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طريقة لتقييم العمق الأمثل لدفن خطوط أنابيب النفط الخام لشروط بحرية مختلفة بدولة الكويت

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الخلاصة

يعتبر تصدير النفط الخام هي التجارة الرئيسية في دولة الكويت. وتستخدم خطوط الأنابيب المغمورة تحت قاع البحر لنقل النفط الخام من محطات النقب إلى السفن الراسية في المياه البحرية العميقة. وتخطط الكويت في المستقبل أيضا لزيادة الصادرات النفطية إلى 4.0 مليون برميل/يوم، مما يترتب عليه زيادة عدد محطات التصدير، والتي تحتاج بدورها لعدد اكبر من خطوط الأنابيب المغمورة. واحدة من أصعب المشاكل هو اختيار عمق الدفن الآمن لخطوط الأنابيب المغمورة للحالة التصميمية السائدة و نوع التربة. عمق الدفن الآمن لخطوط الأنابيب المغمورة هو عبارة عن العمق الذي تكون الأنابيب آمنة للظروف البيئية التصميمية. وذلك يعتمد على تخفيض القوى المؤثرة على الأنبوب من خلال الدفن في قاع البحر. أيضا القوى المؤثرة على خط الأنابيب عند أي عمق الدفن تعتمد على خصائص الموجة، والخصائص الهيدروليكية للتربة في قاع البحر وجميع المعايير البيئية البحرية الأخرى. ويستخدم النمذجة الفيزيائية كأداة لتقييم القوى المؤثرة على نموذج خط الأنابيب لخصائص مختلفة لحالة الموجة و لأعماق دفن مختلفة في أربعة أنواع تربة غير متماسكة من المناطق الساحلية الكويتية، لنطاق معامل التوصيل الهيدروليكي في حدود 0.286 إلى 1.84 ملم/ثانية. وتبين من النتائج أن لجميع أنواع التربة الأربعة تقل القوى الأفقية مع الزيادة في عمق الدفن، في حين أن القوة العمودية تزيد عموما حتى تصل إلى نصف عمق للدفن، ويرجع ذلك أساسا إلى تغيير كبير في حجم القوى و تأخر في مرحلة ضغط المياه الهيدروديناميكي على الجزء العلوي والسفلي من الأنبوب. ومن هذه الدراسة نستنتج أن التربة المتدرجة بشكل جيد تكون جيدة لنصف دفن خط الأنابيب، نظرا لأنها تتعرض لقوى عمودية أقل بالمقارنة مع غيرها من التربة. و من ناحية أخرى، تعتبر التربة المتجانسة وذات معامل توصيل هيدروليكي قليل (مثل تربة منطقة الكوت ذو معامل توصيل هيدروليكي 0.286 ملم/ثانية)، تتعرض

لأقصى قوة عمودية عند نصف الدفن. ولكن تعتبر نفس التربة جيدة لنصف دفن أو أعمق من ذلك حين تتعرض لقوى عمودية أقل مقارنة مع تربة ذات معامل توصيل الهيدروليكي عالي (تربة سواحل الشعيبة ذو معامل توصيل هيدروليكي 1.84 ملم/ثانية). من التجارب التفصيلية وتحليل دراسة الحالة، وجد أن الحد الأدنى لعمق الدفن الآمن لأنابيب الصلب ذات قطر 1.0 م تتراوح بين 1.5-2.0 م لنقل النفط الخام في البيئة البحرية الكويتية. ويمكن استخدام نتائج هذه الدراسة في تحديد الحد الأدنى لعمق الدفن الآمن لمجموعة من التربة الغير متماسكة ولمجموعة مختلفة لحالة الأمواج.

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An approach to estimate the optimal depth of burial of crude oil pipelines for different marine conditions in Kuwait

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ABSTRACT

Crude oil export is the main business in Kuwait. To transfer the crude oil from land to the ships moored in deeper marine water, submarine pipelines are used. Kuwait is also planning to increase the export to 4.0 million barrel/day in the future and hence need more export terminals, which in turn need more submarine pipelines. One of the challenging problems here is selection of optimum burial depth of the submarine pipeline for the prevailing design condition and soil type. The optimum burial depth of submarine pipeline is the depth at which the pipeline will be stable during the design environmental conditions. It depends on the reduction of wave forces due to burial in the seafloor. Also, the wave forces on the pipeline at any depth of burial depend on the wave characters, hydraulic properties of the sea bed soil and all other marine environmental parameters. Physical modeling is used as tool for assessing the wave forces on the pipeline model for a wide range of wave conditions, for different burial depths and for four types of cohesion-less soil types from Kuwaiti coastal area, covering hydraulic conductivity in the range of 0.286 to 1.84 mm/s. It is found that for all the four soil types, the horizontal wave force reduces with increase in depth of burial, whereas the vertical force generally increases for half buried condition, mainly due to the significant change in the magnitude as well as the phase lag between the hydrodynamic water pressures on the top and bottom of the pipe. Among the soils, well graded soil is found to be good for half burial of pipeline, since the least vertical force is experienced for this soil type. On the other hand, uniformly graded and low hydraulic conductivity soil (like Al-Koot soil with hydraulic conductivity of 0.286 mm/s) attracts the maximum vertical force for half burial case. But, such soil type is found to be good for full burial or further increase of burial, since it is found to attract less vertical wave force, when compared to the soils with high hydraulic conductivity (1.84 mm/s from Shuaiba coast). From the detailed investigations and case study analysis, the minimum safe burial depth for a 1.0 m steel pipe is 1.5 m to 2.0 m for transporting crude oil in Kuwaiti marine environment. The results of this study can be used to select the minimum safe burial depth in a range of cohesion-less soils and for a range of marine wave conditions.

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Keywords: Cohesionless soil; crude oil pipe; hydraulic conductivity; safe burial depth; submarine pipeline; wave forces.

INTRODUCTION

Submarine pipeline is one of the important marine structures. Every year hundreds of kilometers of submarine pipelines of different diameters are laid in the marine environment of the global marine waters for different types of applications like transporting liquid hydrocarbons and gases, seawater intake and sewage disposals, subsea tunnels, natural marine life observation structures, cables for power transport etc. These submarine pipelines encounter significant dynamic forces due to the action of waves and currents. In order to reduce such dynamic forces and associated risk of fatigue and failures, they are buried below the seabed. "How deep a submarine pipeline needs to be buried for the prevailing marine conditions?" is a challenging question. The minimum safe depth of burial of the submarine pipeline depends on design marine environment (especially waves and currents), type of seabed soil (engineering and hydraulic properties), pipeline material, fluid to be transported in the pipeline etc. It is safe to bury submarine pipes used for transporting hazardous and inflammable materials like hydrocarbons, acids/bases as well as power transmission cables. Published literatures, standard codes and guide lines to help the engineers to select the minimum safe burial depth are scarce.

Mac Pherson (1978) derived an analytical solution from the potential theory for the wave induced pressure distribution in the sandy soil bed surrounding a buried pipeline. The dynamic seepage force exerted on the pipeline is computed. It is a linear theory based approach and its application for the design extreme wave condition is limited. Lennon (1985) reported three dimensional wave-induced seepage pressures on a buried pipeline in sandy marine soil of finite depth using Boundary Integral Element Method. The soil structure and fluid were assumed as incompressible; seabed was horizontal and extended infinitely in both horizontal and vertical directions. The force on pipeline was found to be a function of relative pipe size, location of wave crest and soil properties. The effect of angle of incidence on the wave-induced pressure on the buried pipeline was studied.

Spierenburg (1986) derived analytical solution for the hydrodynamic force on a submarine pipeline. A comparison was also made with numerical solution based on the finite element method. It was concluded that the hydrodynamic force acting upon a submarine pipeline is about 10-30% of the buoyancy of the pipe depending on the maximum wave load and the burial depth. McDougal *et al*. (1988) developed an analytical model for estimating the pore water pressure in the sandy soil and the resulting hydrodynamic force on the submarine pipelines. The analytical solutions were compared with the results of both small and large-scale tests. Reasonable agreement was obtained for the small-scale tests. Magda (1999) studied the behavior of hydrodynamic uplift force acting on a submarine pipeline in sandy soil and concluded that the uplift force increased with increase in wavelength and degree of saturation of soil. Formula to estimate the force on the buried pipeline was given.

Vijayakumar *et al*. (2001, 2002, 2003, 2005a and 2005b) carried out the physical model studies to estimate the forces and scour around pipeline for few samples of Indian marine clay of different consistency index. The reduction of dynamic pressure on the pipeline due to burial was studied. The investigations were carried out with 3 pressure sensors only and for limited wave heights and period combinations. Madhu Shudan *et al*. (2002) have carried out experimental investigations to analyze wave induced pressures on a pipeline buried in a permeable seabed. The model tests were performed on a 200 mm dia pipeline buried in the soil test bed. The soil used in the formation of the test bed is a poorly graded medium to fine sand with $d_{50} = 0.57$ mm. The average density of the soil bed was 14.83 kN/m^3 and the average hydraulic conductivity of the soil was 8.1×10^{-4} m/s. 96 number of tests were conducted with waves generated for different wave heights. The pipeline was buried in the sandy bed at different burial depth ratios. The pipeline was laid perpendicular to the wave direction. Dynamic pressures were measured with 12 transducers along the outer circumference of the pipeline. The results show that wave induced pressures are significantly controlled by the wave period analyzed in terms of the scattering parameter (ka). Higher pressures were recorded at the top and the lower pressures were recorded at the bottom. It was found that the normalized horizontal force increased with depth of burial, which is very much unexpected. The test was carried out for one soil condition and very limited wave parameters. The variation of vertical force with different depth of burial was provided in figures but nothing is described on why the trend of vertical wave force was different from the horizontal force variation due to different burial of the pipeline.

Xu *et al*. (2010) has carried out studies on bed form evolution around a submarine pipeline and its effects on wave-induced forces under regular waves. The aim of the study was to investigate the scour formation around a submarine pipeline initially, either resting on or half buried in the seabed under regular wave action by means of a series of wave tank experiments, and to evaluate the influence of the scour on the hydrodynamic forces exerted on the pipeline. The evolving bed profile and wave pressure on the pipeline were recorded simultaneously, from which the horizontal and vertical force components were determined by integrating the measured pressure numerically on the circumference of the pipeline. The scour processes and the influence of scour on the hydrodynamic forces on the pipeline were discussed.

From the available literature, it is clear that further investigation is required to understand the variations of wave forces due to burial of the pipelines in order to select a minimum safe burial depth for a given marine environmental condition. The results obtained from the present investigation will help in this direction.

The wave forces on buried pipeline is dictated by the wave height, wave period, water depth, engineering properties of seabed soil (soil size distribution, porosity, submerged density and hydraulic conductivity (k), pipe diameter and depth of burial of the pipeline. The study is carried out with soil, which is well graded (soil with particles of many different sizes) and poorly graded (soil with almost same size) and has high ($k>0.5$ mm/s) as well as low hydraulic conductivity ($k<0.5$ mm/s). Soil with high hydraulic conductivity is preferred as covering material around the buried pipeline to reduce the liquefaction effect of the soil during wave action.

METHODOLOGY

The present problem is solved using physical scale model investigations. Froude scale model is used. Pierson-Moskowitz spectrum with wide range of significant wave heights (H_s) and peak wave periods (T_p) are used. Different depth of burial of the pipeline is selected to cover realistic field conditions. Four different soil types are used. The main mission of the physical model study is to obtain the wave induced forces (both horizontal and vertical direction) on the submarine pipeline for different burial depths in the selected soils for different combinations of (H_s, T_p). The wave force on a buried pipeline cannot be measured using conventional strain gauge type force sensors. Hence, the hydrodynamic pressures were measured at 12 points, equally spaced around the pipeline model. The in-line and uplift forces were estimated from the measured dynamic pressures. Once the hydrodynamic forces at any burial depth are known, then it is possible to assess the stability of the pipeline. Detailed physical model investigations were carried out in the wave flume of Kuwait Institute for Scientific Research, Kuwait. Submarine pipeline with full exposure, half exposure (Figure 1), and no exposure (3 cases) to direct wave action are selected for the investigation. The wave flume is 54.5 m long, 1.2 m deep and 0.6 m wide. The details of the dimensions of the flume, location of test section etc are as shown in Figure 2. The model pipeline is 0.20 m diameter, water depth near the wave maker is 0.90 m and it is 0.45 m at the test section. A mild sloped false bottom (1:35) is fixed in between the wave maker and soil pit. The soil pit is 0.45 m deep. The pipeline width is 0.597 m. 12 Nos. of diaphragm type pressure sensors (RTC28R0.5BV1 by KISTLER, Switzerland), each of capacity of 0.5 bars are fixed on the pipe. The linearity, hysteresis and repeatability of the pressure sensors at 25^0 C are $\leq$ =0.25% of full scale.

A strain gauge type force balance with rated horizontal force, F_x of 500 N and vertical force F_z of 1000 N is used only for measuring the wave force on the pipeline, when it is just resting on the seabed (with a miniature gap between the pipe bottom and seabed for accurate transfer of force to the force balance). The linearity and hysteresis are less than ±0.05% full-scale. The temperature influence on sensitivity is less than ±0.05% full-scale/degree C. Two capacitance type wave gauges of 0.6 m range is used for measuring the incident wave history and are placed as shown in Figure 2. The instruments are periodically calibrated and the repeatability of the calibration constants within ±0.1% of the average calibration constants was assured. The wave maker is piston type and is capable of actively absorbing any wave reflection from the model or beach. It generates wave up to breaking steepness for periods from 1.0 to 2.4 sec. A 12 bit A/D conversion card is used for the conversion of analog data into digital form during data acquisition. The duration and speed of data collection for each combination of (H_s, T_p) was for 420 sec and 40 sample/s respectively.

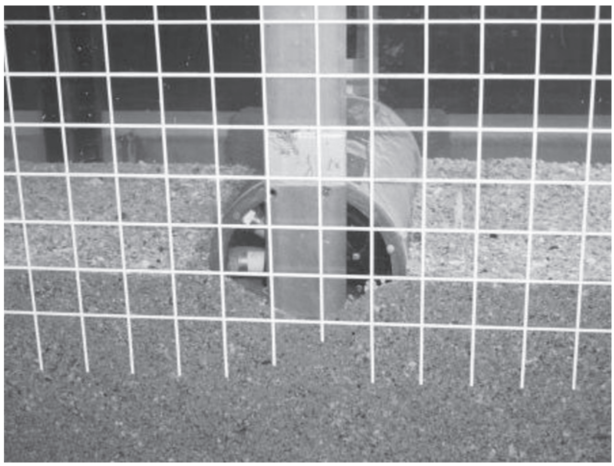

Fig.1. Pipeline model in the wave flume for half buried and half exposed case

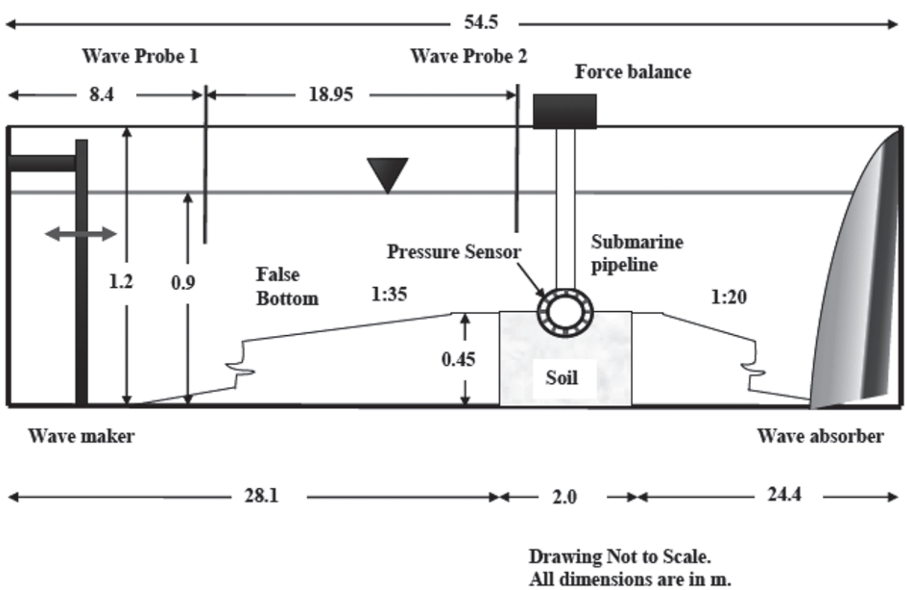

Fig.2. The experimental set-up for measuring forces and dynamic pressures on the submarine pipeline

The pressure sensor location on the pipeline with respect to wave direction is revealed in Figure 3. In this figure, the depth of burial of the submarine pipeline, 'e' is indicated, which is the vertical distance between the sea floor and the bottom of the pipeline.

The angle between the successive pressure sensors along the circumference is 30o. The horizontal wave force, F_x and the vertical wave force, F_z acting on the submarine pipeline is estimated using the following formula:

$$F_x = \sum_{i=1}^{12} P_i \cos\theta \, dA \qquad (1)$$

$$F_z = \sum_{i=1}^{12} P_i \sin\theta \, dA \qquad (2)$$

where θ is the angle between the leading edge and the pressure sensor on the pipe, dA is the segmental outer surface area of the pipeline (= [(πD)/12] W), 'D' is Outer dia of the pipe (0.20 m), 'W' is the width of the pipe (0.597 m) and hence dA= 0.031259 m^2. In the above equations, the dynamic pressures and hydrodynamic forces are functions of time.

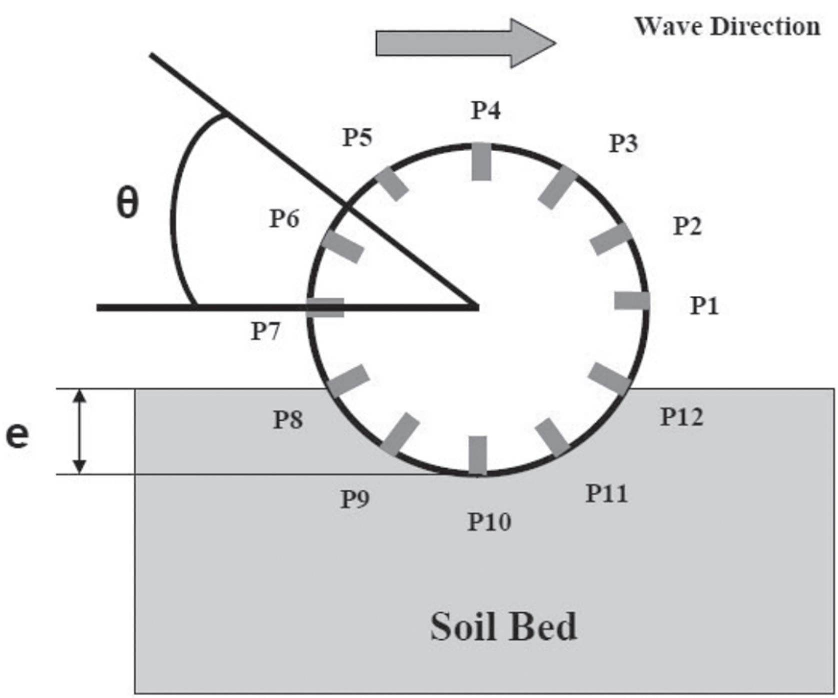

Fig.3. Pressure sensor's location on the pipeline with respect to wave direction

The experiments were carried out for a wide range of random wave conditions. The range of input parameters and the range of normalized hydrodynamic parameters are listed in Table 1.

Table 1. The Range of hydrodynamic input parameters

Hydrodynamic parameter	Range	Unit
Significant Wave Height and Peak Wave Periods, (H_s, T_p)	(0.05,1.0), (0.10,1.0), (0.15,1.0), (0.05,2.0), (0.10,2.0), (0.15,2.0), (0.20,2.0), (0.05,3.0), (0.10,3.0), (0.15,3.0), (0.20,3.0)	(m,s)
Water depth at the test section, d	0.45 m	m
Pipeline burial depth, e	0.0, 0.1, 0.2, 0.3 and 0.4	m
Pipe diameter, D	0.2	m
Wave length, L_p at the test section corresponding to peak period, T_p	1.491, 3.883 and 6.089	m
Relative depth of burial, e/D	0.0, 0.5, 1.0, 1.5 and 2.0	Unitless
H_s/d	0.111 – 0.444	Unitless
H_s/L_p	0.008 – 0.101	Unitless
d/L_p	0.074 – 0.302	Unitless
$k_p d$	0.465 – 1.897	Unitless
D/L_p	0.033 – 0.134	Unitless
$k_p a$	0.103 – 0.422	Unitless
U_r	1.22 – 81.38	Unitless
$U_{max.SWL}$	0.121 – 0.505	m/s
$U_{max.Bed}$	0.048 – 0.435	m/s
KC	0.241 – 6.532	Unitless
R_e	9652.54 – 87094.7	Unitless

In this above table,

- H_s is the incident significant wave height
- T_p is the peak wave period
- d is the water depth at the test section
- D is the pipeline diameter

- L_p is the wave length at the test section and is estimated using the dispersion equation (L_p=1.56 Tp2 tan h ($2\pi d/L_p$)
- H_s/d is the relative wave height
- H_s/L_p is the incident wave steepness
- d/L_p or $k_p d$ is the relative water depth (where 'k_p' is the wave number, $k_p = 2\pi/Lp$)
- $k_p a$ or D/L_p is the scattering parameter (where 'a' is the radius of the pipe)
- U_r is the Ursell parameter ($U_r = HL_p^2/d^3$)
- KC is the Keulegan Carpenter No., ($KC=U_{max} T_p/D$; where U_{max} is the maximum horizontal water particle velocity at the seabed level)
- R_e is the Reynolds No., ($Re = U_{max} D/\gamma$; where 'γ' is the kinematic viscosity of water, $1x10^{-6}$ m^2/sec.)

The variation of hydrodynamic force on the submarine pipeline is functions of the engineering and hydraulic properties of the soil (Please see Table 2).

Table 2. Engineering and hydraulic properties of the soils used

		Soil location			
Soil Property	**Unit**	**Sabiya**	**Al-Koot**	**Shuaiba**	**Al-Khiran**
D_{10}	mm	0.380	0.250	0.410	0.250
D_{30}	mm	0.570	0.275	0.570	0.275
D_{50}	mm	1.450	0.295	0.950	0.310
D_{60}	mm	1.700	0.310	1.500	0.330
C_u	Unitless	4.470	1.240	3.660	1.320
C_c	Unitless	0.500	0.976	0.528	0.917
Bulk density	t/m^3	1.560	1.550	1.621	1.792
Saturated density	t/m^3	1.850	1.855	1.948	2.130
Submerged density	t/m^3	0.811	0.815	0.815	1.090
Porosity	Unitless	0.290	0.360	0.908	0.339
Hydraulic Conductivity, k	mm/s	0.412	0.286	1.840	0.652
Angle of shearing resistance, Φ	Degree	31.460	32.110	32.110	27.010
Coefficient of friction, tan Φ	Unitless	0.612	0.628	0.628	0.510
Passive earth pressure coefficient of the soil, K_p	Unitless	3.183	3.269	3.269	2.664
Remarks	-	Well graded	Uniformly graded	Almost well graded soil	Uniformly graded

In the above table, D_{10}, D_{30}, D_{50}, D_{60} are the diameter of the soil particle at 10%, 30%, 50% and 60% finer on the grain size distribution curve respectively. C_u is the uniformity coefficient ($C_u = D_{60} / D_{10}$) and C_c is the coefficient of curvature of the soil. The particle size distribution of these soils is given in Figure 4.

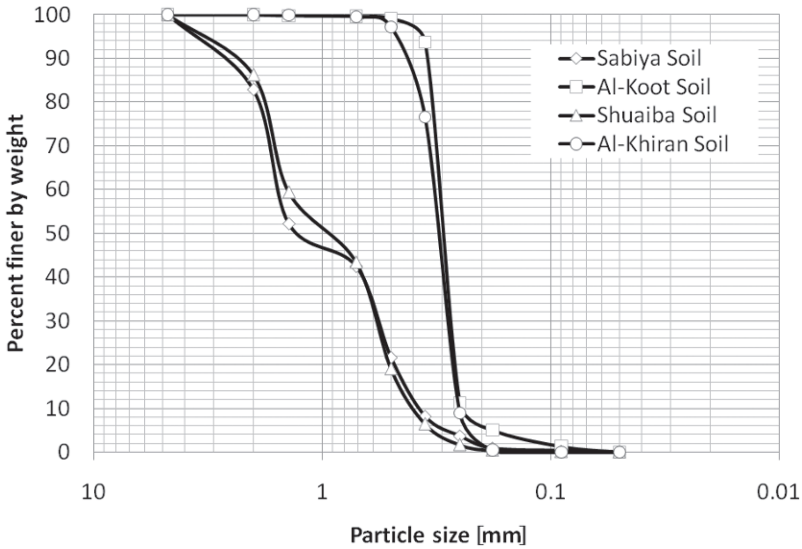

Fig.4. Particle size distribution curve for four different soils

Special efforts were made for preparing the soil bed during each burial condition of the pipeline. For each burial condition of the pipeline, first the pipeine is lowered to the appropriate level, fixed in the space by using the arrangments from the top level of the wave flume. Saturated soil is poured around the pipe gently along with continuous jetting of water in order to get the field compaction condition. After completion of the preparation of the soil pit, the water in the flume is filled to required depth and long period (3.5 sec) high magnitude (H_i=0.20 m) waves were generated for 20 minutes, so that the sand in the pit undergoes dynamic vibration needed to reach the field condition. The actual experiment is then started and measurements are continued.

RESULTS AND DISCUSSIONS

A detailed similarity analysis for the buried pipeline is carried out. The normalized horizontal force, $F_{xs}/0.5\rho g H_s A$ and the normalized vertical force, $F_{zs}/0.5\rho g H_s A$ depends on e/D, H_s/L, d/L_p, D/L_p, H_s/d, KC number apart from the hydraulic conductivity of the soil. Since the experiment is carried out by keeping the water depth and constant pipe diameter, application of the study results are possible by using e/D, d/L_p and Hs/d for the four different soil types selected in this study.

Effect of relative depth of burial on the hydrodynamic force coefficients

One of the main objectives of the present study is to understand the effect of hydraulic conductivity of the soil on the hydrodynamic force coeffcients for different relative buried conditions. The present study was carried out for cohesionless soils of different engineering properties like hydraulic conductivity, porosity, particle size distribution, bulk and saturated density, texture etc. Hydraulic conductivity of soil is the main parameter responsible for development of pore water pressures, phase lag of the pore water pressures around the buried pipeline, especially between the upper and lower surface of the pipe, and hence, the hydrodynamic forces on the buried pipeline. Plots of shoreward, seaward, downward and upward force coefficients for different soils in random waves were presented for some selected relative wave height and peak period combinations.

Figure 5, 6, 7 and 8 show the effect of e/D on shoreward force coefficient $(F_{xp})_{s.Max}/0.5\rho gH_sA$, seaward force coefficient $(F_{xn})_{s.Max}/0.5\rho gH_sA$, downward force coefficient, $(F_{zp})_{s.Max}/0.5\rho gH_sA$ and upward force coefficients, $(F_{zn})_{s.Max}/0.5\rho gH_sA$ repectively for soils of four different hydraulic conductivity for H_s/d=0.444 and d/L_p=0.116. Here $(F_{xp})_{s.Max}$ is the significant maximum shoreward force value. The raw data is the maximum value of the shoreward force from each wave cycle. Similarly, $(F_{xn})_{s.Max}$ is the significant maximum seaward force value, $(F_{zp})_{s.Max}$ is the significant maximum downward force value and $(F_{zn})_{s.Max}$ is the significant maximum upward force value; 'ρg' is the weight density of water, 'H_s' is the significant incident wave height and 'A' is the pipeline exposed area (Diameter: length). In general, change of soil type had some influence on changing the horizontal force coefficients (Figure 5 and Figure 6) and significant influence on vertical force coefficients (Figure 7 and Figure 8). From Figure 5 and Figure 6, it is noticed that soil from Al-Koot (Hydraulic conductivity of 0.286 mm/s) attracts minimum in-line force for different burial case when compared to soil from Shuaiba sea bed with hydraulic conductivity of 1.84 mm/s. The effect of hydraulic conductivity is more pronounced for the vertical force cofficients than for the horizontal force coefficients. It can be observed from Figure 7 and 8 for half buried pipe that the vertical force is very pronounced for Al-Koot soil with k=0.286 mm/s and is the lowest for Shuaiba soil with k=1.84 mm/s. For low hydraulic conductivity soil, the rate of water seepage into the soil is expected to be less and the water particle velocity over the pipe is expected to be high. This results in Bernoulli's effect causing significant uplift force on the half buried pipeline.

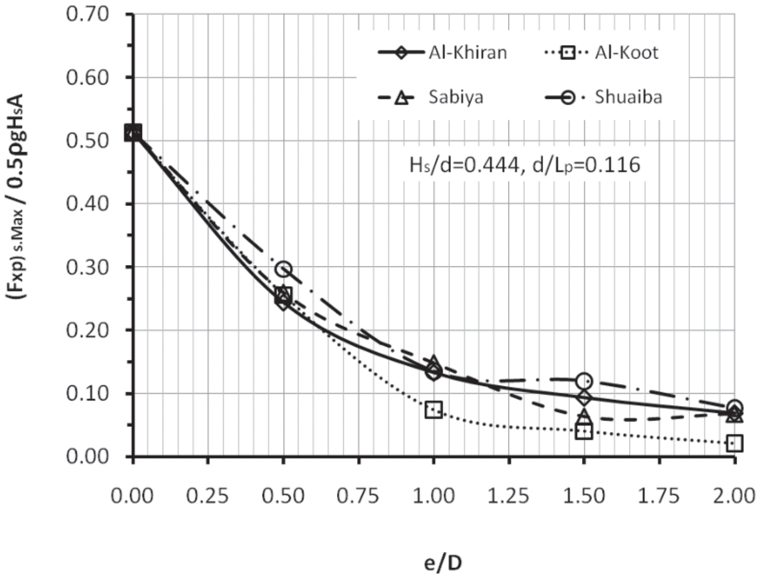

Fig.5. Effect of relative burial depth of submarine pipeline on shoreward force coefficients for four different soil types (H_s/d=0.444, d/L_p=0.116)

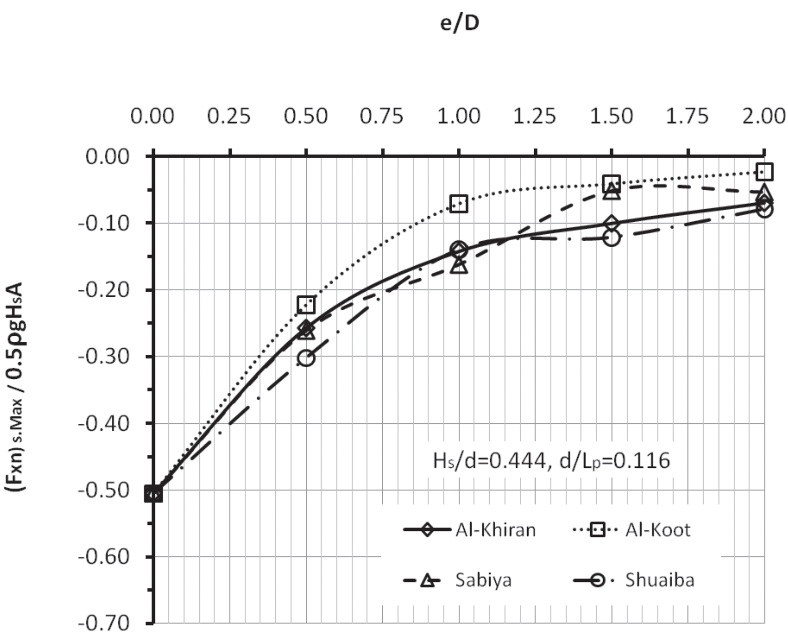

Fig.6. Effect of relative burial depth of submarine pipeline on seaward force coefficients for four different soil types (H_s/d=0.444, d/L_p=0.116)

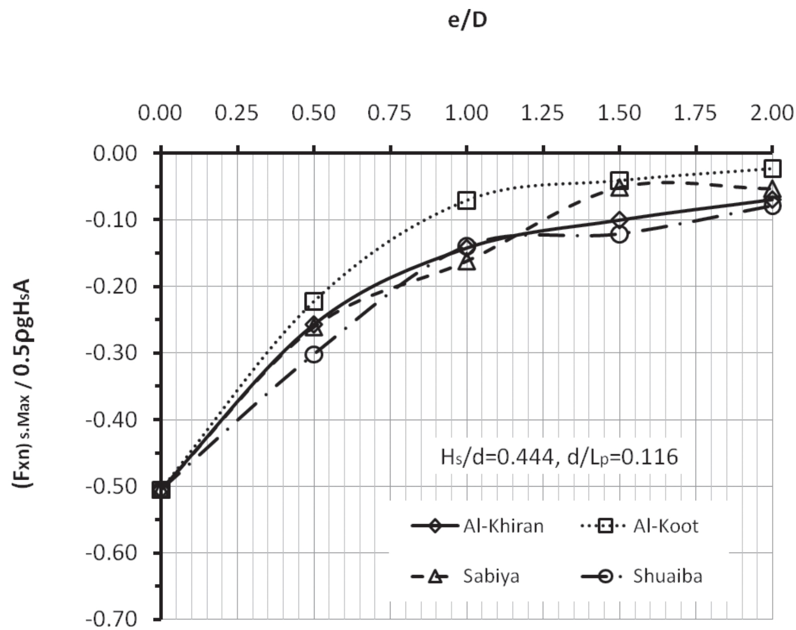

Fig.7. Effect of relative burial depth of submarine pipeline on downward force coefficients for four different soil types (H_s/d=0.444, d/L_p=0.116)

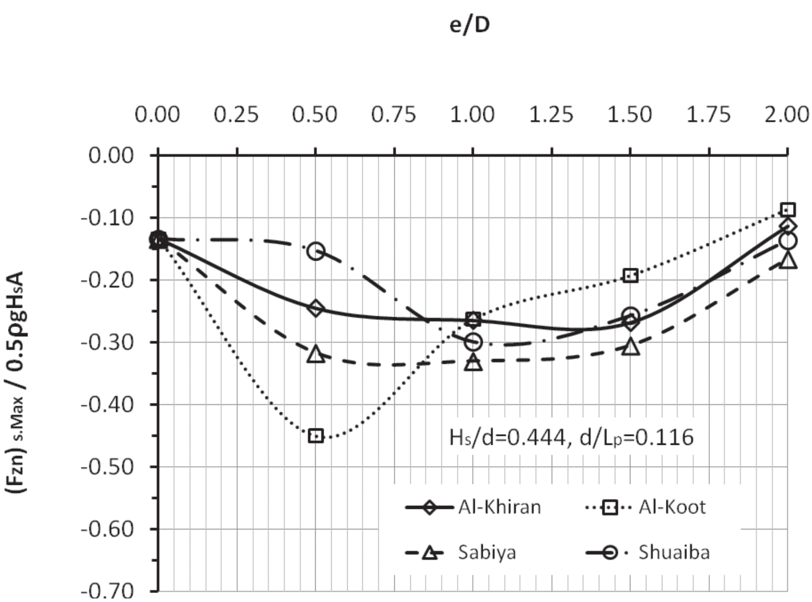

Fig.8. Effect of relative burial depth of submarine pipeline on upward force coefficients for four different soil types (H_s/d=0.444, d/L_p=0.116)

The temporal and spatial changes in dynamic pressure due to wave action cause seepage of water into the porous soil medium. For a high hydraulic conductivity soil, the seepage velocity is high and hence significant volume of water from around the sea bed boundary layer seep through the soil medium. Hence the volume flow around the upper part of the half exposed pipe will be less when compared to a half exposed pipe in a low hydraulic conductivity soil. The flow velocity on the top surface of the half exposed pipe governs the uplift force, similar to flow on the top surface of an aerofoil. This is the reason for high lift force on a half buried pipeline in a low hydraulic conductivity soil and smaller lifting force when a pipeline is half buried in a soil with high hydraulic conductivity. Hence for half buried submarine pipeline in a native soil of low hydraulic conductivity, it is advantage to replace the top surface of the seabed soil with high hydraulic conductivity soil.

Transfer function of horizontal and vertical wave forces on the submarine pipeline for different types of soil

The transfer function is defined as the square root of the ratio of output spectral value to the input wave spectral value. Hence, transfer function for the horizontal wave force TFFx(f) is given as

$$TF_{Fx}(f) = [S_{Fx}(f)/S_w(f)]^{1/2} \tag{3}$$

Where, $S_{Fx}(f)$ is the spectral density value of the horizontal wave force at wave frequency 'f' and $S_w(f)$ is the spectral density value of the incident wave at wave frequency 'f'. Similarly, the transfer function for the vertical wave force $TF_{Fz}(f)$ is given as

$$TF_{Fz}(f) = [S_{Fz}(f)/S_w(f)]^{1/2} \tag{4}$$

Where, $S_{Fz}(f)$ is the spectral density value of the vertical wave force at wave frequency 'f'. It is felt that further normalization is needed for direct use of the present results to the field conditions. Hence the transfer function is further normalized to make it as unitless quantity. The normalized transfer function for the horizontal wave force is calculated by using the formula $TF_{Fx}(f)/\rho gA$ and the normalized transfer function for the vertical wave force is calculated by using the formula $TF_{Fz}(f)/\rho gA$.

Comparing the normalized transfer function for horizontal and vertical force for different type of soil in a single plot is needed. Figure 9 shows the normalized transfer function of horizontal wave force on the submarine pipeline for different soil types for e/D=0.5, d/L_p=0.302, and H_s/d=0.333. For this e/D, Al-Koot soil attracted the minimum value of the normalized transfer function of horizontal wave force and Shuaiba attracted maximum value. Figure 10 shows the normalized transfer function of vertical wave force on the submarine pipeline for different soil types for e/D=0.5, d/L_p=0.302, and H_s/d=0.333. For this e/D, Al-Koot soil attracts the maximum value of the normalized transfer function of vertical wave force and Shuaiba attracted minimum value. This is just an opposite trend as compared with the Figure 9. Hence, Shuaiba soil is better, since it attacted the minimum vertical force for the condition e/D=0.5, d/L_p=0.302, and H_s/d=0.333.

Similar analysis was carried out for all the other input conditions and the soil locations, and are provided in Neelamani *et al*. (2010). The following few points are very clear from the study (Refer Table 3):

- Al-Koot soil (uniformly graded and k=0.286 mm/s) attracted the minimum normalized horizontal transfer function value for all the input conditions used.
- For most of the experimental conditions, Al-Koot soil attracted the minimum normalized vertical transfer function (apart from Shuaiba soil for certain input conditions).

Table 3 can be used to understand which soil type attracts the maximum and minimum normalized horizontal and vertical transfer functions for different e/D and d/L_p values.

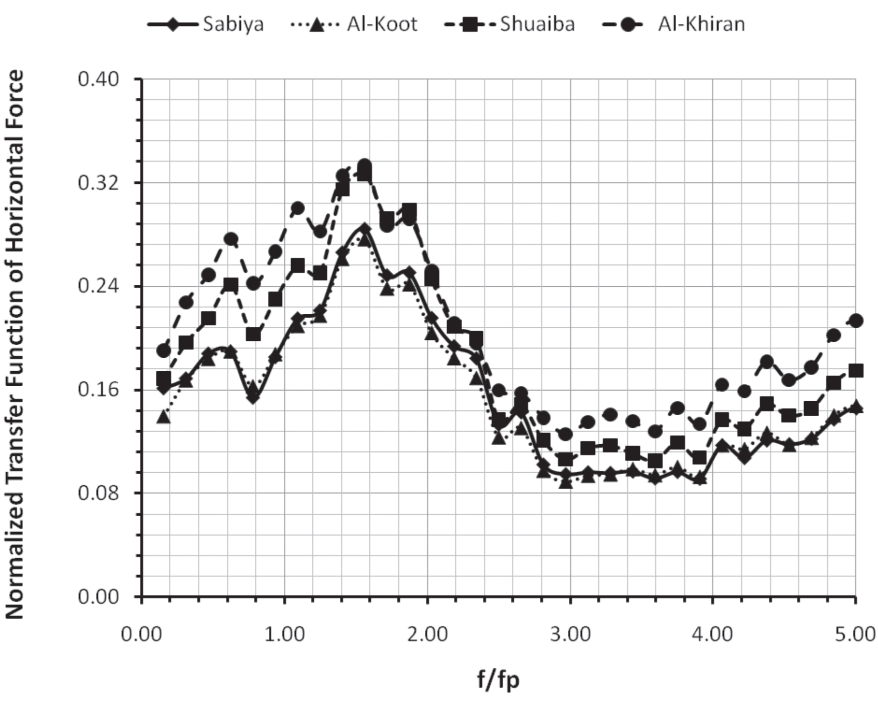

Fig.9. Normalized transfer function of horizontal wave force on the submarine pipeline for different soil type (e/D=0.5, d/L_p=0.116, H_s/d=0.333)

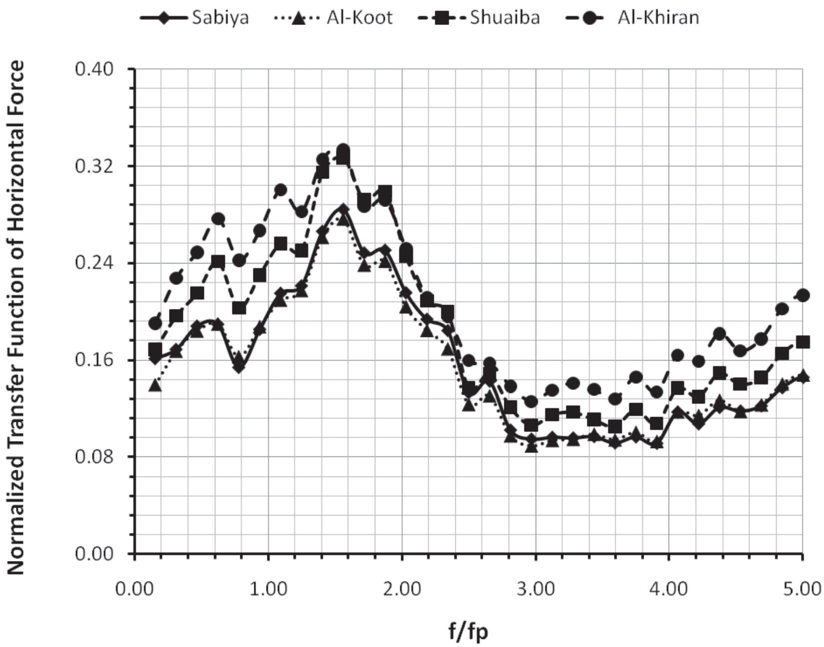

Fig.10. Normalized transfer function of vertical wave force on the submarine pipeline for different soil type (e/D=0.5, d/L_p=0.116, H_s/d=0.333)

Table 3. The soils attracting maximum and minimum normalized horizontal and vertical transfer functions for different e/D and d/L_p Values and for H_s/d=0.333

e/D	d/Lp	Soil attracting MAXIMUM Normalized Horizontal Transfer Function	Soil attracting MINIMUM Normalized Horizontal Transfer Function	Soil attracting MAXIMUM Normalized Vetical Transfer Function	Soil attracting MINIMUM Normalized Vertical Transfer Function
0.5	0.302	Shuaiba	Al-Koot	Al-Koot	Shuaiba
0.5	0.116	Al-Khiran	Al-Koot	Al-Koot	Shuaiba
0.5	0.074	Al-Khiran	Al-Koot	Al-Koot	Shuaiba
1.0	0.302	All other locations	Al-Koot	Al-Koot	Shuaiba and Al-Khiran
1.0	0.116	Al-Khiran	Al-Koot	Almost same for all locations	Almost same for all locations
1.0	0.074	Al-Khiran	Al-Koot	Mixed	Mixed
1.5	0.302	Shuaiba	Al-Koot	Mixed	Al-Koot
1.5	0.116	Mixed	Al-Koot	Al-Khiran	Al-Koot
1.5	0.074	Mixed	Al-Koot	Al-Khiran	Al-Koot
2.0	0.302	Mixed	Al-Koot	Sabiya	Al-Koot
2.0	0.116	Mixed	Al-Koot	Sabiya	Al-Koot
2.0	0.074	Mixed	Al-Koot	Sabiya	Al-Koot

SAMPLE WORKED OUT EXAMPLES TO ILLUSTRATE THE USE OF THIS STUDY TO OBTAIN THE MINIMUM SAFE BURIAL DEPTH OF A TYPICAL CRUDE OIL CARRYING SUBMARINE PIPELINE

Some fundamentals and input details

A typical work out example is provided below to illustrate the application of the study. Imagine a pipeline needs to be laid connecting the shore to the offshore single point mooring system. The pipeline needs to be buried. The main question is how deep is the minimum depth of burial to make sure the pipeline will not get exposed for direct wave attack during design conditions. The present study helps to get the minimum safe depth of burial. Below is the illustration:

Marine projects where submarine pipeline is required to be installed for crude oil transport in Sabiya, Al-Koot, Shuaiba and Al-Khiran area are considered. The pipeline made of steel of 1.0 m OD, wall thickness of 15 mm is considered. The water depth for the purpose of calculation is 2.25 m, peak wave period is 6.7 s and the design significant wave height of 1.6 m is used at this water depth.

It is required to estimate the minimum safe burial depth of the pipeline against pullout in the vertical direction. The wave-induced uplift force on the buried pipeline is the main force for pipeline pullout. It is also necessary to make sure that the pipeline is stable in the horizontal direction due to horizontal hydrodynamic forces acting on it at any burial depth. At any depth of burial, the forces counteracting the uplift force and buoyancy force on the submarine pipeline is the weight of the pipeline material, the fluid inside the pipe and the natural backfill material on the pipe. If the counteracting forces are not enough, then it is necessary to use additional surcharge weights (like rip-rap cover or other solutions). In such situation, it is necessary to estimate the weight of additional surcharge needed for the pipe/m run at any selected burial depth in order to get a factor of safety of say 1.5 against uplift. It is also needed to make sure that the factor of safety against horizontal sliding is also 1.5 at any buried depth.

The detailed procedures for the solution are explained by Neelamani *et al*., (2010). The results for a crude oil carrying pipeline are provided in Tables 4, 5 and 6. For submarine pipeline stability, at first, it must be stable against vertical uplift; then it is necessary to make sure that it is also stable against horizontal sliding.

The following additional input conditions and information are used:-

Pipeline OD, D = 1.0 m and Pipeline ID = 0.97 m

Density of steel = 7.6 t/m^3

Seawater density = 1.04 t/m^3

The weight of the pipe/m run, $W_{pipe} = \pi/4\ (1^2 - 0.97^2) \times 7.6 = 0.353$ t/m

Weight of fluid inside the pipe/m, $W_{fluid} = \pi/4\ (0.97^2)$ x Fluid density inside the pipe

Buoyancy force on the pipe/m run, $F_B = \pi/4 \times 1^2 \times 1.04 = 0.817$ t/m

Uplift force due to the design wave/m run, F_v = (Coefficient of vertical force in the upward direction) x 0.5 $\rho g H_s A$

It is to be assumed that for any depth of burial of the pipeline, the native soil will be used as backfill on the top of the pipeline for vertical stability, called surcharge.

For pipeline resting on the bed (e/D=0.0), the surcharge due to the native soil cover, $W_{native\ soil\ fill} = 0.0$ t/m

For pipeline half buried (e/D=0.5), the surcharge due to the native soil cover = 0.0 t/m

For pipeline with e/D=1.0, the surcharge = $(1.0 \times 0.5 - \pi/8 \times 1^2)$ x submerged density of the soil in t/m^3

The submerged density of soil for Sabiya, Al-Koot, Shuaiba and Al-Khiran soils are 0.81, 0.815, 0.908, and 1.09 t/m^3, respectively.

For pipeline with e/D=1.5, the surcharge due to the native soil cover = $(1.0 \times 1.0 - \pi/8 \times 1^2)$ x submerged density of the soil in t/m^3.

For pipeline with e/D=2.0, the surcharge due to the native soil cover = $(1.0 \times 1.5 - \pi/8 \times 1^2)$ x submerged density of the soil in t/m^3.

The total downward force on the pipeline, W_{down} = Weight of pipe/m (W_{pipe}) + Weight of fluid inside the pipe/m (W_{fluid}) + Surcharge load over the pipe due to the native soil fill up to the original seabed ($W_{native\ soil\ fill}$)

The total upward force on the pipeline, W_{up} = Buoyancy force/m run (F_B) + Hydrodynamic uplift force/m run (F_v)

The factor of safety against uplift, $FS_{Uplift} = W_{down} / W_{up}$

It is advisable to have the value of factor of safety against uplift equal to 1.5.

If the factor of safety against uplift is less than 1.0 for a particular depth of burial, then the pipeline will not be stable in the vertical direction and will pop up above the seabed and receive direct wave loading. In such situation, it is necessary to go for additional surcharge by either placing sufficient weight/m run of pipe using rip-raps or any other stabilization method.

If the pipeline is buried, and still it is not safe against the uplift force, then the weight of additional surcharge required/m run, W_{as} on the pipe for a factor of safety of 1.5 against uplift can be estimated as follows:

$W_{as} = (1.5 \times W_{up})$ - Weight of pipe/m - Weight of fluid inside the pipe/m – Weight of native surcharge over the top surface of the submarine pipeline up to the original seabed.

The estimate of the minimum safe burial depth against uplift forces for the given pipe of 1.0 m OD is carried out considering crude oil as flow material.

Minimum safe burial depth against uplift for submarine pipeline carrying crude oil.

The density of the crude oil at 48° C = 0.79 t/m³. Table 4 provides the details of the calculations of uplift force, surcharge weight of the soil, downward force, upward force, and factor of safety against uplift for the four different soil types and five different e/D values. The pipeline is carrying crude oil. If the factor of safety is less than 1.0, then the pipe will not be stable in the vertical direction and will popup during the action of the design wave condition. From the table, it is clear that the pipeline cannot be stable for e/D = 0.5 and 1. For Sabiya and Shuaiba coastal waters, it is safe to bury the pipe with e/D between 1.5 and 2.0. For Al-Koot it is recommended that e/D a bit more than 1.5. be used. For Al-Khiran, e/D=1.5 is enough. The last column of the Table 4 provides the additional weight of surcharge needed/m run of the submarine pipeline for obtaining a factor of safety of 1.5, once the depth of burial is frozen. For example, in Shuaiba, if the relative depth of burial, e/D is 1.0, then riprap of 0.58 t/m must be placed over and above the native soil cover, placed already up to the seabed level. The value 0.58 t/m is the submerged weight of the riprap.

Stability against horizontal sliding of the submarine pipeline

The restraining force preventing the submarine pipeline against horizontal sliding due to the hydrodynamic force in the horizontal direction, F_H is the frictional force, $F_{friction}$ and the passive earth resistance, $F_{passive}$ of the soil surrounding the pipeline. The frictional force, $F_{friction}$ between the pipe and the seabed soil depends up on the coefficient of friction, μ between the pipe and seabed soil.

$F_{friction}$ = μ [Weight of pipe/m (W_{pipe}) + Weight of fluid inside the pipe/m (W_{fluid}) + Surcharge load over the pipe due to the native soil fill up to the original seabed ($W_{native\ soil\ fill}$) - Buoyancy force/m run (F_B) - Hydrodynamic uplift force/m run (F_v)]

$F_{passive} = 0.5\ \gamma_{sub}\ e^2\ K_p$ for partially buried pipe.

$= 0.5\ \gamma_{sub}\ D^2\ K_p$ for just buried pipe.

$= 0.5\ \gamma_{sub}\ (2\ e\ D - D^2)\ K_p$ for buried pipe with depth of burial $e > D$.

Where, γ_{sub} is the submerged weight of the soil, 'e' is the vertical distance between the seabed and the pipeline bottom, and K_p is the passive earth pressure resistance of the surrounding soil.

The factor of safety against horizontal sliding, FSHorizontal sliding = $(F_{friction} + F_{passive}) / F_H$

If $FS_{Horizontal\ sliding}$ is greater than 1.0, then it is safe against sliding. However, it is recommended that a value of 1.5 for the purpose of safety is taken. If the pipeline is not safe against horizontal sliding with a factor of 1.5, then the additional surcharge load needed is estimated using the formula $W_{as} = [(1.5 \times F_H - F_{passive}) / \mu] - (W_{pipe} + W_{fluid} + W_{native\ soil\ fill} - F_B - F_v)$

Table 4. Minimum safe relative burial depth, e/d of a submarine pipeline against uplift for crude oil transport for four various soils and for typical design input conditions in Kuwait

Location	e/D	Upward Vertical Force Coefft.	Uplift Force, (t/m)	Surcharge, (t/m)	Downward Force, W_{down} (t/m)	Upward Force, W_{up} (t/m)	Factor of Safety against Uplift, W_{down} / W_{up}	Minimum Safe e/D Value	Additional Surcharge, W_{as} Needed in t/m for Factor of Safety of 1.5
Sabiya	0.0	0.11	0.09	0.00	0.94	0.90	1.04	e/D between 1.5 and 2.0	0.42
	0.5	0.31	0.26	0.00	0.94	1.08	0.87		0.68
	1.0	0.33	0.28	0.09	1.02	1.09	0.94		0.62
	1.5	0.30	0.25	0.49	1.43	1.07	1.34		0.17
	2.0	0.14	0.11	0.90	1.84	0.93	1.97		0.0
Al-Koot	0.0	0.11	0.09	0.00	0.94	0.90	1.04	e/D bit more than 1.5	0.42
	0.5	0.47	0.39	0.00	0.94	1.21	0.78		0.87
	1.0	0.27	0.22	0.09	1.02	1.04	0.98		0.54
	1.5	0.21	0.18	0.50	1.43	0.99	1.44		0.06
	2.0	0.09	0.08	0.90	1.84	0.90	2.05		0.0
Shuaiba	0.0	0.11	0.09	0.00	0.94	0.90	1.04	e/D between 1.5 and 2.0	0.42
	0.5	0.14	0.11	0.00	0.94	0.93	1.01		0.46
	1.0	0.31	0.26	0.10	1.03	1.08	0.96		0.58
	1.5	0.28	0.23	0.55	1.49	1.05	1.42		0.08
	2.0	0.15	0.12	1.01	1.94	0.94	2.07		0.0
Al-Khiran	0.0	0.11	0.09	0.00	0.94	0.90	1.04	e/D = 1.5	0.42
	0.5	0.25	0.21	0.00	0.94	1.02	0.92		0.60
	1.0	0.27	0.22	0.12	1.05	1.04	1.01		0.51
	1.5	0.27	0.23	0.66	1.60	1.05	1.53		0.0
	2.0	0.12	0.10	1.21	2.14	0.92	2.33		0.0

Minimum safe burial depth against horizontal sliding for submarine pipeline carrying crude oil

As stated previously, the density of the crude oil at 48° C is considered as 0.79 t/m^3. Table 5 provides the details of the calculations of wave-induced seaward horizontal force, F_H, wave-induced uplift force, F_V, surcharge weight of the native soil up to the original seabed level, $W_{native\ soil\ fill}$, downward force, W_{down}, frictional force between the pipe and the soil, Ffriction, the passive earth resistance of the soil surrounding the pipeline, Fpassive, factor of safety against horizontal sliding, FSHorizontal sliding, minimum safe e/D value for the four different soil types and the additional surcharge load required for any selected burial depth in order to get FSHorizontal sliding of 1.5. The pipeline is carrying crude oil; and hence, any sort of horizontal sliding cannot be allowed. If the factor of safety is less than 1.0, then the pipe will not be stable in the horizontal direction and will slide horizontally due to the action of the design wave condition.

Table 5. Minimum safe relative burial depth, e/d of a submarine pipeline against horizontal sliding for crude oil transport for four various soils and for typical design input conditions in Kuwait

Location	e/D	Seaward Force Coefft.	F_H (t/m)	Upward Force Coefft.	F_V (t/m)	$W_{native\ soil\ fill}$ (t/m)	W_{down} (t/m)	$F_{friction}$ (t/m)	$F_{passive}$ (t/m)	$FS_{Horizontal\ sliding}$	Minimum Safe e/D Value	W_{as} in t/m for Factor of Safety of 1.5
Sabiya	0	0.46	0.38	0.11	0.09	0.00	0.02	0.01	0.00	0.02	e/D in between 0.5 and 1.0	1.10
	0.5	0.22	0.18	0.31	0.26	0.00	-0.19	-0.12	0.32	1.13		0.09
	1.0	0.13	0.11	0.33	0.28	0.09	-0.13	-0.08	1.29	10.96		0.0
	1.5	0.13	0.11	0.30	0.25	0.49	0.31	0.19	2.58	26.02		0.0
	2.0	0.05	0.04	0.14	0.11	0.90	0.88	0.54	3.87	101.80		0.0
Al-Koot	0	0.46	0.38	0.11	0.09	0.00	0.01	0.01	0.00	0.02	e/D in between 0.5 and 1.0	1.10
	0.5	0.20	0.16	0.47	0.39	0.00	-0.35	-0.22	0.33	0.71		0.17
	1.0	0.08	0.07	0.27	0.22	0.09	-0.06	-0.04	1.33	19.82		0.0
	1.5	0.04	0.03	0.21	0.18	0.50	0.40	0.25	2.66	85.08		0.0
	2.0	0.02	0.02	0.09	0.08	0.90	0.93	0.58	4.00	230.83		0.0
Shuaiba	0	0.46	0.38	0.11	0.09	0.00	0.01	0.01	0.00	0.02	e/D=0.5	1.10
	0.5	0.26	0.22	0.14	0.11	0.00	-0.02	-0.01	0.37	1.64		0.0
	1.0	0.13	0.11	0.31	0.26	0.10	-0.09	-0.06	1.48	13.12		0.0
	1.5	0.12	0.10	0.28	0.23	0.55	0.39	0.25	2.97	31.87		0.0
	2.0	0.08	0.06	0.15	0.12	1.01	0.98	0.61	4.45	78.25		0.0
Al-Khiran	0	0.46	0.38	0.11	0.09	0.00	0.01	0.01	0.00	0.02	e/D=0.5	1.10
	0.5	0.23	0.19	0.25	0.21	0.00	-0.13	-0.06	0.36	1.54		0.0
	1.0	0.13	0.10	0.27	0.22	0.12	-0.03	-0.02	1.45	13.77		0.0
	1.5	0.09	0.08	0.27	0.23	0.66	0.51	0.26	2.90	40.96		0.0
	2.0	0.07	0.06	0.12	0.10	1.21	1.20	0.61	4.36	85.14		0.0

From the table, it is clear that the pipeline cannot be horizontally stable for e/D = 0.0 for all soil conditions, and also cannot be stable for e/D=0.5 for Sabiya and Al-Koot soil. It was stable for e/D=0.5 for Shuaiba and Al-Khiran soils, since the value of

$FS_{Horizontal\ sliding}$ was greater than 1.5. Hence, the minimum safe burial depth for Sabiya and Al-Koot is when e/D is in between 0.5 and 1.0 and for Shuaiba and Al-Khiran soils, the minimum safe e/D value is 0.5. The last column of the Table 5 provides the additional weight of surcharge needed/m run of the submarine pipeline for obtaining a factor of safety of 1.5 against horizontal sliding, once the depth of burial is frozen. For example, in Al-Koot coastal waters, if the relative depth of burial selected, e/D is 0.5, then riprap of 0.17 t/m must be placed over and above the native soil cover, in order to get $FS_{Horizontal\ sliding}$ equal to 1.5. It is to be remembered that the value 0.17 t/m is the submerged weight of the riprap.

Stability against uplift and horizontal sliding of the submarine pipelines

In the previous two sections, the stability assessments are carried out individually for vertical pull out and for horizontal sliding of the submarine pipelines. However, both horizontal sliding and vertical pop-up conditions must be considered simultaneously for selecting the minimum safe burial depth of the submarine pipeline. If the user decides to go for a particular depth of burial then the additional surcharge weight to be added to the pipe must be the higher value estimated among the two sections for vertical and horizontal stability.

Table 6 lists the soil location, e/D values studied, factor of safety against uplift, FS_{Uplift}, minimum safe e/D value to prevent vertical pop-up, the factor of safety against horizontal sliding, $FS_{Horizontal\ sliding}$, and the minimum safe e/D value to prevent horizontal sliding. The minimum safe e/D value considering both vertical and horizontal stability is also listed in column 7. This value is the highest among the two values listed in columns 4 and 6. It can be seen that the minimum safe burial depth was governed by the vertical force and not by the horizontal force for any e/D values.

The weight of additional surcharge, W_{as} required to obtain factor of safety against uplift, FS_{Uplift} of 1.5 and factor of safety against horizontal sliding, $FS_{Horizontal\ sliding}$ of 1.5 is also listed in columns 8 and 9. The minimum weight of additional surcharge, W_{as} for satisfying both FS_{Uplift} and $FS_{Horizontal\ sliding}$ of 1.5 is listed in column 10. This value must be the higher value among columns 8 and 9. It can be seen that for e/D=0.0, the horizontal wave force dictated the additional surcharge weight for stability. For e/D from 0.5 onwards, the vertical force dictated the additional surcharge weight for all the soil types studied.

Similar workout can be performed for different design wave heights, wave periods and water depths. The detailed results of this research project study can be used by public and private organizations in Kuwait for selecting minimum safe burial depth of the submarine pipelines, or for estimating the additional surcharge weight needed to be added on the pipe for stability, once a particular depth of burial is selected for the project.

Table 6. Minimum safe relative burial depth, e/d of a submarine pipeline against vertical pop-up and horizontal sliding for crude oil transport for four various soils and for typical design input conditions in Kuwait

Location	e/D	FS_{Uplift}	Minimum Safe e/D Value to Prevent Vertical Pop-up	$FS_{Horizontal Sliding}$	Minimum Safe e/D Value to Prevent Horizontal Sliding	Minimum Safe e/D Value Considering Both Vertical and Horizontal Stability	W_{as} for FS_{Uplift} of 1.5 (t/m)	W_{as} for $FS_{Horizontal Sliding}$ of 1.5 (t/m)	Minimum W_{as} for Satisfying Both FS_{Uplift} and $FS_{Horizontal Sliding}$ of 1.5 (t/m)
Sabiya	0	1.04	e/D between 1.5 and 2.0	0.02	e/D in between 0.5 and 1.0	e/D between 1.5 and 2.0	0.42	1.10	1.10
	0.5	0.87		1.13			0.68	0.09	0.68
	1.0	0.94		10.96			0.62	0.0	0.62
	1.5	1.34		26.02			0.17	0.0	0.17
	2.0	1.97		101.80			0.0	0.0	0.0
Al-Koot	0	1.04	e/D bit more than 1.5	0.02	e/D in between 0.5 and 1.0	e/D bit more than 1.5	0.42	1.10	1.10
	0.5	0.78		0.71			0.87	0.17	0.87
	1.0	0.98		19.82			0.54	0.0	0.54
	1.5	1.44		85.08			0.06	0.0	0.06
	2.0	2.05		230.83			0.0	0.0	0.0
Shuaiba	0	1.04	e/D between 1.5 and 2.0	0.02	e/D=0.5	e/D between 1.5 and 2.0	0.42	1.10	1.10
	0.5	1.01		1.64			0.46	0.0	0.46
	1.0	0.96		13.12			0.58	0.0	0.58
	1.5	1.42		31.87			0.08	0.0	0.08
	2.0	2.07		78.25			0.0	0.0	0.0
Al-Khiran	0	1.04	e/D = 1.5	0.02	e/D=0.5	e/D = 1.5	0.42	1.10	1.10
	0.5	0.92		1.54			0.60	0.0	0.60
	1.0	1.01		13.77			0.51	0.0	0.51
	1.5	1.53		40.96			0.0	0.0	0.0
	2.0	2.33		85.14			0.0	0.0	0.0

CONCLUSIONS

It is important to understand how the in-line and vertical wave force vary due to burial in soils of different hydraulic conductivity in order to select the minimum safe burial depth of submarine pipelines. Well planned physical model investigations were carried out on a scaled submarine pipeline model in a wave flume. The investigations were carried out on four different soil types covering hydraulic conductivity in the range 0.286 to 1.84 mm/s, for a wide range of random wave conditions and for different relative burial depths of the submarine pipeline. The horizontal and vertical hydrodynamic forces on the submarine pipeline were estimated by measuring the dynamic pressures around the outer surface of the submarine pipeline at 12 points. Frequency domain analysis was carried out. The important conclusions obtained from this study are as follows:

- For all the four soil types, the horizontal force reduces consistently with increase in depth of burial. Varying the hydraulic conductivity has not changed the in-line wave forces significantly for different buried conditions.
- The vertical wave force generally increases up to certain depth of burial before it starts reducing, mainly due to the significant change in the magnitude as well as the phase difference between the pore water pressures in the vertical direction.
- Among the soils, well graded and high hydraulic conductivity soil (Shuaiba soil with k=1.84 mm/s) is better for half burial of the submarine pipeline, since the least vertical wave force is occurring for this type of soil.
- On the other hand, uniformly graded and low hydraulic conductivity soil (Al-Koot soil with k=0.286 mm/s) attracts the maximum vertical wave force for half burial of the submarine pipe. Hence it is not preferable to select half burial conditions in low hydraulic conductivity soil.
- In general, for soil with high hydraulic conductivity, varying the relative burial depth from e/D=0.5 to 1.0 or 1.5 does not provide any advantage from vertical stability point of view, since the vertical forces are of the same order from e/D=0.5 to 1.5. On the other hand, for a soil with low hydraulic conductivity, changing the burial from e/D=0.5 to 1.5 could reduce the force more than 50%.
- In general, the horizontal wave force dictates the stability of the submarine pipeline, if the pipeline is placed on the sea floor since the highest horizontal force occurs when the pipe is not buried.
- For half buried pipeline or pipeline just fully buried, the upward wave force dictates the stability of the pipeline.
- A case study is presented for estimating minimum burial depth of a typical crude oil pipe for the four locations in Kuwait.

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