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Effect of Significant Wave Height on the Concrete Coat Thickness of Submarine Pipeline in Shallow Water

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ABSTRACT : *This paper investigated the relationship between the significant wave height and the concrete coat thickness of a submarine pipeline in shallow water. The Simplified lateral stability method was used alongside a developed predictive model in MATLAB for the determination of the minimum required concrete coat thickness of such pipelines at different significant wave heights. The model used the optimal submerged weight of the pipeline to predict the minimum required concrete coat thickness needed to ensure on-bottom stability of a* 508 mm *diameter, 14.3mm wall thickness pipeline at 4 m water depth, and a peak wave period of 16.60s. The results revealed that an increase in the magnitude of the significant wave height resulted in increased thickness of the concrete coat around the pipeline and vice versa. This phenomenon occurred at larger significant wave heights due to an increase in the hydrodynamic effect, which eventually required a higher submerged weight for on-bottom stability. Thus, it can be concluded that the concrete coat thickness for on-bottom stability of a submarine pipeline is directly related to the magnitude of the significant wave height.*

KEYWORDS: - *Significant wave height, Shallow water, Hydrodynamic forces, submerged weight, Concrete coat thickness.*

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I. INTRODUCTION

Offshore structures are developed to support the exploration, production, and transportation of hydrocarbon. Hydrocarbon resources are transported from the offshore field to onshore processing facilities using subsea pipelines. Carbon steel pipelines are proven to be the most efficient and reliable means of transporting hydrocarbon to onshore or offshore locations [1]. Pipelines are made in different forms, which include a single-pipe, pipe-in-pipe, or a bundled system. Subsea pipelines are categorized to serve different purposes: Flow-lines refer to pipelines that carry hydrocarbon from the wellhead to the riser base, service lines transport service fluids such as corrosion inhibitor, lift gas and injection water or chemical from the platform to the wellhead, inter-field lines convey hydrocarbon or water between offshore installations in a given field and pipelines or transmission pipelines or trunk-lines pass on a large volume of oil or gas from offshore facility to the shore, particularly when there is no storage capacity on the platform [2]. Regardless of some internal and external loads, subsea pipelines are influenced by the forces created by waves, currents, and gravity, as shown in Figure 1 below. The hydrodynamic impact of the consolidated effect of waves and currents can cause tremendous displacement of the pipelines (when not stabilized), leading to consequential structural damage and regrettable ecological and economic losses. Consequently, it is imperative to keep subsea pipelines stable on the seabed. Pipelines are laid bare on the seabed of deep water where there is no danger of drop objects and over trawling [3]. Nevertheless, the pipelines penetrate the seabed with a fraction of their diameters because of their self-weight and contact stresses at touch down during installation [4].

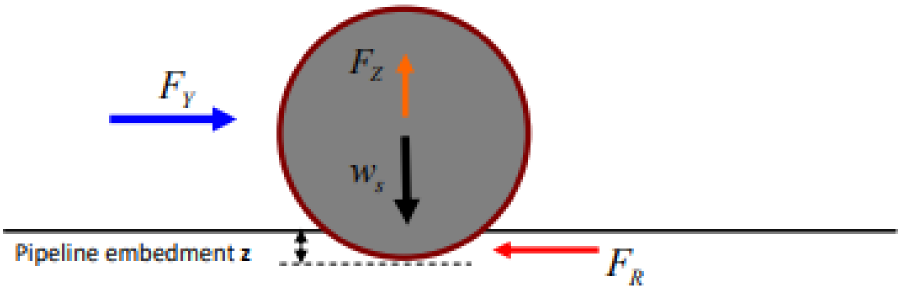

Figure 1: Schematic of Loads on pipeline

Most times, the weight of the pipe is based on the density of the piping material, wall thickness of the pipe, and additional concrete coatings. However, secondary stabilization methods are used when the pipe has an insufficient weight that will not ensure on-bottom stability. As presented in Figures 2(a), (b), and (c), secondary stabilization methods such as rock dumping, concrete mattress, anchors, and trenching respectively have a substantial cost and schedule implications to a project. Based on the installation point of view, offshore pipelines are classified into two categories; Trenched (buried) and Untrenched.

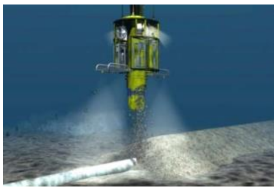

Figure 2-a: Rock dumping

Figure 2-b: Concrete Mattress

Figure 2-c: Trenching machine

The untrenched method with well-designed concrete coat thickness is reliable enough to provide the needed submerged weight that will ensure pipeline on-bottom stability [5]. The pipe gross weight (W) is the total sum of the weight of the available pipe layers, which includes the pipe steel wall and concrete coating. However, extra weight components like internal corrosion liner, internal coating, insulation coating, marine growth, and the internal content should be considered in the pipe weight calculation if they exist (6).

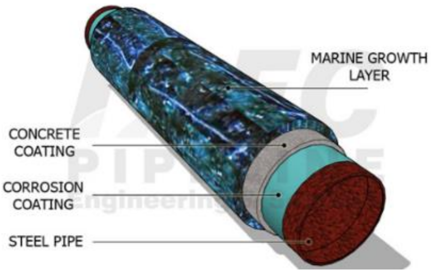

Figure 3 - A Section of Pipe Layers

The codes used in the design of subsea pipelines are BS8010, DNV-RPF109, ISO-13623, API 1111, and American Gas Association (AGA). Among these codes, the DNV-RPF109 and AGA guidelines are frequently used in on-bottom stability design [7]. According to DNV-RPF109, there are three recommended on-bottom stability design methods; dynamic lateral stability, generalized lateral stability, and absolute lateral static stability. Dynamic lateral stability method (as a time-domain simulation of pipe) allows the displacement of the pipe by an amount that is less than half of the pipe diameter and estimates the lateral displacement of the pipe by considering time-varying hydrodynamic forces [8]. It is mainly used to carry out analysis on certain critical areas of pipelines such as pipeline crossings, riser tie-in points, and reanalysis of existing pipelines when adequate structural responses are needed [9]. However, the use of the dynamic lateral stability method is limited due to the complexity of finite element analysis and the comparative advantage of the other two methods to give accurate values of concrete thickness [10].

Pipeline resting on the seabed has constant hydrodynamic coefficients such as, Drag coefficient(C_D), Lift coefficient(C_L), and Inertia coefficient(C_I). For this study, $C_D = 0.7$, $C_L = 0.9$, and $C_I = 3.29$. Note that these hydrodynamic coefficients are functions of both the Keulegan-Carpenter (KC) number and the Reynolds number (Re) [11].

Several works have been carried out to study the stability of offshore pipelines using the three stability analysis methods, namely absolute lateral stability, generalized stability, and dynamic stability method. For example, the simplified lateral stability method was used to estimate the on-bottom stability of offshore pipelines in the shallow water of the Gulf of Guinea by Ogbonda [12]. In that study, the hydrodynamics of forces on the pipeline were studied to enable the determination of the limiting wall steel thickness and the minimum submerged weight required to prevent collapse, buckling along the pipeline, the effect of contained pressure, and provide stability to the pipeline. The analysis was carried out with a developed user-friendly interface (in Mathcad) that has multiple settings to study the dynamic behavior of a *Φ*765 mm x 34 km pipeline using actual site data. This pipeline was to be installed in the Escravos offshore region of the Gulf of Guinea under different environmental and pipeline conditions such as wave height, water depth, pipe thickness, and concrete thickness. The result of the study showed that, for a 20.60 mm thickness pipeline, the following concrete coat thicknesses of 78.796 mm, 61.386 mm, 53.043 mm, and 42.58 mm were found to correspond to 5 m, 10 m, 15 m, and 20 m water depths respectively. Also, when the platform was used to study another *Φ*825.5 mm x 34 km pipeline, it was found that secondary stabilization methods would be needed to stabilize the pipeline since the concrete thickness exceeded the required limit.

Hamdy et al. used MATLAB software to develop a program to study the dynamic stability of un-trenched sub-marine cables and pipelines that laid on the bottom of shallow water of 14m deep by applying the Fourier decomposition method. This research was carried out to gain a better understanding and correct estimation of the hydrodynamic forces acting on the cables and pipelines due to the combined effect of waves and currents. Dynamic analysis was also carried out according to the guidelines of DNV-RP-F109 to investigate the dynamic response of cables/pipelines. The research also looked at the tendency of submarine pipelines/cables to be stable on the seabed with the help of its own weight, and if necessary, determine the extra weight to be added to make it stable on the seabed based on DNV-RP-F109 recommendation. Their hydrodynamic forces model was validated with the UWAHYDRO program developed at the Western Australian University by Youssef. The results of the research proved that some submarine elements can be stable in the presence of worst storm conditions in some areas, as observed with a 609.6 mm diameter pipeline case in the Arabian Gulf area. Whereas some could attain stability by the addition of reasonable and cost-effective mass per meter length, while in other cases other stabilization methods would be incorporated other than the added mass [13].

Another study was done by Hazhen&Aijung using the dynamic stability analysis method to analyze pipeline based on the reliability of the Surrogate model. The hydrodynamic forces on the pipeline were resolved using the Fourier model and thereafter, experimental sampling was utilized to build the surrogate model and the Monte Carlo technique was employed to perform the reliability quality assessment. The outcomes and conclusion of the analysis uncovered that the Surrogate model decreased the computational cost fundamentally and produced a very accurate assessment of pipeline stability. Additionally, it was affirmed that based on the sensitivity study of arbitrary variables, the significant wave height (Hs), friction coefficient (U), peak wave period (Tp), and water depth (h) affect the likelihood of stability failure enormously. More so, the significant wave height and peak wave period have comparable effects on the reliability assessment, and stability. Reliability records diminish as their values increase. Thus, more consideration should be given to these factors during pipeline design. They however recommended that in a future study, practical soil resistance should be incorporated [14].

This research investigates the effect of significant wave height on the concrete coat thickness of offshore pipelines in shallow water under the combined effect of waves and currents. It entails the development of a predictor model for determining the minimum required concrete coat thickness of a submarine pipeline. The DNV-RP-305 procedures are implemented on the MATLAB platform to graphically demonstrate the dependency of the minimum required concrete thickness on the significant wave height of the offshore pipeline.

II. METHODOLOGY

The methodology used in this research, as shown in figure 4, starts with the collection of input data, such as metocean, pipeline, and soil data. These inputs are implemented in a developed MATLAB code and used to perform hydrodynamic analysis of the pipeline before the determination of submerged weights that was used to calculate the minimum required concrete coat thickness of the pipeline.

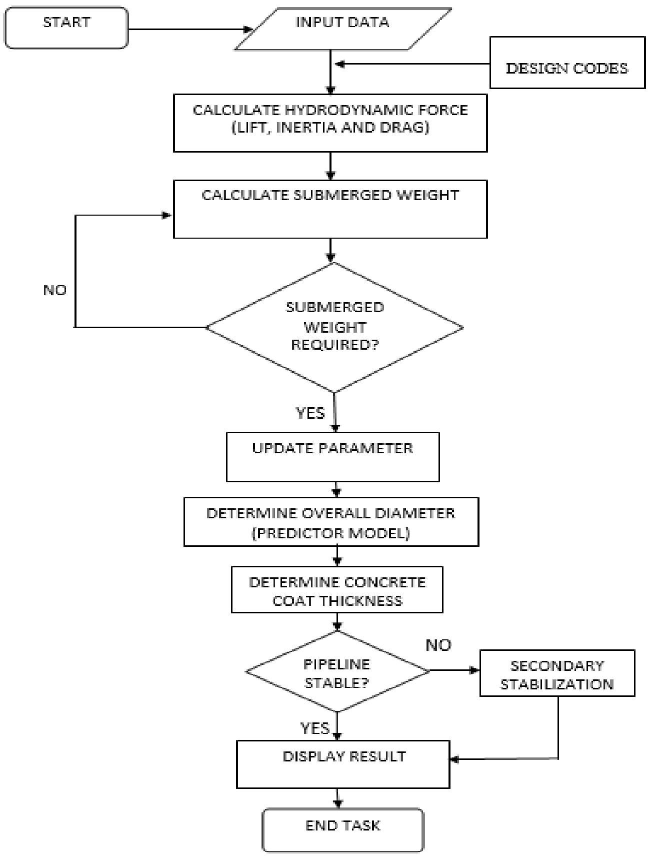

Figure 4 - Research Analysis Sequence

Three categories of data were used in this study; metocean, soil, and pipeline data as presented in Table 1 below. These data were used to predict the minimum required concrete coat thickness of the offshore pipeline and developed a graphical dependency of significant wave height and concrete thickness using the developed model predictor.

Table 1- Pipeline Design and Metocean data

Description	Value	Unit
Water Depth	4	m
Pipe Diameter	508	mm
Pipe thickness	14.3	mm
Pipeline joint length	12.2	m
Corrosion coating thickness t_{cc}	6	mm
Peak wave period	16.60	S
Significant wave height	1.2 to 3.2 @ intervals of 0.2	m
Density of steel material ρ_s	7850	Kg/m3
Density of corrosion coating ρ_w	1026	Kg/m3
Density of field joint filler ρ_{fj}	3040-	Kg/m3
Density of sea water ρ_w	1025	Kg/m3
Density of pipeline content ρ_f	860	Kg/m3
Pipeline length per joint	12.2	mm
Density of concrete coating ρ_c	3040	Kg/m3
Concrete Cut-back length L_{cb}	350	mm
Corrosion Cut back length	280	mm
Concrete water absorption	5	%
Coefficient of friction	0.7	

2.1 Mathematical Model

According to DNV-NRP 305 procedures, the following equations are useful in on-bottom stability analysis of offshore pipeline. To determine the hydrodynamic forces acting on the submarine pipeline, the equations below are used.

$$F_I = \pi \rho_w C_M \frac{{D_o}^2}{4} A_x \sin\theta \qquad 1$$

$$F_D = \tfrac{1}{2}\rho_w C_D D_o / U_s \cos\theta + V_c / (U_s \cos\theta + V_c) \qquad 2$$

$$F_L = \frac{1}{2}\rho_w C_L D_o (U_s \cos\theta + V_c)^2 \qquad 3$$

WhereD_o is the outer diameter of the pipe, ρ_w is the density of seawater, θ is the phase angle of the wave, U_s is the water particle velocity, V_c is the current velocity, A_x is the water particle acceleration, while C_I, $C_D$and C_L are the coefficient of inertia, drag and lift force, respectively andF_I, $F_D$and F_L are the associated inertia, drag and lift force, respectively.
The submerged weight of a submarine pipeline is a function of the hydrodynamic forces, phase angle, friction coefficient and calibration factor as presented in equation 4 below, according to DNV-RP 305 [15].

$$W_{smin} = \left[\frac{\left(F_D(\theta) + F_I(\theta)\right) + \mu F_L(\theta)}{\mu}\right] F_w {}_{Max} \qquad 4$$

Where µ is the coefficient of friction, F_w is the calibration factor, θ is the phase angle of the wave, W_{smin} is minimum submerged weight, while F_I, $F_D$and F_L are the associated inertia, drag, and lift force, respectively. After determining the submerged weight as a function of phase angle for one complete wave cycle, the minimum required submerged weight is determined with equation 5 below.

$$W_{Subreq} = Max[W_{smin}(\theta)] \qquad 5$$

Where W_{smin} is the minimum submerged weight, θ is the phase angle of the wave and W_{Subreq} is the required submerged weight, which is the largest value of the submerged weights calculated for one complete wave phase angle.

Equation 6 below is used to estimate the overall diameter of the pipeline (D_{ovo}), which includes: the outer diameter of the pipe, the external corrosion coating and the concrete coat thickness to be determined. Lastly, equation 9 is applied to determine the minimum required concrete coat thickness (t_{cc}) needed to ensure on-bottom stability.

$$D_{OVO} = 1.15\left\{\frac{1}{\left[\rho_{cc}\left(L_j - 2L_{cc}\right) + \rho_w\right]}\left[\frac{4w_{rs}L_j}{\pi} + (D_o + 2t_c)^2\left(L_j - 2L_{cc}\right)\rho_{cc} - {D_i}^2\rho_f - \left({D_o}^2 - {D_i}^2\right)\rho_{st} - \left[(D_o + 2t_c)^2 - {D_o}^2\right]\left(L_j - 2L_c\right)\rho_c\right]\right\}^{0.5} \qquad 6$$

$$t_{cc} = \frac{(D_{ovo} - D_o - 2t_c)}{2} \qquad 7$$

Where w_{rs} is the required submerged weight, L_j is the joint length of the pipe, andρ_f,ρ_w,$\rho_{st}\rho_c$ and ρ_{cc} are the densities of fluid in the pipe, saltwater, steel pipe, concrete and corrosion coating, respectively.

III. RESULT AND DISCUSSION

3.1 Hydrodynamic Forces

Figure 5 below presents the graphs of the hydrodynamic forces for one complete phase angle of wave. Inertia and drag forces have both positive and negative values, indicating that they oscillate in both directions (left and right). On the other hand, the lift force only has positive values, signifying that it is an upward force. In our context, the greatest hydrodynamic force is the lift force, with the magnitude of 500 N. It is also evident that when the lift and the drag forces are maximum, the inertia force is zero. Hence, the lift force is a critical factor to be considered for the on-bottom stability of a submarine pipeline. It also shows that the lift force is independent of the inertia force, but varies in magnitude to that of the drag, regardless of the phase angle. Generally, the inertia force is sinusoidal, with its zeros at 0°, 180°and 360°; while its peaks are at 90° and 270°. As the inertia force approaches a phase change, the drag and the lift curves diverge in equal magnitudes about the x-axis(at120°), and later converge to zero (at 240º). It is only within this range that the drag becomes negative, and the net hydrodynamic effect is minimal (having a zero value at 180º).

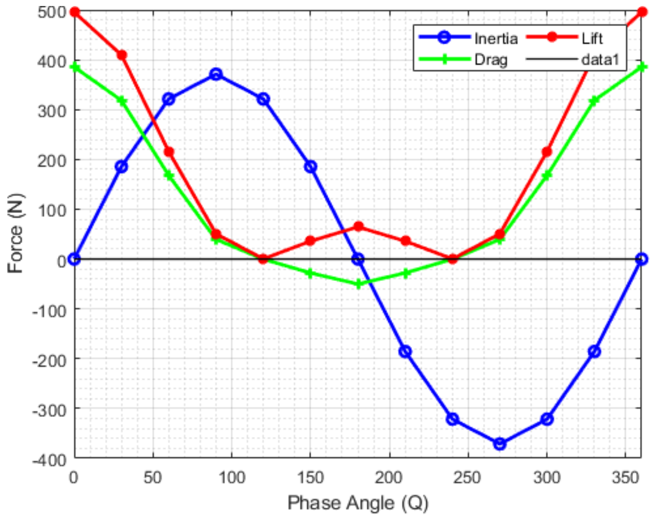

Figure 5 - Hydrodynamic Forces Vs Phase Angle

3.2 Submerged Weight

The required submerged weight increases from 1500 N/m at 0º to a maximum of 1600 N/M at 30º, as shown in Figure 6 below. Thereafter, it decreases progressively as the phase angle increases to 0 N/m at 180º. This implies that the resultant force on the pipeline due to drag, lift, and inertia forces is zero. Beyond this point, the resultant submerged weight becomes apparently negative and reaches a minimum of -620 N/m at 240º. This trend is caused by a growing negative inertia force. For phase angles greater than 300º, the resultant submerged weight grows in positive magnitude to a peak of 1450 N/m at 360º. Also, where the phase angle is 0º or 360º, the lift and drag forces are found to be maximum, while the inertia is zero. The analysis shows that the lift force is the ultimate determinant of the required submerged weight needed to keep pipelines stable on the seabed. Therefore, pipelines should be positioned in a direction where the influence of the hydrodynamic forces will be surpassed by their submerged weights to avoid drifting upward and sideways.

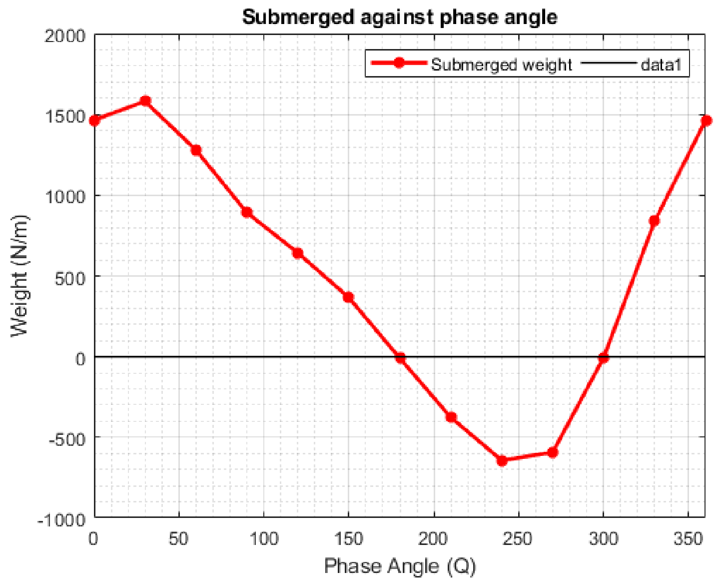

Figure 6 - Submerged Weight Vs Phase Angle

3.3 Concrete Coat Thickness

Figure 7 below displays the result of the parametric analysis of the test-case of a 508 mm diameter pipeline of 14.3 mm thickness in a water depth and peak wave period of 4 m and 16.6 sec, respectively. Various wave conditions are implemented to ascertain the relationship between the significant wave height and the concrete coat thickness of the submarine pipeline. The resultant graph indicates that the required concrete coat thickness is directly proportional to the significant wave height (the average of the highest one-third of the waves measured from crest to trough). This means that as the significant wave height increases, more concrete coat thickness is needed to ensure that the pipeline remains stable on the seabed. Therefore, for pipelines located in a harsh stormy environment where the significant wave height is predominantly high with the associated severe hydrodynamic effect that may cause it to drift, increasing the thickness of the surrounding concrete coat on the pipeline could maintain stability.

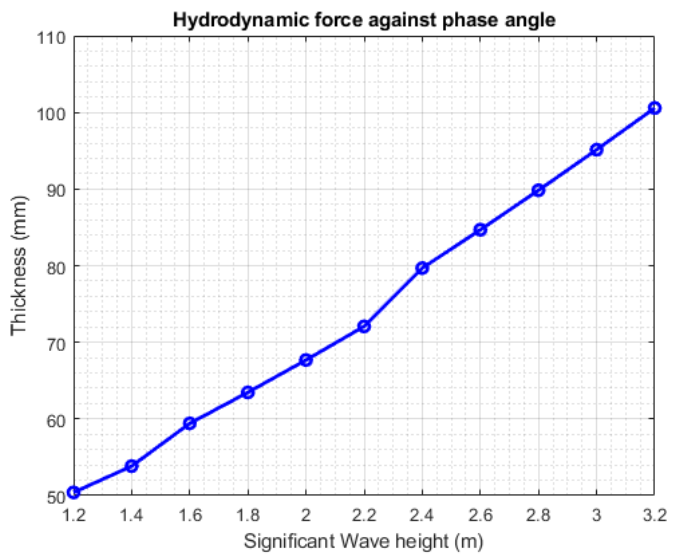

Figure 7 - Concrete Thickness Vs Significant Wave Height

IV. CONCLUSION

The hydrodynamic effect around a submarine pipeline is due to several parameters, which are water depth, significant wave height, current, the topology of the seabed, etc. This research investigated the relationship between the minimum concrete coat thickness around the submarine pipeline for on-bottom stability and the hydrodynamic effects that are associated with the prevalent significant wave height in offshore fields. The parametric study is based on a 508 mm diameter pipeline of thickness 14.3mm in a shallow water depth of 4 m and a peak wave period of 16.6 sec. DNV-NRP 305 procedures were implemented on the MATLAB platform for the analysis.

The results of this study showed that the minimum required concrete coat thickness around a submarine pipeline in shallow water is directly proportional to the variation in the significant wave height. This phenomenon is due to an increased hydrodynamic effect that eventually leads to an increase in the submerged weight of the pipeline resulting from additional coating for stability as the significant wave height rises. Since extra cost is involved for additional concrete coating for pipeline on-bottom stability, it can thus be inferred that the cost of a pipeline project varies with sea state. In the North Sea and the Gulf of Mexico where the significant wave heights are relatively high, more concrete coat thickness and additional stability approach are required. In contrast, a lesser cost is needed for the Gulf of Guinea with smaller significant wave height. Therefore, a proper understanding of the relationship between the pipeline concrete coat thickness and the prevalent significant wave height at the offshore project site is imperative for correct pipe-laying and project cost evaluation.

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