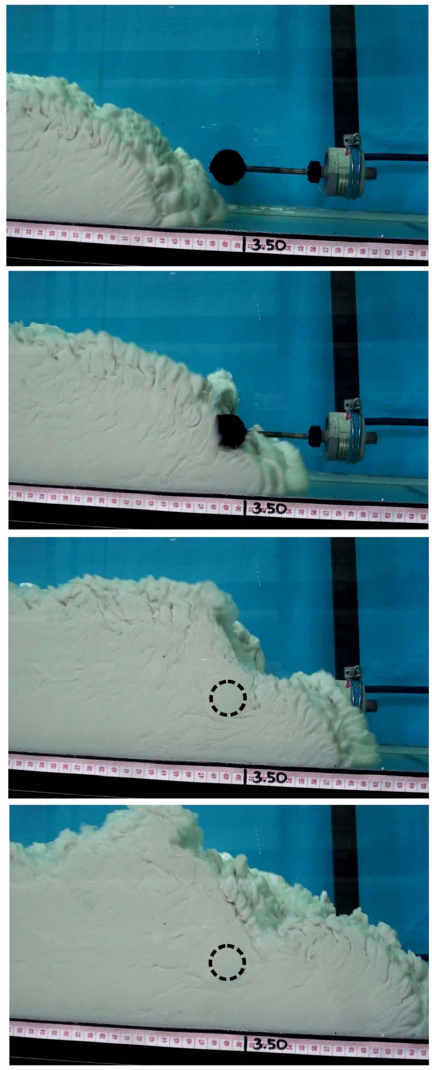


Figure 3. Collision events of 15% KCC mudflows against suspended pipe stem of 21.3 mm OD; *H*/*d* ratio: 18.3; *u*: 0.25 m/s. Consecutive captured images are taken within duration of 0.81 s.

Fig. 4 shows the result of noise filtration produced by FFT filter that the maximum force occurred in collision is not as high as data logger output.

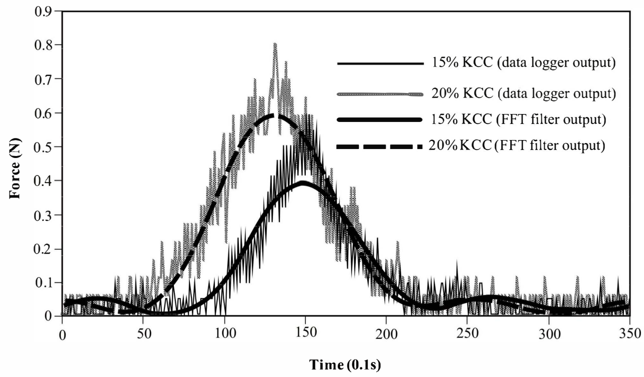


Figure 4. Force responses of data logger output and FFT filtered output of 15% KCC and 20% KCC mudflows on suspended pipe stem (OD 21.3 mm)

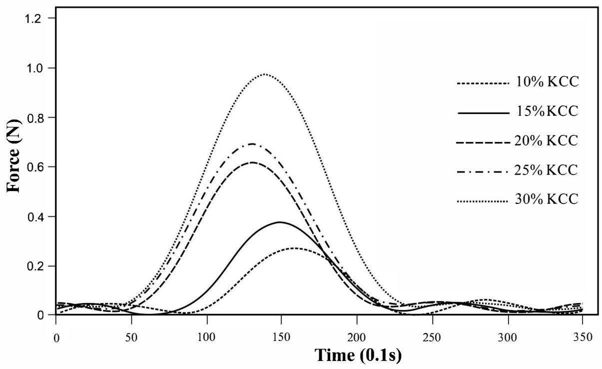


Figure 5. Force responses of FFT filter output of each percentage of KCC (H/d: 18.3)

This condition is caused by the noise of signal affected the load cell and involved in data logger recording. Hence, FFT filter output which has noise removal is representing the actual drag force exerted by mudflow. Then, drag force analysis is made by referring to this result. It is also used to determine the magnitude of drag force coefficient (C_d) of all collision events by using the following equation which is as other expression of (1).

$$C_d = \frac{F_d}{\frac{1}{2} \cdot \rho_f \cdot A \cdot u^2} \quad (4)$$

Fig. 5 shows the typical responses of drag force exerted by mudflow for each percentage of KCC resulted by FFT filtration process. Data filtering using the current FFT filter addressed the maximum drag force of all current experiments in range of 0.248 N to 1.104 N. Coefficients of drag forces (C_d) are calculated based on the maximum values of F_d for each percentage of KCC because in order to observe the maximum impact of mudflow to pipe model. The calculation using (4) obtained magnitudes of C_d in range of 0.74 to 3.34 and are presented in Table II. Flow measurement and analysis results including drag force as well as the coefficient, and Reynolds number are listed in the same table.

TABLE II. FLOW FRONT VELOCITIES AND COLLISION ANALYSIS INCLUDING REYNOLDS NUMBER, DRAG FORCES, AND THE COEFFICIENTS

Mud model	ρ (kg/m^3)	u (m/s)	Re	$F_{d\text{-max}}$ (N)	C_d
10%KCC	1054	0.264	34.44	0.248	0.80
	1054	0.278	38.19	0.252	0.74
	1054	0.285	40.14	0.267	0.74
15%KCC	1092	0.256	14.54	0.376	1.25
	1092	0.251	13.98	0.361	1.25
	1092	0.248	13.65	0.336	1.19
20%KCC	1134	0.289	6.85	0.603	1.52
	1134	0.281	6.48	0.573	1.52
	1134	0.274	6.16	0.515	1.44
25%KCC	1152	0.256	2.06	0.679	2.14
	1152	0.264	2.19	0.705	2.09
	1152	0.259	2.11	0.694	2.14
30%KCC	1236	0.237	1.34	0.974	3.34
	1236	0.264	1.66	1.104	3.05
	1236	0.251	1.50	1.038	3.17

As a non-dimensional parameter, Re is used to make a comparison between values of C_d provided by certain percentage KCC. By using Re, factors of density, velocity, and shear stress (see Table I and Table II) of mudflow are represented; thus, it is becoming more general comparison. By taking (3) and (4), it is possible to put across the C_d as relative to Reynolds number (Re). Furthermore, C_d-Re relationship is expressed as the following.

$$C_d = a_i + b_i \cdot Re^{c_i} \quad (5)$$

where a, b, and c are constants. In doing so, C_d-Re relationship was obtained by applied a solver of least squares approach of curve fitting method to laboratory experiments data. The approximation error (ε) is formulated as follow;

$$\varepsilon = \sum_{i=1}^{n} (C_{d_i} - (a_i + b_i \cdot Re^{c_i}))^2 \quad (6)$$

where n is the number of experiments.

Fig. 6 presents the results of drag force coefficient analysis as relative to Reynolds number. There are three types of graph those are C_d propagation obtained from calculation of laboratory data, fitted curve of calculation of laboratory data, and results of calculation using C_d formulation proposed by previous study. As mentioned in introduction that Zakeri [13] observed the drag force coefficient of debris flow which was mixture of kaolin clay, silica sand, and black diamond coal slag. The study proposed the C_d formulation as $C_D = 1.6 + \frac{12.8}{Re^{1.45}_{non\text{-}Newtonian}}$; where C_D is the drag coefficient [13].

The fitted curve shown in Fig. 6 is the proposed formulation of drag force coefficient of this current study. It is expressed as follow;

$$C_d = 0.84 + 3.24 \cdot Re^{-0.98} \quad (7)$$

The proposed equation of current study addressed the lower values of C_d compared to previous study. However, the trends of both graph lines are similar. Since the mixture of slurry used for each study was different, this similarity of trend indicates that kaolin clay content plays the major role in mudflow movement and collision, whereas granular materials just provide an extra density which increases the flow velocity.

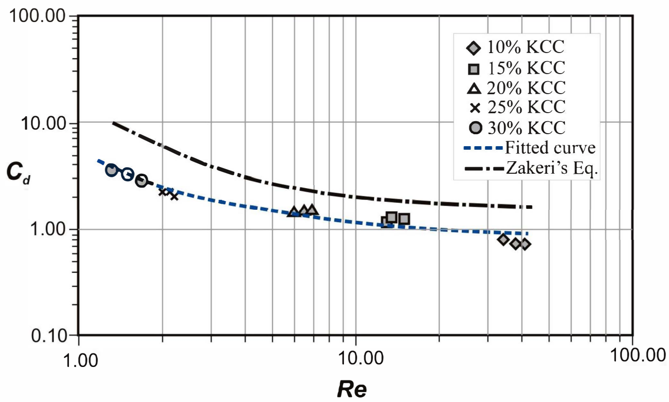


Figure 6. Drag force as relative to Reynolds number for each percentage of KCC, fitted curve, and previous study's formulation

CONCLUDING REMARK

Experimental work series of collision between mudflow and crosswise pipe stem was conducted to investigate the characteristics and coefficients of drag force exerted by mudflow. Mud model was mixtures of kaolin and water with densities in the range of 1054 kg/m^3 to 1266 kg/m^3. Herschel-Bulkley rheological model fitted very well the rheological properties, which were tested using Brookfield Digital Viscometer DV-I+.

Fluid mechanics approach and gravity flow concepts were implemented by development of lock-exchange system. It generated mudflow in water ambient on 3 degrees sloping base, which was colliding with the crosswise pipe stem at position of 3.5 m of run-out distance. The collision attributes of velocity, Reynolds number, maximum drag force exerted by mudflow and drag force coefficient were analyzed based on percentage of kaolin clay content. The current experiment generated a high similarity result of trend line graph with the previous study. It indicated that the content of clay material (i.e. kaolin) play a major role in mudflow movement and collision, whereas granular materials (used in previous study) provide an extra density. In further, the results addressed by this current study may be represented the basic reference for investigation of drag forces exerted by sub-aqueous mudflow on pipe considering the simple mud model used in the experiments as pure slurry of mud without granular material.

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