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Review of Offshore Pipeline Span creation mechanism

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ABSTRACT
The various span creation mechanisms have been studied in great detail and this work has presented the state of the art in the area of offshore pipeline span creation mechanism analysis. The different span creation mechanisms of a pipeline during operation include residual uplifts, scouring, sandwaves, underwater landslides, strudel scour, etc. With this information a software can be formulated which can incorporate the different characteristics of elements of span creation.

INTODUCTION
A free span can be defined as a section of submerged pipeline not in contact with the seabed over its length [90]. According to Gou et al. [36], pipeline spanning usually occurs when the contact between the pipeline and seabed is lost over a long depression on a rough seabed. Due to highly uneven sea bed terrain, the pipelines can be said to rest on mountains with possible free spans ranging between 50-100m [126] [81].
Presently, the oil and gas industry is moving towards harsher environments often characterized by uneven seabed and deep water [2]. The number of submarine pipelines being laid in such environments is increasing at a massive rate in different parts of the world. Thus, free spanning pipelines are becoming more frequent and are often unavoidable during pipeline installation [80]. The formation of submarine pipeline spans may have a critical influence on the safety and integrity of the pipelines [44]. There are records of recent failures due to free spanning of pipelines thus necessitating an increased attention on pipeline span analysis. Spans can develop during pipelay due to irregular bedform, (coupled with factors such as pipe weight, pipe stiffness, etc.) or during the service life of the pipeline, due to dynamic seabed [84]– scouring, etc. and, in some cases, due to horizontal movements. A background on span creation mechanisms can be found in the Appendix.
The existence of a pipeline free span can cause excessive deformation and bending or vibration of the pipeline section. Pipeline free span evaluation involves the determination of the maximum or critical span length under the effects of hydrodynamic loads [25]. Span analysis involves consideration of structural failure due to overstress from steady state loads, fatigue failure due to vibrations from dynamic loads (such as Vortex Induced Vibrations) and severe damage due to third party activities (hooking from trawl gears or drop objects) [73; 113].

Span creation mechanism

According to Wei et al [110], submarine pipeline spanning mechanism may occur due to (i) absence of sediment sources, (ii) complexity in subsea floors and (ii) strong hydrodynamics.

Residual Uplifts

Residual uplifts can be described as isolated protuberances in the surrounding seabed that have not eroded. Scour holes are concaves formed by hydrodynamic differential erosion, in which the strike is parallel to the direction of tide. The strike of residual uplifts and scour holes are basically considered perpendicular to the direction of the pipelines. Their presence and development impacts the integrity of submarine pipelines. This is according to results obtained from studies in a certain gas field.

Wei et al. noted that since pipelines in certain areas studied are not completely susceptible to mud and piping effects leads to more intensive erosion, the expansion of scale of the grooves is an inevitable trend.

It was also reported that for a particular area in the field a stratum associated with factors such as sand waves, lack of sediment sources, etc. was formed which prevented pipeline trenching; and sediment transportation in the area associated with hydrodynamic effect lead to the burial of grooves resulting in an illusion about the pipeline integrity and an intermittent exposure of the groove resulting in large free spans.

High temperature high pressure (HP/ HT) flow can cause the creation of free spans if upheaval buckling takes place due to restricted thermal expansion in buried pipelines [106]. Reduced overburden due to liquefaction may, in some cases, lead to upheaval buckling particularly in high temperature pipelines [41]. Details on upheaval buckling mechanisms and design can be found in DNV RP F110 (2007), Ommundsen (2009) and Bartolini et al. (2011).

For flowlines installed on uneven seabed, the combination of lateral buckles during operation (due to conditions such as pressure and temperature) and shut-downs may cause tension in the pipeline and the development of several free spans [121].

Scour

Several studies [39][14][27][114][16][56][57][58][60][15][11][33][34] [118][28][117][32][119] [91] [112] [17] [62] have been carried out recently under this subject some of which include:

The scour processes around pipelines include the onset of scour, the tunnel and lee-wake erosion and then the three-dimensional scour processes. An extensive literature on this can be found in Sumer and Fredsoe [94] where scour depth under various conditions; effects of factors such as pipe roughness, angle of attack, armouring, water depth, shields parameter, pipeline verticality, etc.; width of scour hole under various conditions; time scale in various conditions; effect of sagging on scour; free span length; mathematical modelling; etc. were covered.

According to Gou et al. [35], there may exist two phases in the sand scouring process around pipelines with initial embedment: (a) Phase I: scour beneath pipe without VIV, and (b) Phase II: scour with VIV of pipe.

During Phase II, the pipe vibration amplitude gets larger and its frequency gets smaller whilst the sand below the pipe is being scoured, and finally the pipe vibration and sand scour reaches an equilibrium state. This indicates that sand scouring has an effect upon not only the amplitude of pipe vibration but also on its frequency [35].

Gao and Luo [34], noted that during the onset of scour the influences of soil internal friction angle and pipe embedment on the critical flow velocity for pipeline spanning are significant. The critical dimensionless flow velocity, V_{cr}, changes approximately linearly with soil internal friction angle for $0 < e / D < 0.25$. Figure 0-1 shows the criteria for the onset of scour in currents based on analysis by Cheng et al [16].

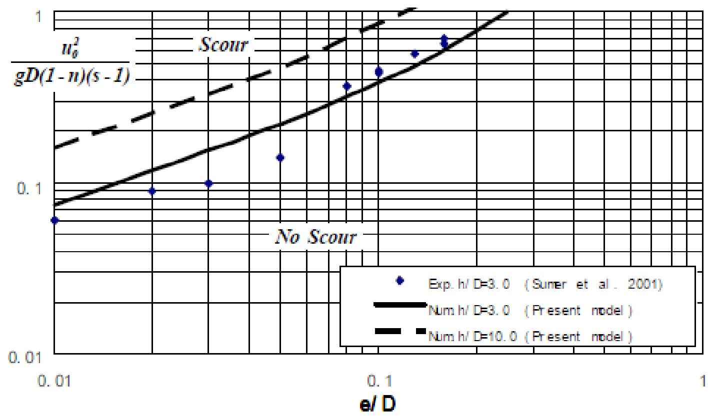

Figure 0-1: Onset condition for scour in currents. Source: Cheng et al [16]

The equilibrium scour depth decreases with increasing initial gap-to-diameter ratio for both fixed pipes and vibrating pipes [33].

According to Wu and Chiew [112], the development of 3D scour below pipelines can be divided into a rapid phase and slack phase. In the rapid phase of the development, the scour hole propagates in a faster and constant velocity; while in the slack phase of development, the scour hole propagates in a slower and reducing velocity. The temporal development of the 3D pipeline scour exhibits three patterns, namely, (1) rapid-phase dominant (2) Rapid and slack phase coexistent (3) slack-phase dominant, which is determined by the balance between environmental force and stability force. Lastly, the propagation velocity is very sensitive to Froude number, F for $0.155 \leq F \leq 0.249$, but not so to the shields parameter, θ in the range of $0.014 \leq \theta \leq 0.021$.

Cheng and Zhao, [17], revealed that scour development in the span wise direction is primarily caused by the flow velocity around the span shoulders, provided the gap between the pipeline and bed is small.

Mirmohammadi and Ketabdari [62] developed a model claimed to be a powerful tool to simulate complex free surface and Newtonian-non Newtonian fluid interaction problems.

Myrhaug et al [65] provided a practical method for estimating the scour depth below pipelines exposed to nonlinear random waves plus current for wave-dominated flow conditions with $0 \leq U_c/(U_c + U_{rms}) \lesssim 0.4$. Under the condition studied the scour depth below the pipeline can be expressed as Eq. (0-1).

$$S = \hat{S}D \qquad (0\text{-}1)$$

Where

$$\hat{S} = \frac{S_{scur}}{D}\frac{5}{3}KC_{rms}^{a}\beta^{a}\left(1+\frac{1}{2}a\beta t\right)exp(2.3b)$$

$$a = 0.557 - 0.912\left(U_{cw1/n} - 0.25\right)^2$$

$$b = -1.14 + 2.24\left(U_{cw1/n} - 0.25\right)^2$$

$$U_{cw1/n} = \frac{U_c}{(\beta + (1/2)t\beta^2)U_{rms} + U_c}$$

Myrhaug et al [66] provided a practical approach for estimating the scour depth below a pipeline exposed to random waves with normal incidence to the pipeline '*in shoaling conditions*'. Eq. (0-2) can be used to calculate the scour depth for a certain condition studied.

$$\frac{S}{D} = aU_{RPrms}^{b}\left(E\left[\widehat{H}_{1/n}\right]\right)^{3b} \qquad (0\text{-}2)$$

$$E\left[\widehat{H}_{1/n}\right] = \binom{1.416}{1.800} - \binom{0.140}{0.830}k - \binom{0.749}{0.447}k^2 + \binom{0.887}{0.985}k^3 - \binom{0.413}{0.478}k^4;\;\; n = \binom{3}{10}$$

The vibration forces shed from the bottom side of the vibrating pipeline due to currents contribute to an increase in scour depth and scouring is always stronger in the case of vibrating pipe than in the case of the fixed one [32; 119]: The smaller the gap ratio the larger the effect of the pipe vibration. The scour pit underneath a two-degree-of-freedom vibrating pipeline is deeper than that under a pipeline vibrating only in the transverse flow direction. Water depth has a weak effect on the scour depth but it affects the time scale of the scour. The shallower the water depth is, the less time it requires to reach the equilibrium state of the scour.

Cao and Qin [11] studied the relationship between the scour depth and certain factors by numerical simulation.

Sandwaves

Sand waves also referred to as tidal dunes are large scale rhythmic [8] offshore bed forms which develops a prominent regular pattern occurring at water depths of 10 to 50 m of sandy seas observed in the continental shelf far from the near-shore region [69; 70].

Steady and superharmonic velocity components are generated by the interaction of the forcing oscillatory tidal current with the bottom waviness [8]; and when the hydrodynamic and morphodynamic parameters (particularly the wavelength of the bottom waviness) gives rise to steady recirculating cells [9] such that the sediment is steadily dragged by these velocity components from the troughs towards the crests of the bottom perturbation. The latter grows and gives rise to sand waves.

Several authors [69; 101; 120] have stated that sand waves can lead to the formation of pipeline free spans. According to Zou et al. [120] due to the movement of sand waves, pipelines may become exposed which may result in free spans, which in turn cause the pipeline to buckle or break.

According to Wei et al. [110], a pipeline laid on sand waves can cause spanning near the crest, and the direction of sand wave movement is a crucial factor for span evolution. Due to sand crest movement the pipeline may sink thereby reducing the dimensions of the span.

Several authors [21] [22] [42] [55][69][70] [49][50][61][69][72] [69] [97] [100][101] [102] [67] [102] have carried out extensive research on the mechanisms of sand waves and others their impact on pipelines [72; 76].

Wavelength of sand waves increases with increasing water depth, tidal ellipticity and grain size (coarse sand), while it decreases with increasing tidal current amplitude and grain size (fine sand). Also, the influence of factors such as sand wave shape, tidal current type, grain size, etc. on factors such as migration speed, wave length, timescale, etc. have been studied [102].

Li et al [55], developed an effective formula Eq. (0-3) to predict the migration rate of sand waves which takes the effects of the environment and the features of sand waves into consideration.

$$c = SIG(\alpha)(\varphi_1\theta + \varphi_2\phi) \tag{0-3}$$

$$\phi = \omega A\zeta\alpha^2\beta \tag{0-4}$$

$\theta =$ Shields parameter, $\varphi_1 = 0.013$, $\varphi_2 = 0.86$, $\omega =$ tidal frequency, $A =$ $0.535Q^2$ (embodies the influence of the wind-driven flow) and $SIG(\alpha)$ a sign function.

Sand waves are usually assumed to migrate in the direction of the residual current. The tidal flow can change the sea floor shape through sand transport; and in turn the shape of the sea floor can then affect the tidal flow, creating a feedback mechanism [102]. According to da Silva et al [21], sediment transport is mainly caused by the oscillatory motions induced by surface short gravity waves.

Nemeth [69], discovered that a steady current inducing an asymmetry in the basic state can cause migration of sand waves; the stabilisation mechanism which causes sand waves to saturate is based on the balance between the shear stress at the seabed and the fact that sediment is transported easier downhill than uphill; the magnitude of the resistance at the seabed and the eddy viscosity influence both the timescale and the height of the fully-developed sand wave among others.

Wavelength of sand waves increases with increasing water depth, tidal ellipticity and grain size (coarse sand), while it decreases with increasing tidal current amplitude and grain size (fine sand) [102]. The speeds of different shapes of sand waves are different and their shapes have an

influence on their migration [120].
According to Tonnon et al [102], sand waves grow in the case of dominant bed-load transport (weak tidal currents, relatively coarse sediment, small roughness height, low waves) and decays in the case of dominant suspended transport (strong currents, relatively fine sediment, large roughness height, storm waves).
Komarova and Newell [50] noted that there are at least two mechanisms responsible for the growth of sand banks and sand waves. One is linear instability, and the other is nonlinear coupling between long sand banks and short sand waves. One novel feature of their work was the suggestion that the latter is more important for the generation of sand banks.
Several authors [8][21][97][42][55][67][68][100][101][102] developed numerical simulation models which has been proven to be able to describe sand wave excitation and select the initially most unstable mode assuming sand waves are free instabilities of the water-seabed system. As a result, several mechanisms and characteristics of sand waves were revealed.

Underwater landslides

The action of an underwater landslide can result in the creation of pipeline free spans [41][124]. Submarine Landslides are characterised by outward and downward movement of sediments and rocks sometimes from shallower to deeper regions of the ocean floor. The travel distance of deposits is called the run-out distance and can be several kilometres from the original location. They can be referred to as all types of gravity-induced submarine mass movements such as avalanches, slump and flows [102].
Slope instability is the movement of seabed mass [29]. Submarine landslides/ slumps and submarine flows are classified as types of slope instability. Submarine flows according to the type of sediment can involve grain, debris, liquefaction, and turbidity and these are more liquid than other types of slope instabilities. Debris flows usually involve a combination of fine and granular soils while liquefaction flows involve sands. Unlike liquefaction flows grain flows can only occur on very steep slopes and are usually made up of granular soils.
Slides can either be translational or rotational of which translational slides are the most frequent [20]. Inclination is one of several crucial factors which dictate slope instability. Examples of types of translational submarine landslides include elongate slides and slumps, mudflow gullies, block slides, shallow slab slides, successive slides, collapse depressions, and bottlenecks slides [20; 29].
According to Liu and Rourke [59], one of the causes of damage to offshore pipelines in the Gulf of Mexico during past Hurricanes is Landslides. Deepwater pipelines are at greater risk from landslide impact than other subsea structures because of the increased length of installed pipelines which results in increased exposure to landslide hazards; and due to the small structural resistance of pipelines compared to landslides. Large hurricane waves can trigger mudslides on the seafloor offshore and pipelines can span over failed zones caused by mudslides [72].
According to several authors [37; 54], the triggering mechanisms for landslides include

earthquakes and faulting [52], rapid sedimentation, gas and disassociation of gas hydrates [20], ocean storm waves [20; 72], tidal events, human activity, erosion, mud volcanoes, magma volcanoes, salt diapirism, flood events, creep, tsunamis and sea-level fluctuations. An extensive description of each of these mechanisms can be found in Hance [37].

According to Martel [61], landslide scars will tend to have elliptical shapes in map view and width-to-length values ranging from 0.5-1. As the shear fracture spreads, the stress concentration at its perimeter enhances its propagation up towards the surface. Sliding at depth causes and precedes fracturing at the surface. For a shear fracture less than twice as long as its width, surficial fracturing should start in the head and from there 'unzip' down along the slide flanks. Depending on the ambient stress state and whether there is loss in shear strength at the slide base or not, it may be necessary for a shear fracture to be several times wider and longer than its depth to develop a significantly intense stress concentration to propagate out of plane to the surface. This is why many natural slides are characterised by large length-to-thickness ratios. Landslide characteristics include an echelon pattern of opening-mode fractures along the flanks and sub-parallel to the head scarp trace; a steep, arcuate, concave-downhill head scarp; subsidence and normal faulting near the head of a slide; and uplift with thrust faulting near the slide toe.

Hitchcock et al. [38], developed a geomorphology-based approach to map mudflow susceptibility on the sea floor bottom. Their research was designed to provide regionally-consistent hazard information for the siting and design of pipelines using readily available datasets.

Fernandez-Nieto et al [30] presented a two-layer model of Savage-Hutter type to study submarine avalanches. It was assumed that a layer composed of fluidized granular material flows within an upper layer composed of an inviscid fluid. The model was derived in a system of local coordinates following a non-erodible bottom and takes into account its curvature.

Liquefaction

According to Sumer and Fredsoe [94], liquefaction can be described as the state of the soil where the effective stresses between the individual grains in the bed vanish, and thus the water-sediment mixtures as a whole acts like a fluid. As a result of this, the soil fails resulting in instability of a subsea pipeline. Liquefaction could be induced by either build-up of pore pressure / residual liquefaction or by upward-directed pressure gradient/ transient liquefaction.

The process of liquefaction depends on the wave induced shear stresses in the soil, the pore process and the ground-water flow which are basically governed by the Biot consolidation equations [115].

Inadequate trenching such as in situations whereby the supporting materials under the pipeline are not completely moved away, laying a pipeline on the edge of the groove but not in the groove completely and in cases where the anchor holes expand under piping effect can lead to pipeline spanning [110].

The number and complexity of free spans for pipelines in deepwater can increase substantially depending on the seabed roughness along the pipeline route from the continental shelf break to the deepwater fields [Pereira, 2008].

Spans can be classified into isolated or interacting depending on the soil type and span/span support lengths. For spans with horizontal supports the interaction between spans increases as the soil becomes softer under certain conditions. Again, for a given seabed profile, softer soils tend to have shorter and fewer spans and perhaps less interacting spans than harder soils [104].

Strudel scour

Strudel scour can be described as a localized seasonal phenomenon [18] that occurs during spring when melting fresh water in rivers and streams, flow into the sea (such as Beaufort sea and Arctic coast of Alaska which will still be frozen during this period) in such a way that if the frozen river cover encounters a crack, it pours downward through the crack, forming a powerful rotating vortex ('strudel') and a jet directed downwards with high velocities, scouring a hole in the seabed [1;74]. See **Error! Reference source not found.**.

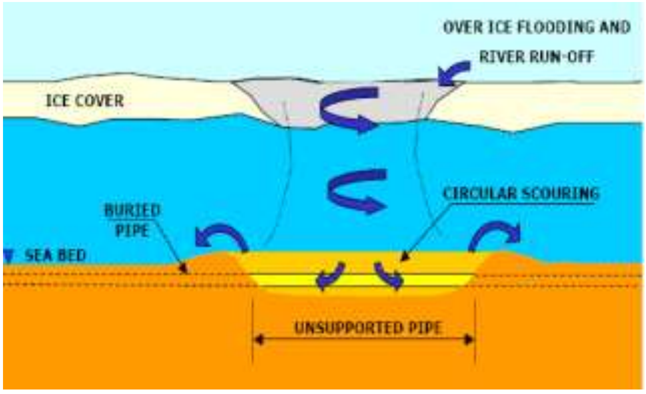

Figure 0-2: A schematic of strudel scour. Source: Abdallah et al [1].

According to Palmer [74], a seabed pipeline, which the scour happened to coincide with may be damaged, due to the high velocity in the jet which could induce so much drag that the pipeline deforms, or might induce vortex-excited oscillations. Given that ice and water above are in isostatic equilibrium, and the water then breaks through a crack, then the driving pressure difference is $(\rho_w - \rho_I)gh$, where ρ_w and ρ_I are the densities of ice and fresh water, g is the acceleration due to gravity, and h is the ice thickness. The velocity in the jet can be estimated from Eq. (0-5).

$$U = c\sqrt{2gh\left(1 - \frac{\rho_I}{\rho_w}\right)} \qquad (0\text{-}5)$$

Where c is the discharge coefficient.

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Appendix

Span creation mechanisms

A low depression in the sea floor for example seafloor gullies can induce a free span if the natural curvature of the pipeline is unable to follow the sea bed contour. This depends on factors such as the seabed profile, the type of soil, the residual tension, the pipe flexural stiffness and its submerged weight. The pipeline sags at the middle of the depression which causes increased static bending stresses at the depression boundaries of a free span and at mid-span. The static failure of a free span induced by a low depression can be due to the dead weight of the pipeline and contents causing severe bending stresses in the pipe. As the pipe sags at the middle of the depression, the pipe may be uplifted on each side of the depression causing additional free spans on each side of the depression.

Natural seabed obstructions or elevated obstructions such as boulders, pipeline crossing, rock beams, etc. can cause free spans [89][44]. In this case, the pipe tension has little effect on the static bending stress. The maximum static bending stress occurs at the crest of the span and is the governing stress in this case. As pipe tension increases, the pipeline touch down points on the sea bed will move further away from the elevated obstruction that is causing the span. This effectively increases the free span length. The stresses however increase only marginally. Therefore an increase in pipe tension will cause an increase in the maximum allowable span length [80].

The residual lay tension depends on the type of installation method used. The effect of the residual lay tension on span creation depends on the pipe weight. A large residual lay tension tends to generate more spans, and increase span length, whereas a heavy pipe will normally rest on seabed, thus reducing the number and length of spans. However, greater tension is necessary during installation to prevent overstress, if the pipe is heavy [44].

The residual tension in the pipe in contact with the sea bed is also dependent on the soil friction. If the anchor point is reached the full residual lay tension remains effective in the rest of the pipe. A pipe which is relatively stiff will tend to develop more and longer spans than a less stiff pipe on the same seabed.

A particular challenge in free span analysis is non-stationary spans. Examples are scour and erosion which have been identified by Mouselli [64]. It is claimed that erosion depends on factors such as bottom currents and soil properties. Due to the cohesion between clay particles it will require a high current velocity to initiate its movement with respect to that of sand, silt or gravel. According to the same author, the movement consists of random rolling and sliding of individual grains. It was claimed that as flow increases, at certain velocities the following occurs: (a) First, more particles roll and slide near the seabed, this motion being referred to as threshold of particle movement (b) Second, with increase in velocity, more particles move with some lifted off the seabed for a short trajectory before falling back on the seabed whereby the particle transportation can be referred as siltation of sediment. (c) An increase in turbulence will result in some of the particles being lifted increasingly higher above the seabed until they are in suspension and can be transported with flow. (d) At extremely high flow rates, the flow will cause ripples whereby the suspended particles are free to travel in the mixed flow until the velocity decreases to a level such that the particles cannot remain in suspension any longer. This velocity can be referred to as the settling velocity.

Submarine mudslides have been identified as being associated with pipeline spanning. It was claimed that a development sequence for mudslide evolution and elongation include three major stages. An extensive work on this subject can be found in Prior and Suhayda [79].

Other mechanisms which have been reported to cause soil movements at the seabed include turbidity, rapid soil deposition on steep slopes and passage of large surface waves. Factors such as gravity forces, waves, etc. are associated with sediment instability. Also, finite element analyses (FEA) has been used to calculate wave induced seabottom movements, where the effect of gravity, cyclic and permanent soil movements were considered (Wright (1976) as cited in Mouselli [64]). An extensive literature on this can be found in Mouselli [64].

The number and complexity of free spans can increase significantly depending on the seabed roughness along the pipeline route. Spans could be classified into interacting or isolated based on the soil type and span/ span support lengths. Table 0-1) shows an overview of the characteristics of free spans.

Table 0-1: Characteristics of free spans. DNV RP F105 [103]

L/D	< 30	$30 < L/D < 100$	$100 < L/D < 200$	$L/D > 200$
Description	Short free span caused by local unevenness in or at the start of erosion of the seabed.	Free spans in form of fully developed scour holes created as a result of erosion	Long free spans formed due to uneven seabed.	
Response	Very little dynamic amplification	Response dominated by beam behaviour	Response dominated by combined beam and cable behaviour.	Response dominated by cable behaviour.

According to Alam and Cheng [3], for live bed conditions, the net effect of superimposing a current on waves is to make the downstream width of the scour hole larger and the upstream width slightly smaller, probably due to the effect of the lee-wake the critical regime of the 2-D scour process is up to one pipe diameter away in both directions from the middle of unsupported length of pipelines (See Figure 0-1).

Figure 0-1: Equilibrium scour bed profiles presented with or without cylinder and selected streamlines. Source: Alam and Cheng [3].

It was claimed that for a pipeline laid on the seabed, for every 35 feet installed 1 foot was spanned initially and after five years of operation, for every 15 feet installed, 1 foot was spanned. The free-span length is governed by the following effects:

(1) Changing flow conditions: When the flow velocity is below the threshold value for the onset of scour, a developing free span may stop growing.

(2) Changing soil conditions: When the support reaches a non-erodible bed area, further development of the free span will be hindered.

(3) Sinking of the pipeline at the span shoulder: This will stop the development of a free span as the 3-D scour process will be terminated. This may be as a result of shear failure or liquefaction. Liquefaction potential is a function of the relative density of the soil, the permeability, the presence of the pipe, influence of stress history, etc.

(4) Sagging of the pipeline in the scour hole: As the pipe sag and reaches the bed, the free span length will be cut into half.

The span length can be calculated using Eq. (0-1).

$$L = 3.35 D^{\frac{1}{4}} L_s^{\frac{3}{4}} \tag{0-1}$$

Where L_s is the stiffness length and is defined as

$$L_s = \left(\frac{EI}{p}\right)^{1/3}$$

The scour model developed by Alam and Cheng [3] was able to predict stream-wise and span-wise propagations of scour with respect to lattice unit of time and the shape of the stream-wise equilibrium scour hole. The speed of propagation of scour along the pipeline length maintains an almost constant rate. The scour slope at the shoulder region remains fairly constant throughout the whole scour process. The scour process along the stream-wise direction is stronger than that of the span-wise direction [3].