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Scour depth under pipelines placed on weakly cohesive soils

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Abstract

We here study the scouring processes that evolve around a submarine pipeline placed on a weakly cohesive seabed. We first analyze some laboratory tests carried out by Vijaya Kumar et al. (2003), Xu et al. (2010) and Zhou et al. (2011) that focused on the scouring around a horizontal cylinder lying on a cohesive bed, subject to waves and currents. The specific purpose is that of finding a new formula for the prediction of the equilibrium scour depth under submarine pipelines. After a theoretical analysis of the main parameters, the sought formula has been found to be a function of: i) the hydrodynamic forces acting on the cylinder (through the Keulegan-Carpenter parameter KC), ii) the clay content of the soil C_c, and iii) the burial depth e_0/D. In the presence of small amounts of clay ($C_c < 5\%$), the scour depth depends directly on KC (as confirmed by many literature works for pipelines lying on sandy soils, e.g. Sumer and Fredsøe, 2002) and inversely on C_c (as already seen for bridge abutments on cohesive soils, e.g. Abou-Seida et al., 2012), the best-fit law being characterized by a coefficient of determination $R^2 = 0.62$. If some burial depth is accounted for, this being a novelty of the present work, a more general formulation can be used, valid in the presence of weakly-cohesive soils and with burial depths of the pipe smaller than 0.5 ($R^2 = 0.79$). For large clay-content ranges ($2\% < C_c < 75\%$), the scour depth depends directly on both KC and C_c, this giving $R^2 = 0.79$ (no burial depth) and 0.91 (some burial depth). However, this finding is at odds with the main literature, because, for large amounts of clay, it is fundamental to consider the liquidity index LI, which accounts for some important clay properties, like the plasticity. We argue that the absence of LI is balanced by the direct dependence of the scour depth on C_c. Notwithstanding the small number of available data, a formula for the prediction of the scour depth under pipelines lying on cohesive soils is fundamental for several engineering applications. The present contribution represents the first attempt to build such a formula, when the pipeline is subject to the wave-current forcing and the seabed is characterized by a relatively small clay content.

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1. Introduction

The ever increasing need of energy pushes the search of new resources in all fields (i.e. Oil&Gas, renewables, etc.) and directions. That is why also the Oil&Gas industry is exploring new regions for the extraction of oil and gas. This, in turn, leads to a continuous growth of offshore fields and of underwater pipelines. In fact, most offshore hydrocarbon products are transported to shore by underwater pipelines that lay on either rigid or erodible seabeds. Understanding the flow that waves and currents induce around these pipelines is critical in assessing the loads that they experience (e.g. Mattioli et al., 2013) and in identifying necessary measures to ensure stability and safety (e.g. DNV, 2010).

The stability and safety of an underwater pipeline can be put at risk because of the interactions that the water flows can have with the pipeline itself and with the seabed. Such interactions are particularly varied in the case of an erodible seabed, i.e. made of soils which can be broadly classified as non-cohesive (e.g., gravel, sand) and cohesive (e.g., clay) materials, the latter being characterized by a non-zero percentage of clay. As an example, silty soils can be still taken as cohesive when a small clay content exists. In this case mobilization of the sediment can lead to different forms of erosion around a pipeline. Of particular interest is the scouring beneath a pipeline.

Placing a pipeline near a seabed significantly alters the local environment. As a result, a pressure gradient may occur between the upstream and downstream sides of the pipeline, forming vortices in the neighborhood of the pipeline. Piping underneath the erodible seabed (generation of a seepage flow in the sand beneath the pipeline), is followed by a second stage of tunnel erosion (large flows in the gap lead to large bed stresses) and by the final lee-wake erosion, which is characterized by significant vortex shedding (e.g. Sumer and Fredsøe, 2002; Mattioli et al., 2012; Kizilöz et al., 2013).

The above process has been the object of significant research efforts. For example, the critical conditions for the onset of scour have been studied by Mao (1986), Chiew (1990) and Sumer et al. (2001). While the detailed sediment dynamics which occurs during scouring has been the focus of the contributions of Sutherland (1967), Kaftori et al. (1985a), Kaftori et al. (1985b) and Mattioli et al. (2012). All these studies of detail have led to some simple relationships for the calculation of the scour dimensions.

However, virtually all of those studies have focused on the analysis of scour around pipelines placed over either sandy or silty seabeds. Very little is available in terms of basic knowledge and modeling of scouring processes around pipelines placed over cohesive sediments. This is true to the point that even studies dedicated to the field assessment of scouring processes that evolve on cohesive seabeds have to resort to formulas derived and validated for non-cohesive sediments (see, for example, Xu et al., 2012).

Only very recently, also due to the increasing extension of submerged pipelines over cohesive seabeds, significant attention is being paid to the prediction of scouring processes affecting pipelines placed over cohesive seabeds (e.g., see Vijaya Kumar et al., 2003). Much of the knowledge and experience is derived from scouring of bridge piers placed over cohesive sediments (Abou-Seida et al., 2012).

The difficulty in describing the cohesive-sediments scouring comes from the rather different small-scale behaviour of cohesive and non-cohesive sediments. Non-cohesive sediments have a granular structure, with individual particles being susceptible to erosion when the applied fluid forces (drag and lift) are greater than the stabilizing forces due to gravity and cohesion with adjacent bed particles. The threshold of motion of non-cohesive particles depends on their size, density, shape, packing and orientation of bed material. In the case of cohesive sediments, relatively large forces are typically required to detach the particles and initiate movement, but relatively small forces to transport the particles away. In summary, in cohesive soils such as clay/clay mixtures, both local scour and contraction scour magnitudes may be similar. However, scour takes place considerably later than in the non-cohesive soil.

Scope of the present work is to contribute to the understanding and modeling of scouring processes which evolve in cohesive seabeds. This is achieved on the basis of a reduced number of data, i.e. the only data available in the literature, but we think that the present attempt represents an important step for tackling a fundamental, never before faced, engineering problem. In particular, building on the works of Sumer and Fredsøe (2002) and Abou-Seida et al. (2012), we propose an approach based on dimensional analysis for the construction of a new formula for the scouring in cohesive seabeds (section 2). The new formula is, subsequently, validated and discussed on the basis of available data (section 3). The paper is closed by some concluding remarks.

2. Theory and data

2.1. Theoretical analysis

The analysis of the scouring around submerged structures in either marine or riverine environments is fairly complex, due to the large amount of parameters affecting the main processes described in section 1.

With specific focus to underwater pipelines, beyond the pipeline geometry, i.e. diameter D, length l and burial depth e_0 (Fig. 1), the forcing is the first issue to be taken into account in the scour-process evolution: wave characteristics (height H, period T), depth-averaged current velocity (U_c) and their combination.

Scouring under a pipeline lying on a non-cohesive soil also depends on both flow properties, i.e. density ρ, kinematic viscosity ν, gravity acceleration g, water depth h, and physical properties of the sediment, like density ρ_s, median size d_{50}, porosity n, permeability k (Sumer et al., 2001). The presence of some cohesive soil introduces new variables, which mainly refer to the physico-chemical

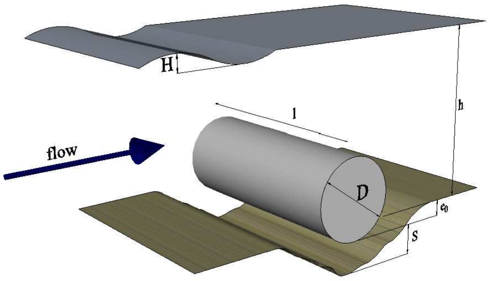

Figure 1: Schematic of a pipeline portion lying on the seabed.

properties of the sediments: salinity difference between out-of-bed and in-bed water Δs, clay content C_c, compaction degree related to the optimum value C_{omp}, water content W_c, liquid limit W_{LL}, plastic limit W_{PL}, liquidity index LI. Some of these properties are strictly correlated through the relationship:

$$LI = \frac{W_c - W_{PL}}{W_{LL} - W_{PL}}. \tag{1}$$

The property LI, together with the plasticity ($PI = W_{LL} - W_{PL}$) and the consistency ($IC = 1 - LI$) indices, makes use of the water content and Atterberg limits (W_{LL} and W_{PL}) to better identify silts and clays, which cannot be only classified using the grain size, but also their mineralogy. More details about such aspects may be found, among others, in Casagrande (1948) and Standard ASTM (2011).

The equilibrium scour depth, also defined as ultimate scour depth (e.g., see Vijaya Kumar et al., 2003; Xu et al., 2010), is the maximum depth observed under the pipeline when the scour process reaches a steady state, i.e. when the bed shear stress under the pipeline becomes constant and equal to an undisturbed value (e.g., see Sumer and Fredsøe, 2002; Manes and Brocchini, 2015). This is generated under the pipeline due to the direct action of a flow and develops during three different phases, i.e. onset of scour, tunnel erosion and lee-wake erosion (Sumer and Fredsøe, 2002). Depending on the type of forcing, whether waves, currents or a combination of them, scouring may be generated in correspondence or downstream of the pipe invert. The scour depth induced by waves and currents approaching perpendicularly the longitudinal axis of a pipeline lying on the seabed (i.e., with $e_0 = 0$), can be taken to depend on several parameters:

$$S = f(D, h, H, T, U_{wc}, \rho_s, d_{50}, n, k, \Delta s, C_c, C_{omp}, W_c, W_{LL}, W_{PL}), \tag{2}$$

where U_{wc} is the wave-current combination. This is given by the sum of the orbital velocity amplitude U_w and the current velocity $U_{c,bed}$, both perpendicular to the longitudinal axis and estimated at the bed:

$$U_{wc} = U_w + U_{c,bed}, \tag{3}$$

with the current velocity at the bed being estimated as

$$U_{c,bed} = \left(\frac{z}{0.32h}\right)^{\frac{1}{7}} U_c, \tag{4}$$

following Zhou et al. (2011) and Whitehouse (1992).

Dimensionless numbers describing the hydrodynamics around the pipeline can be derived from the variables appearing in (2): i) the Reynolds number $Re = U_{wc}A_{bed}/\nu$, based on both the wave-current velocity combination and the particle orbital amplitude at the seabed A_{bed}, ii) the Keulegan-Carpenter parameter $KC = U_{wc}T/D$, based on the wave-current velocity combination, the wave period and the pipeline diameter, and iii) the Froude parameter $F = U_{wc}/\sqrt{gh}$, still based on the wave-current velocity combination and the water depth.

Following Sumer and Fredsøe (2002) and Myrhaug et al. (2009), the dimensionless scour depth S/D under a pipeline lying on a sandy soil depends on: i) a Keulegan-Carpenter parameter KC_w estimated using the undisturbed linear near-bed orbital velocity, and ii) the velocity induced by the combined action of waves and currents, through the dimensionless term $U^* = U_c/(U_c + U_w)$. Such an approach disregards the dependence of the scour depth on the sediment characteristics, and uses two different parameters for the description of the hydrodynamics, i.e. KC_w and U^*, instead of the above-defined KC, which accounts for both waves and currents.

Further, since F depends on h, which is also accounted for in U_{wc}, but does not depend on the pipe geometry D, we assume that KC is sufficient to properly represent the hydrodynamic processes occurring around the pipeline.

The presence of cohesive soil should be taken into account by means of the soil resistance to erosion or critical shear stress τ_{cr}, which depends on several parameters. Some authors (see, for example, Mitchener and Torfs, 1996; Whitehouse et al., 2000) suggest a dependence on the bulk density only, while others found more complicated laws. For example, Mostafa et al. (2008) suggest that the soil resistance also depends on d_{50} and LI. However, they agree in taking into due account C_c when this is relatively small (i.e. smaller than $10\% - 15\%$), because such small percentages represent the transition between a sandy-like to a clayey-like behavior (Mitchener and Torfs, 1996), thus affecting the estimate of the soil erodibility.

Conversely, Abou-Seida et al. (2012) account for the presence of cohesive soil by means of the parameters C_c, C_{omp} and LI. However, the compaction C_{omp} is correlated to both water content and plastic limit (e.g., see Yesim and Sridharan, 2004), such variables appearing in the definition of LI, i.e. equation (1).

Hence, taking into due account the above-mentioned considerations and recalling the typical formulas valid for sandy soils (e.g. Sumer and Fredsøe, 2002), where no influence of d_{50} and bulk density on the scour depth is accounted for, we assume that the shear stress mainly depends on the clay properties, i.e. on C_c and LI. Such an assumption is also supported by the fact that cohesive soils are often classified, in classical soil mechanics, following their physico-chemical properties, described through, e.g., clay fraction, colloidal activity, Atterberg limits, rather than sediment grain characteristics, like for the non-cohesive soils. Hence, equation (2) can be reduced to

$$S/D = f(KC, C_c, LI). \tag{5}$$

The liquidity index LI is function of the plasticity index PI, which is at the denominator of equation (1), and of the water content W_c. This is also confirmed by Winterwerp and van Kesteren (2002), who found a direct dependence of the soil resistance to erosion τ_{cr} on W_c/PI.

As stated by Skempton (1953a,b), the ratio between PI and the clay fraction C_c gives the activity term A. Large values of A correspond to more pronounced colloidal properties of the clay fraction. The clay activity depends on the specific clay type and mineralogy. In particular, a large value of clay content may be associated to a large range of PI values, the largest PI value indicating the most colloidally active clay. However, small values of C_c correspond to small ranges of PI, the activity term being almost independent of the clay type (e.g., see Skempton, 1953a). In this case, an almost linear relation between PI and C_c may be identified.

Since W_c is the ratio between the weight of the fluid portion and that of the solid portion and it is related to bulk properties of the soil only, the dependence on W_c can be disregarded because: i) classical laws for non-cohesive soils (e.g. Sumer and Fredsøe, 2002) disregard the dependence on bulk properties and ii) the clay contribution is more in the cohesive properties rather than in the bulk properties.

Finally, since PI directly depends on C_c (e.g. Skempton, 1953a), we can state that, for weakly cohesive soils, at the seabed surface $\tau_{cr} \approx f(W_c/PI) \approx f(PI) \approx f(C_c)$. Hence, the dependence of the scour depth on LI can be neglected and equation (5) reduces to

$$S/D = f(KC, C_c), \tag{6}$$

which is only valid for small values of C_c.

2.2. Available experimental data

In the present section, having verified that very few data sets are available for the scope at hand, data sets coming from two different experimental campaigns are presented.

The first (Vijaya Kumar et al., 2003, hereafter VK03) illustrates some investigations carried out the wave flume of the Department of Ocean Engineering (Indian Institute of Technology Madras, Chennai, India). The tests consisted in measuring both dynamic pressures and uplift forces exerted on a pipeline lying on a silty-clayey soil, under the action of regular and random waves. Further,

author	test	d_{50} [mm]	C_c [%]	PI [%]	LI [$-$]	IC [$-$]	D [cm]	e_0/D [$-$]	h [m]	H [m]	T [s]	U_c [m/s]	U_w [m/s]	U_{wc} [m/s]	F [$-$]	KC [$-$]	S/D [$-$]	S [cm]
Zhou et al. (2011)	1	0.287	2.27	-	-	-	4	0	0.5	8	1.3	0	0.106	0.106	0.05	3.46	0.230	0.92
	2	0.287	2.27	-	-	-	4	0	0.5	17	1.3	0	0.226	0.226	0.10	7.35	0.220	0.88
	3	0.287	2.27	-	-	-	4	0	0.5	17	1.9	0	0.306	0.306	0.14	14.5	0.428	1.71
	4	0.287	2.27	-	-	-	4	0.5	0.5	17	1.9	0	0.306	0.306	0.14	14.5	0.000	0
	5	0.287	2.27	-	-	-	4	0	0.5	17	1.9	0.3	0.306	0.506	0.23	24	0.500	2
	6	0.287	2.27	-	-	-	4	0.5	0.5	17	1.9	0.3	0.306	0.506	0.23	24	0.000	0
	7	0.057	2.82	-	-	-	4	0	0.5	17	1.9	0	0.306	0.306	0.14	14.5	0.650	2.6
	8	0.057	2.82	-	-	-	4	0.5	0.5	17	1.9	0	0.306	0.306	0.14	14.5	0.330	1.32
	9	0.057	2.82	-	-	-	4	0	0.5	17	1.9	0.3	0.306	0.506	0.23	24	0.538	2.15
	10	0.057	2.82	-	-	-	4	0.5	0.5	17	1.9	0.3	0.306	0.506	0.23	24	0.000	0
	11	0.034	4.23	-	-	-	4	0	0.5	8	1.3	0	0.106	0.106	0.05	3.46	0.000	0
	12	0.034	4.23	-	-	-	4	0	0.5	17	1.3	0	0.226	0.226	0.10	7.35	0.213	0.85
	13	0.034	4.23	-	-	-	4	0	0.5	17	1.9	0	0.306	0.306	0.14	14.5	0.338	1.35
	14	0.034	4.23	-	-	-	4	0.5	0.5	17	1.9	0	0.306	0.306	0.14	14.5	0.000	0
	15	0.034	4.23	-	-	-	4	0	0.5	17	1.9	0.3	0.306	0.506	0.23	24	0.193	0.77
	16	0.287	2.27	-	-	-	4	0.15	0.5	17	1.9	0	0.306	0.306	0.14	14.5	0.205	0.82
Vijaya Kumar et al. (2003)	17	-	74.50	20	0.83	0.17	16	0	0.3	20	1.5	-	-	0.45	0.26	4.2	0.420	7.1
	18	-	74.50	20	0.77	0.23	16	0	0.3	20	1.5	-	-	0.45	0.26	4.2	0.340	5.6

Table 1: Test data.

two specific tests have been performed to study the scour evolution. In this case, the initial water depth over the bed was $h = 0.3m$ and the consistency indices of the silty clay of the soil $I_c = 0.17, 0.23$. A regular wave train (height $H = 0.2m$ and period $T = 1.5s$) was generated by a piston-type wavemaker for about 7200 wave cycles.

A second experiment, carried out in the wave flume of the laboratory of Shengli Petroleum Manage Bureau (China) and described in Xu et al. (2010) and Zhou et al. (2011) (hereafter XU10 and ZH11, respectively), aimed at investigating the soil behavior around a pipeline that was either half buried or resting on the seabed. The authors defined the tested soils as sand ($d_{50} = 0.287$), sandy silt ($d_{50} = 0.057$) and silt ($d_{50} = 0.034$), each characterized by a specific clay content. The forcing conditions, run over a $50cm$-deep bed, were either regular waves or waves plus currents, the wave period being of $1.3s, 1.9s$, the wave height of $8cm, 17cm$ and the current, when present, of $0.3m/s$.

The available details of the experiments used in the present work are given in Tab. 2.2.

3. Results

In the following sections, the evolution of S/D with respect to some of the parameters described in section 2.1 is presented. For the data referring to ZH11 the dependence of S/D on one single variable is first analyzed, then the dependence described by equation (6) is illustrated. The dependence of S/D on a further term, i.e. the dimensionless burial depth e_0/D, is also shown. Some speculations about the contemporary use of both ZH11 and VK03 data sets are provided.

3.1. Scour depth in soils with small amount of clay: one-variable dependence

The first analysis of the available data concerns the dependence of the dimensionless scour depth on some of the single dimensionless parameters introduced in section 2.1. Such analysis is performed for tests 1-16, i.e. those characterized by small clay percentages, for which (6) has been taken to be valid.

Fig. 2 illustrates the dependence of S/D on the hydrodynamic parameters F (top panel) and KC (bottom panel), for specific values of e_0/D and C_c. In particular, both panels illustrate the cases $(e_0/D, C_c) = (0, 2.27)$ (◆: tests 1, 2, 3, 5), $(e_0/D, C_c) = (0, 2.82)$ (■: tests 7, 9), $(e_0/D, C_c) = (0, 4.23)$ (▲: tests 11, 12, 13, 15), $(e_0/D, C_c) = (0.5, 2.27)$ (◇: tests 4, 6) and $(e_0/D, C_c) = (0.5, 2.82)$ (□: tests 8, 10). Except for some data characterized by a vanishing scour, i.e. some with $e_0/D = 0.5$ for which the onset of scour is more unlikely, the initial dependence (i.e. $KC < 14.5$, $F < 0.14$) of each data group is a growth of S/D with both F and KC, this being in line with, respectively, the most common relationships for the scour depth under pipelines lying on sandy soils (e.g., see Sumer and Fredsøe, 2002; Myrhaug et al., 2009) and the formula of Abou-Seida et al. (2012), which refers to the scour depth around bridge abutments in clayey soils. For the sake of clarity, the law proposed by

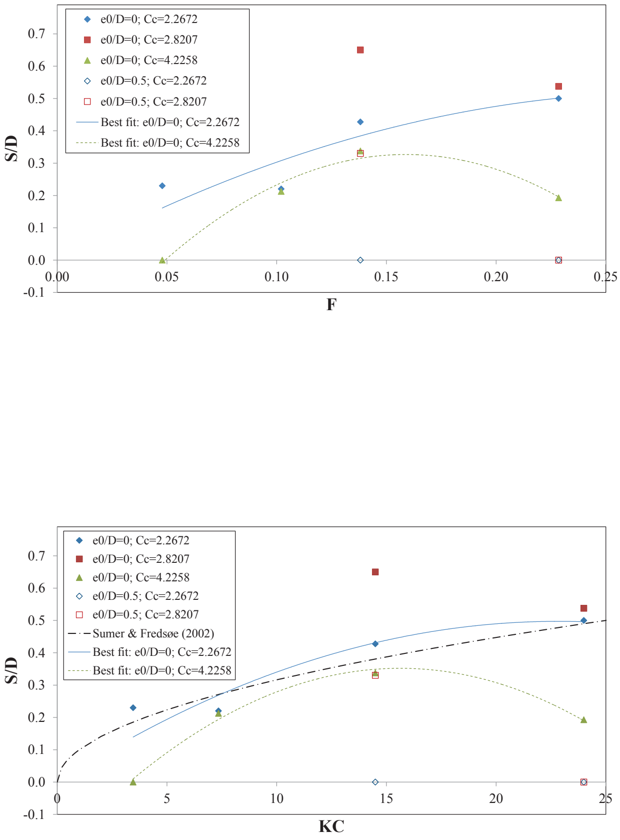

Figure 2: Dependence of S/D on F (top panel) and KC (bottom panel) for constant values of e_0/D and C_c. The best-fit laws of cases $(e_0/D, C_c) = (0, 2.27)$ and $(e_0/D, C_c) = (0, 4.23)$ are also shown with, respectively, solid and dashed lines. The empirical law by Sumer and Fredsøe (2002) is also illustrated in the bottom panel (dash-dotted line).

Sumer and Fredsøe (2002) is also illustrated in the bottom panel (dash-dotted line), this being valid in the presence of waves only and non-cohesive soils. The trend of the solid interpolating line, i.e. $(e_0/D, C_c) = (0, 2.27)$, slightly recalls this trend. However, for $KC > 14.5$ and $F > 0.14$, S/D decreases with both F and KC, except for one case. Since the soil characteristics are the same in each case, such a decrease, which is not physical, can be explained either with a different compaction of the soil during the bed reshaping performed after each test or with a soil heterogeneity under the pipeline obtained after the bed reshaping. The scour-depth evolution is also illustrated by the polynomial best-fit lines of two representative cases: one represents the above-described behavior, i.e. initial increase and final decrease (solid line), the other always increases with F and KC (dashed line).

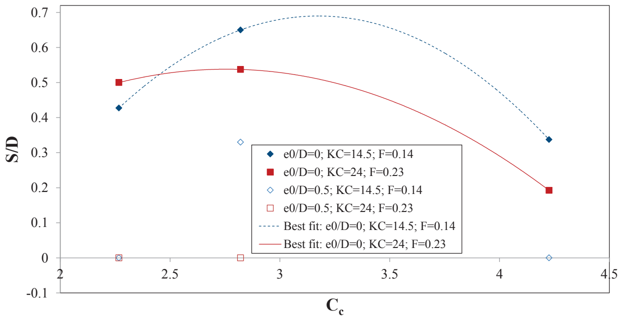

Figure 3: Dependence of S/D on C_c for constant values of e_0/D KC and F. The best-fit laws of cases $(e_0/D, KC, F) = (0, 14.5, 0.14)$ and $(e_0/D, KC, F) = (0, 24, 0.23)$ are also shown with, respectively, dashed and solid lines.

Fig. 3 illustrates the dependence of S/D on the clay content C_c. The illustrated data represent the cases $(e_0/D, KC, F) = (0, 14.5, 0.14)$ (◆: tests 3, 7, 13), $(e_0/D, KC, F) = (0, 24, 0.23)$ (■: tests 5, 9, 15), $(e_0/D, KC, F) = (0.5, 14.5, 0.14)$ (◇: tests 4, 8, 14) and $(e_0/D, KC, F) = (0.5, 24, 0.23)$ (□: tests 6, 10). Except for the third case, characterized by a growth for small values of C_c, the scour depth always decreases with C_c, this being consistent with the formulation derived by Abou-Seida et al. (2012). In the third case, the scour depth of test 3 is unusually lower than those given by tests with a larger amount of clay. We believe that such an exception is probably due to the bed reshaping, as above suggested. Best-fit lines are also shown.

The inverse dependence of S/D on the burial depth e_0/D is confirmed in Fig. 4, where the following cases are reported: $(C_c, KC, F) = (2.27, 14.5, 0.14)$ (◆: tests 3, 4, 16), $(C_c, KC, F) = (2.27, 24, 0.23)$ (◇: tests 5, 6), $(C_c, KC, F) = (2.82, 14.5, 0.14)$ (■: tests 7, 8), $(C_c, KC, F) = (2.82, 24, 0.23)$ (□: tests 9, 10) and $(C_c, KC, F) = (4.23, 14.5, 0.14)$ (▲: tests 13, 14). A best-fit line illustrates the decreasing dependence of S/D with the burial depth in the only case represented by three data.

As already mentioned, from the analysis of Fig. 2 and 3, some trends are probably affected by the local effects introduced during the bed reshaping. In

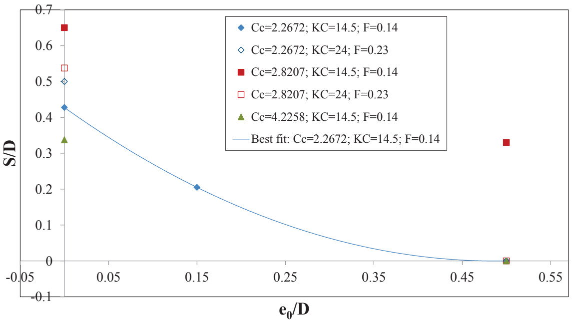

Figure 4: Dependence of S/D on e_0/D for constant values of C_c KC and F. The best-fit line of case $(C_c, KC, F) = (2.27, 14.5, 0.14)$ is also shown.

particular, test 15, included in the third data groups of Fig. 2 (▲) and characterized by $(S/D, F, KC) = (0.19, 0.23, 24)$, can be definitely taken as an outlier, given the increasing trend of S/D with both KC (e.g., confirmed by Sumer and Fredsøe, 2002) and F (confirmed by Abou-Seida et al., 2012).

Since the second and fifth groups of Fig. 2 are made by only two points, these also describing an unlikely decreasing trend, it is difficult to identify the actual outlier in each pair. However, tests 7 (■) and 8 (□), if analyzed with reference to 3 (◆) and 4 (◇), which are characterized by the same pair $(F, KC) = (0.14, 14.5)$ and by smaller clay fractions (i.e. $C_c = 2.27$), this indicating larger scour depths, suggest a non-physical scour over-prediction and could be regarded as outliers.

Further, in Fig. 3, there is not enough solid literature to confirm that the datum referring to test 3 (◆), first series and $(S/D, C_c) = (0.43, 2.27)$, can be taken as an outlier.

3.2. Scour depth in soils with small amount of clay: multi-variable dependence

The dependence of the dimensionless scour depth S/D on both forcing characteristics, through KC, and soil features, through C_c, as shown in equation (6), is illustrated in Fig. 5.

The left panel of Fig. 5 illustrates the ZH11 data characterized by a zero burial depth $e_0/D = 0$ (○, see Tab. 2.2) and the related best-fit line. This can be described by the law:

$$S/D = 0.22KC^{0.5}e^{-0.29C_c}, \tag{7}$$

characterized by a coefficient of determination $R^2 = 0.62$. The 3-dimensional map representing the best-fit law (7) is shown in the right panel of Fig. 5.

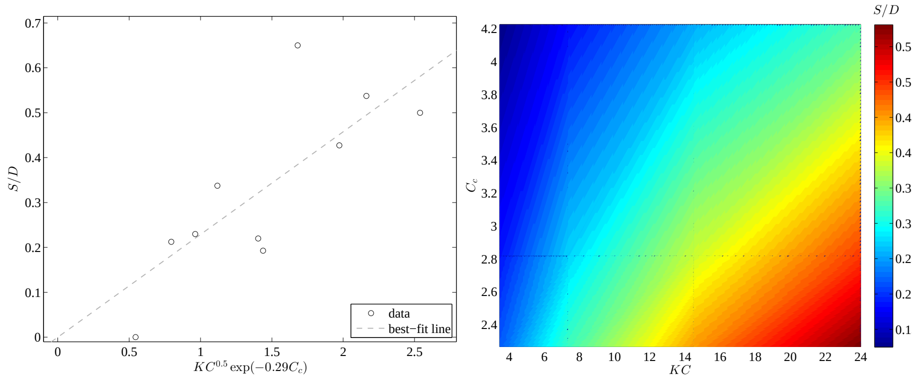

Figure 5: Dependence of S/D on KC and C_c using all ZH11 data characterized by a null burial depth: single test data ($\circ$), best-fit line ($--$, left panel) and 3-d map representing equation (7) (right panel).

We can argue that eq. (7) well describes the scour depth underneath a pipeline subject to both waves and currents, lying on a cohesive seabed with reduced clay fraction ($C_c < 5\%$) and characterized by a zero burial depth ($e_0/D = 0$).

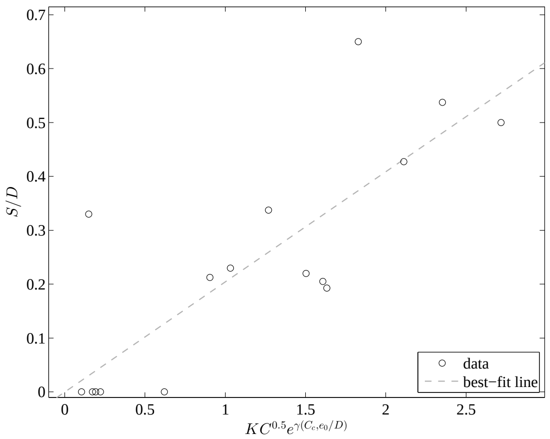

Figure 6: Dependence of S/D on KC, C_c and e_0/D using all ZH11 data: single test data ($\circ$) and best-fit line ($--$).

Accounting for the dimensionless burial depth e_0/D, the best-fit laws slightly change. Fig. 6 illustrates all of the ZH11 data ($\circ$, tests 1-16 of Tab. 2.2) and the related best-fit line. This can be described by the law:

$$S/D = 0.20KC^{0.5}e^{\gamma(C_c,e_0/D)}, \text{ with } \gamma(C_c, e_0/D) = -0.26C_c + \frac{e_0/D}{e_0/D - 0.7}, \quad (8)$$

characterized by a coefficient of determination $R^2 = 0.64$.

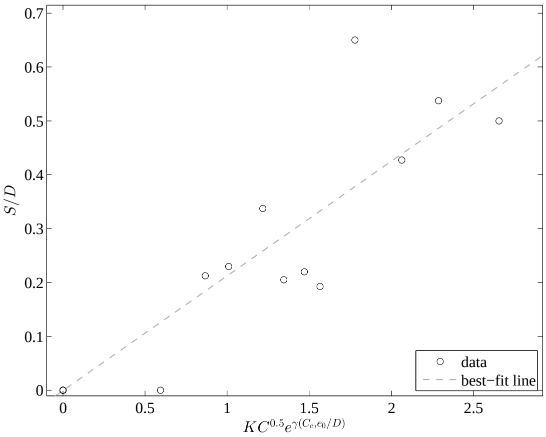

Figure 7: Dependence of S/D on KC, C_c and e_0/D using all ZH11 data except for test 8: single test data (○) and best-fit line (−−).

Removing test 8, the best-fit law (Fig. 7) becomes:

$$S/D = 0.21KC^{0.5}e^{\gamma(C_c,e_0/D)}, \text{ with } \gamma(C_c,e_0/D) = -0.27C_c + \frac{e_0/D}{e_0/D - 0.5}, \quad (9)$$

characterized by $R^2 = 0.79$.

After the above-detailed analysis we can state that for engineering practical purposes, law (9) is a good choice for several reasons: i) its structure is similar to that of the original law (8), ii) the formula can be used whether or not the pipeline is partially buried, iii) the removal of the outlier improve significantly the best fit in terms of R^2 and iv) at the lower limit (i.e., $C_c = 0$), in the case of non-buried pipeline ($e_0/D = 0$), it converges to $S/D = 0.21KC^{0.5}$, which is consistent with the well-known formulas derived for non-cohesive soils (e.g., see Sumer and Fredsøe, 2002).

3.3. Scour depth in clayey soils with large clay-content ranges

In the present section we use both data coming from ZH11 and VK03, the latter being also characterized through PI and LI (Tab. 2.2), this being fundamental when C_c is large (see also section 2.1). Since PI is not available for the ZH11 data, we here attempt to find the relationship between S/D, KC, C_c and e_0/D.

Figs. 8 and 9 show the dependence of S/D, respectively, on KC and C_c when $e_0/D = 0$ and on KC, C_c and e_0/D. Both best-fit lines have been plotted disregarding three outliers of ZH11, i.e. tests 7, 8, 15 (see also the discussion in section 3.1). Both figures shows a direct dependence of the scour depth on both KC and clay content, the former data fitting being described by

$$S/D \propto KC^{0.76}C_c^{0.29}, \quad (10)$$

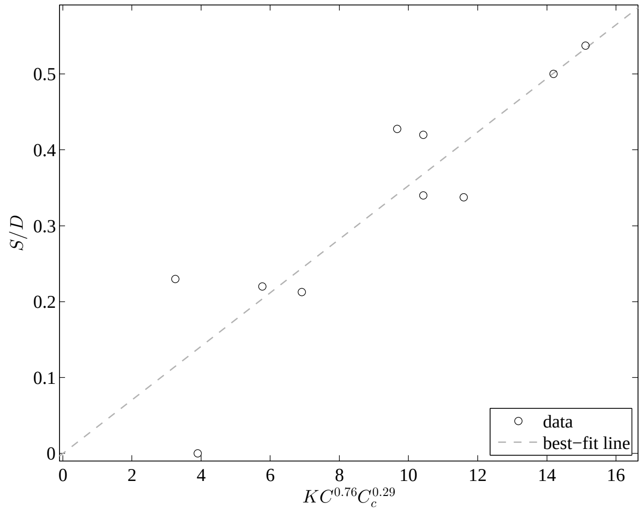

Figure 8: Dependence of S/D on KC and C_c with $e_0/D = 0$ using both ZH11 and VK03 data except for tests 7, 8, 15: single test data ($\circ$) and best-fit line ($--$, left panel).

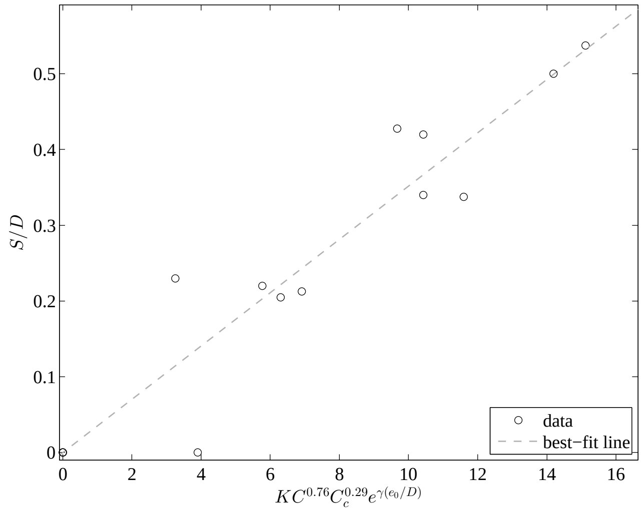

Figure 9: Dependence of S/D on KC, C_c and e_0/D using both ZH11 and VK03 data except for tests 7, 8, 15: single test data ($\circ$) and best-fit line ($--$).

the latter by

$$S/D \propto KC^{0.76}C_c^{0.29}e^{\gamma(e_0/D)}, \text{ with } \gamma(e_0/D) = \frac{e_0/D}{e_0/D - 0.5}. \tag{11}$$

In both equations, the exponents of KC and C_c are the same, respectively

0.76 and 0.29. The dependence on the burial depth is described in (11) by an exponential function, whose denominator is $e_0/D - 0.5$. Such a formulation is clearly valid for cases where the burial depth is not larger than 0.5. In fact, this represents a limiting value for the experiments at hand, with $e_0/D \to 0.5$ providing $S/D \to 0$.

The overall fitting is good, the coefficient of determination being $R^2 = 0.79$ (fig. 8) and $R^2 = 0.91$ (fig. 9). However, the unexpected consequence of such a fit is the direct dependence of S/D from C_c. This may be due to LI (not available in the experiments of XU10 and ZH11), which is not taken into account but should play an important role, as confirmed by Abou-Seida et al. (2012). The contributions of LI and C_c, giving respectively a direct and inverse dependence in Abou-Seida et al. (2012), probably compensate each other, the former being of larger importance. This provides the illustrated trends, characterized by a direct dependence of the scour depth on the clay content.

Conclusions

The morphological evolution of the seabed depends on the wave/current forcings, but also on the submerged obstacles lying on that, like the pipelines used by the Oil&Gas companies or the wind-farm foundations. The research works on the scouring process at offshore structures mainly concerned sandy seabeds. In particular, no formulations are currently available to predict the scour induced by a pipeline lying on a cohesive soil and subject to waves and currents. We here analyze some existing experimental data with the scope to account for the main parameters which characterize the scouring process in a cohesive soil and to find suitable laws for the scour-depth prediction beneath the pipe.

The most important findings are:

- the scour depth under a pipeline lying on a cohesive soil only depends on the Keulegan-Carpenter parameter KC (directly) and on the clay content C_c (inversely), if this is small ($C_c < 5\%$), the best-fit law giving a coefficient $R^2 = 0.62$, with no outliers removed;
- if some burial depth e_0/D is also accounted for through an exponential function, the best fitting gives $R^2 = 0.79$;
- when the clay-content range is large ($2\% < C_c < 75\%$), the scour depth depends directly on both KC and C_c, as the liquidity index LI is not accounted for.

The formulations found for the prediction of the scour depth when the clay content is small may be used in the engineering practice because their feasibility and suitability are demonstrated by the literature. New experiments characterized by several clay content and mineralogy are needed to enrich the existent data-set. It will be fundamental to extend the validity of the present formulations to larger values of clay percentage, this requiring to also account for the liquidity index.

Finally, a law for the estimate of the scour depth under pipelines lying on cohesive soils is required for several engineering applications. Hence, despite the reduced number of available data, the present work represents the first attempt to build a formula which is valid when the pipeline is subject to the combined wave-current action and the seabed is characterized by a relatively small clay content. Such a range of validity is of great importance since it falls in the transition between a sand-type to a clayey-type behavior (i.e. $C_c < 10\%$, following Mitchener and Torfs, 1996). This makes the proposed relationships fundamental for the engineering practice and pipeline design, also in the perspective of evaluating the benefit of choosing a slightly more clayey/less erodible site or modifying the resistance to erosion of the soil under the pipeline, e.g. by adding a given clay fraction to the natural soil, estimated following the formulas proposed in the present work.

We hope that the present contribution will also highlight the need and motivate the execution of many more laboratory tests of wave-current-induced scouring at submerged pipelines placed over cohesive seabeds.

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