Scour-Mechanism, Detection and Mitigation for Subsea Pipeline Integrity

Adarsh Kumar Arya[1]*,
Assistant Professor,
Department of Chemical Engineering
University of Petroleum and Energy Studies,
Dehradun, Uttarakhand ,India

B. Shingan[2]
Assistant Professor
Department of Chemical Engineering
University of Petroleum and Energy Studies,
Dehradun, Uttarakhand, INDIA

Abstract

Scour in the underwater pipeline is complex process which has not been fully understood. Scour is a major cause for the failure of the underwater pipeline. This process involves the complexity of three dimensional flow and sediment transport. A comprehensive study of the mechanism for the onset of scour and its subsequent development into two dimensional, three dimensional processes has been presented. The scour underneath the pipeline can expose the pipe to span and undermine its integrity. The importance of various factors affecting the scour, methods to detect the progress of scour and its effective remedial solution are examined.

Keywords: Scour, Onset of scour, Scour detection, Scour mitigation.

1. Introduction [1]

Pipelines installed in marine environments for transportation of oil and gas from the offshore platforms has become "lifelines" of the oil industry. The water depths in which these pipelines are laid may vary from tens of meters to hundreds of meters. These offshore pipelines can be laid on the sea bed surface, they can be buried, or they can be trenched. When the pipelines are laid in the sea, they are exposed to direct flow of sea water .This causes scour around the pipeline, which leads to suspended free spans of the pipeline. The pipeline along the length of the suspended span may or may not sag in the generated scour hole. In case of a sagging pipeline, the pipeline may reach the bottom of the scour hole, which is followed by backfilling which eventually leads to self-burial of the pipeline.Fig.1

2. Mechanism of Scour below pipeline: [2]

For a pipeline lying on an erodible bed, if the initial embedment is not very large, and the flow induced by currents/waves is sufficiently strong, the bed may be washed away underneath the pipe, that results in the onset of scour. The onset of scour is related to the seepage flow in sand beneath the pipeline .The seepage flow is induced due to the pressure difference between the upstream and downstream sides of the pipe.

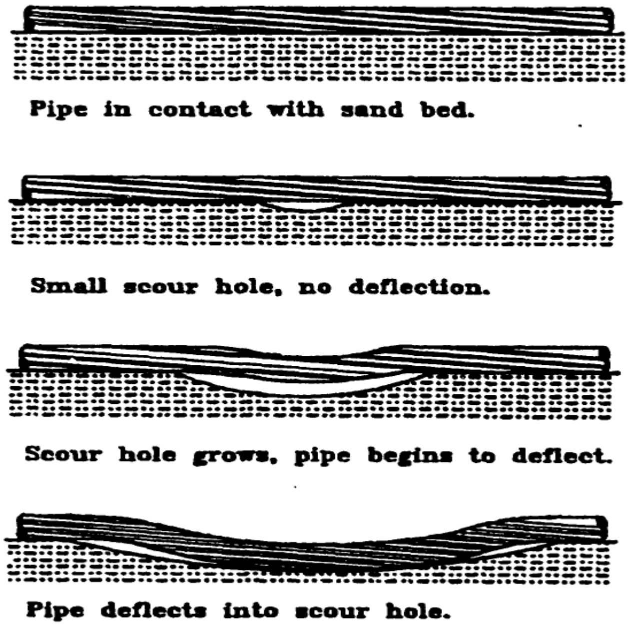


Fig. 1: Progress of scour

As the current velocity increases, the discharge of the seepage flow increases more rapidly than what the driving pressure difference dictates. The surface of the sand at the immediate downstream of the pipe starts to rise, and causes a mixture of sand and water to break through the space underneath the pipe. This process is called piping.

For cohesion-less granular material, the critical condition for piping has basically two forces: one is the agitating force or the seepage force, and the other is the resisting force or the submerged weight of the sand).

The seepage force (i.e., the point where the sand-water mixture is expelled from the bed is directed vertically upwards (considering the bed as a potential line, Fig. 2) can be written as

$$P = \frac{\partial p}{\partial x} \Delta x \qquad (1)$$

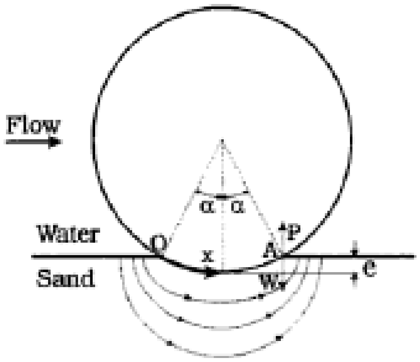


Figure 2: Seepage flow underneath the pipe.

The submerged weight of the sand, W (Fig. 1), on the other hand, is

$$W = (\gamma_s - \gamma)\,\Delta x\,(1 - n) = \gamma(s - 1)\,(1 - n)\,\Delta x \qquad (2)$$

.

For the critical condition to be arrived the seepage force (P) has to be greater than the submerged weight (W). The friction forces are practically zero at the instant of failure:

$$P \geq W \qquad (3)$$

Thus, from equations (1) and (2), the critical condition is given by the following equation

$$\frac{\partial}{\partial x}\left(\frac{p}{\gamma}\right) \geq (s - 1)\,(1 - n) \qquad (4)$$

The above eqn. 3 shows that the critical condition occurs when the pressure gradient $\frac{\partial}{\partial x}\left(\frac{p}{\gamma}\right)$ exceeds the floatation gradient (s - 1) (1 - n).

Criterion for the onset of scour

In steady current:

The criterion for the onset of scour (Eq.4) can be written in the following non-dimensional form. Onset of scour occurs if

$$\left\{\frac{\partial p*}{\partial x*}\,\frac{U^2}{gD\,(1-n)(s-1)} + R\right\}_{cr} \geq 1 \qquad (5)$$

$p* = \frac{p}{\rho U^2}$,
$x* = \frac{x}{D}$,
ρ is the water density,

The term R is a small, non-dimensional term, representing the effects other than the pressure gradient force (mainly the effect of the vortices forming in front of the pipe and in the lee wake). Both $\frac{\partial p*}{\partial x*}$ and R are essentially a function of the burial-depth-to-diameter ratio, e/D. Therefore, the criterion for the onset of scour can be written in the following form.

$$\left[\frac{U^2}{gD\,(1-n)(s-1)}\right]_{cr} \geq f\left(\frac{e}{D}\right) \qquad (6)$$

Here the function *f* (e/D) is determined from experiments. It may be noted that the function f is actually a function of not only e/D, but also the pipe Reynolds number, Re = UD/*ν*, and the relative roughness k. Also, soil properties (including permeability) will also influence the onset of scour (clearly, in the case when the permeability→0, the breakthrough will never occur).

The burial depth plays important role in causing piping effect. As the burial depth increases, the pressure gradient will be decreased; therefore relatively higher velocities will be required to cause piping.

This can be represented by the following empirical expression

$$\left\{\frac{U_{cr}^{2}}{gD\,(1-n)(s-1)}\right\} = 0.025\ \exp[9(e/D)^{0.5}] \qquad (7)$$

in which U_{cr} is the critical undisturbed flow velocity (measured at the level of the top of the pipeline) for the onset of scour.

It may be noted that the time required for the flow to remove the grains and open a "breach" will be appreciably longer for larger diameter pipes.

Tunnel erosion

The onset of scour is followed by the stage called tunnel erosion. At this initial stage, the gap between the pipe and the bed (e) remains small, i.e., e < D in which D is the pipe diameter. During this stage, a substantial amount of water is diverted to the gap leading to very large velocities and thus resulting into very large shear stresses on the bed underneath the pipeline, as shown in Fig. 3.

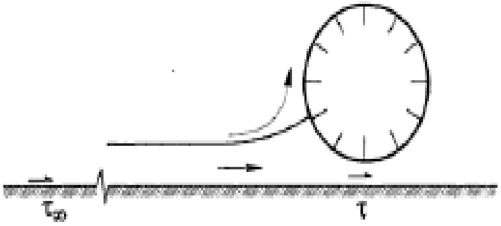


Fig. 3: Approach flow

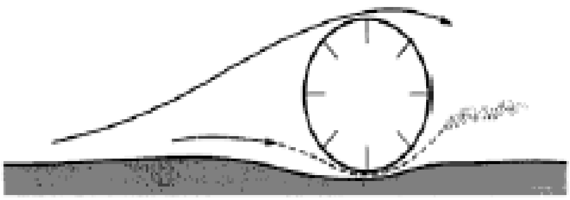


Fig. 4: Tunnel erosion below a pipeline.

2.3 Two Dimensional Scour (Lee-wake erosion)

The tunnel erosion stage is followed by the stage called the lee-wake erosion. Scour below pipelines occurs in a three-dimensional fashion: the scour breaks out underneath the pipe locally, and it propagates along the length of the pipeline in both directions, as shown in the Fig. 5.

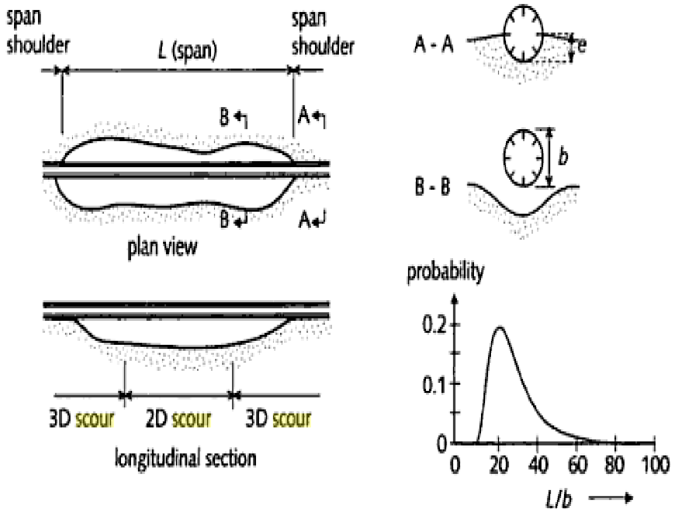


Fig.5.General scour picture around a pipeline.

The scour holes formed in this way are interrupted by stretches, called span shoulders, where the pipe obtains its support, section A-A in Fig. 5.

However, once the process has reached a developed stage, the scour in the middle part of a scour hole can be considered as a two-dimensional process.

The scour occurs extremely fast at the beginning (tunnel erosion) and then a dune begins to form at the downstream side of the pipe. However, this dune gradually migrates downstream, and finally may disappear as the scour progresses and also there will be more scour at the downstream side of the pipe than at the upstream side of it, resulting in a steep upstream slope and a gentler downstream slope.

Figure 6: Sediment motion caused by vortex passing overhead.

Vortex shedding controls the scour process and its characteristics at the lee- wake erosion stage. Vortex shedding starts occurring, the moment the gap between pipeline and bed reaches critical value. The bed is swept by the vortices formed on the bed side of pipe and get carried downstream. This results in the lee-wake erosion. [Fig.6]

Scour depth

For a pipe rigidly placed on a bed with initially a zero gap, the scour depth develops towards the equilibrium stage through a transition period. The scour depth at the fully-developed stage is called the Equilibrium scour depth.

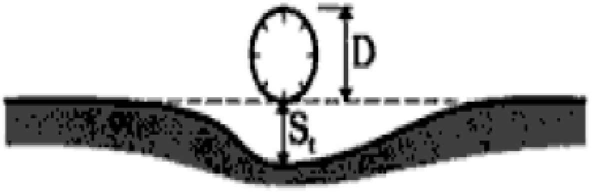


Figure 7: Scour depth

Scour depth in steady currents:

The empirical relation between the equilibrium scour depth, S, the pipe diameter, D, and the flow velocity, V is given as Kjeldsen et al. (1973) as

$$S = 0.972 \left(\frac{V^2}{2g}\right)^{0.2} D^{0.8} \tag{8}$$

The above equation is dimensionally homogeneous. The non-dimensional scour depth (S/D) is proportional to θ.

$$\frac{S}{D} \propto \theta^{0.2} \tag{9}$$

where θ is the Shield's parameter.

The exact flow picture due to the presence of the pipe depends on the following quantities:

- the pipe diameter, D,
- the flow velocity, V (often taken as the undisturbed flow velocity at the center of the pipe),
- the kinematic viscosity of the fluid, *ν*,
- the pipe roughness, k_s, and
- the grain diameter of the bed material, d.

Dimensional analysis reveals that the non-dimensional scour depth (S/D) depends upon the following factors:

$$\frac{S}{D} = f\left(k^*, Re, \theta\right) \tag{10}$$

where, *k** is the relative roughness, given as

$$k^* = \frac{k_s}{D} \tag{11}$$

Re the Reynolds number, given as

$$Re = \frac{VD}{\nu} \tag{12}$$

and θ is the Shields parameter, given as

$$\theta = \frac{U_f^2}{g(s-1)d} \tag{13}$$

where U_f, is the undistributed bed shear velocity which can be calculated from the Colebrook-White formula:

$$\sqrt{\frac{2}{f}} = \frac{V}{U_f} = 8.6 + 2.5 \ln\left(\frac{D}{2k_b}\right) \tag{14}$$

. The bed roughness k_b is usually taken as 2.5d.

Three-dimensional scour

Pipeline scour occurs in a three dimensional fashion in the field, however in the middle portion of the suspended span it is considered to be of two dimensional nature. At the span shoulders the scour process is a definite three dimensional affair. Though no detailed study are available to substantiate the three dimensional flow behavior around the pipeline span shoulders, however the studies on flow patterns of two dimensional scour process i.e., tunnel erosion and the lee-wake effects suggests that a spiral type of vortex may form in front of the pipe. This vortex is caused by the three-dimensional separation under the adverse pressure gradient produced by the pipe in which the separated boundary layer rolls up to form a spiral vortex.

The three dimensional scour processes may occur in different fashion in actual field depending upon the various factors like the flow, the soil, and the pipe stiffness.

- One process may involve scour, sagging, backfilling, and eventual self-burial of the pipeline in the free-span areas.
- In another process, the self-burial of the pipeline can occur at span shoulders.
- In a third case, the soil supporting the pipeline over a pipeline stretch may fail as a result of liquefaction, causing the self-burial of the entire pipeline.

Following the onset of scour, the scour spreads along the length of the pipe (Fig. 5). When the length of the suspended span of the pipeline becomes sufficiently large, the pipeline begins to sag into the scour hole until it reaches the bottom of the scour hole (Figs. 8 c-d). As the pipe sags into its scour hole, it will obviously influence the scour process. When the pipe comes in the neighborhood of the bottom of the scour hole, it will more or less block the flow; and as a result, the scour process will come to an end (Figs.9d), and the so-called backfilling process will start. The latter may result in partial or complete burial of the pipe in the span areas (the self-burial of pipelines) (Fig.8e).

The formation of free spans is a complex process, and is still not very well understood.

The free-span length is governed by various effects:

1) **Changing flow conditions**: A developing free span may stop growing when the flow velocity decreases below the threshold values for the onset of scour.
2) **Changing soil conditions**: The development of a free span will obviously stop when a support reaches a non-erodible bed area, an area where the soil contains a substantial amount of silt, or clay, or gravel.
3) **Sinking of the pipeline at the span shoulders:** The three dimensional scour process comes to end when the pipeline sinks in the span shoulder substantially thereby stopping the formation of further free spans. This may be caused due to general shear failure, or liquefaction. However the liquefaction potential strongly depends upon the relative density of the soil, the permeability, the presence of the pipe, the influence of the stress history.
4) **Sagging of the pipeline in the scour hole**: As the span develops, the pipe may sag in the scour hole. When the pipe reaches the

bed, the length of the free span will be cut

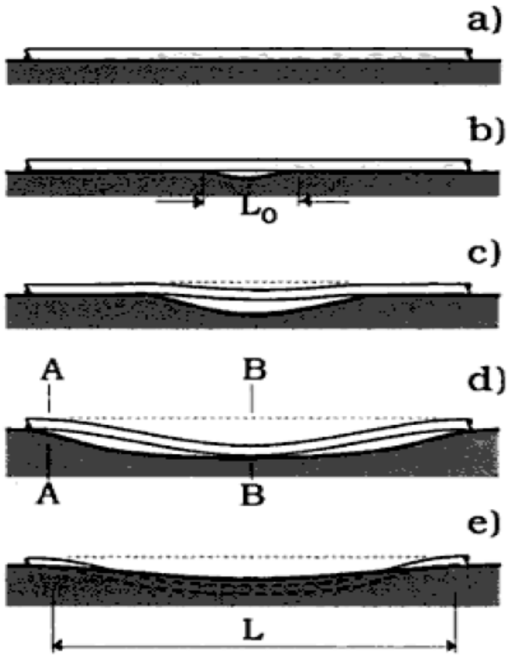


Fig.9: Sketch of 3D scour process and self - burial.

Free-span length

The span length for a pipeline under scour process can be obtained from the following equation:

$$L = 3.35\, D^{1/4} L_s^{3/4} \qquad (16)$$

Where L_s is the stiffness length, defined by

$$L_s = \left(\frac{EI}{p}\right)^{1/3} \qquad (17)$$

3. Scour Detection:

Monitoring of pipeline is the key requirement of any integrity management plan for pipeline operators. Proper and effective monitoring is required for optimized operation and maintenance of assets, higher availability and environmental safety.

When scour occurs, the foundation material gets eroded leaving the pipeline exposed to flow forces. Scour failures tends to happen quickly and results in catastrophically failures. Therefore the scour monitoring system faces the challenge of real-time, robust and reliable detection methods and techniques to prevent any damage.

Various methods have been developed namely sonar, radar, and optical fibre health monitoring etc., these method for detection are explained below.

Digital sonar

Digital sonar has been used as a basic tool of underwater surveys for decades.

An acoustic pulse is generated by a programmable, narrow-beam sonar head. Depending upon the field conditions the sound frequency and pulse generated by the head can be modified and calibrated. Data points are generated by the echo produced from sound pulse being reflected back from a target and is displayed. Depending upon the sonar head inclination angle, sound's speed in medium and the time taken by it, Data points are calculated.

When the rotating sonar head sweeps about its axis and travels the designated pre-determined path, continuous profile are generated about the seafloor condition. The detection system can be deployed on various platforms suiting the operators need like from a boat, ROV, or skid.

Scanning or side-scan sonar

Scanning or the side-scan sonar is used extensively to investigate the seabed conditions like scour patterns, etc. and the condition of pipelines. This method has been very useful in monitoring the underwater subsea facilities.

Side-scan sonar device emits fan-shaped pulses directed to the seabed. These devices can be towed by vessel, or they may be mounted on a rotary platform to perform the scan. The acoustic reflections from the seafloor (i.e., their intensity) get stored in form of slices (cross- track pattern). These outputs are combined together along their direction of motion forming a 3D wire mesh image of the sea floor. These data are used along with the Sub bottom profiling system for calculating pipe cover or exposure, areas of concern along the pipeline length.

Rotating head Sonar:

Rotating head sonar is used to survey bottom and sub-bottom river crossing hazards. Pipeline crossings the river changes their location with respect to the original bottom position over a period of time due to floods, poor installation practices, current flow and river traffic and fishing actions. This may lead to potentially disastrous situation by exposing the pipeline.

A Rotating head sonar can be put to real-time assessment of pipeline river crossing. This is a fast and reliable method employed from a small vessel or a dock with high accuracy. It provides real time data that can be used for further investigation in case of a suspected event.

Some of the advantages of this method are:

- Accurate measures of scouring and undermining.
- Small and can be easily set-up and mobilized.
- Economical in use.

Differential global positioning system (DGPS)

This is an enhanced GPS that uses an array of fixed reference stations on ground to differentiate between the known fixed positions and those indicated by the satellite systems.

Data acquired from various technology sources helps in accurate positioning and allows precise geo referencing.

Fiber Optic Sensor:

Pipeline industry recognizes seabed scour, geohazards or ground movements as a major threat to pipeline. These hazards to pipeline integrity range from geotechnical, hydro technical and tectonic in nature. Fiber optic sensing technique for pipeline scour detection is based upon the measurement of strain along a sensing fiber which in turns can be detected and monitored. Strain introduced by ground movement effectively is the parameter that can be monitored to detect the development of a scour depth. When scour takes place, a portion of pipeline is exposed to excessive strain compared to other side.

Due to high sensitivity strain measurement capabilities of the optical fibers, small cable displacement can be detected and localized with meter accuracy anywhere along tens of kilometer of SMC over the pipeline route.

4. Scour Protection

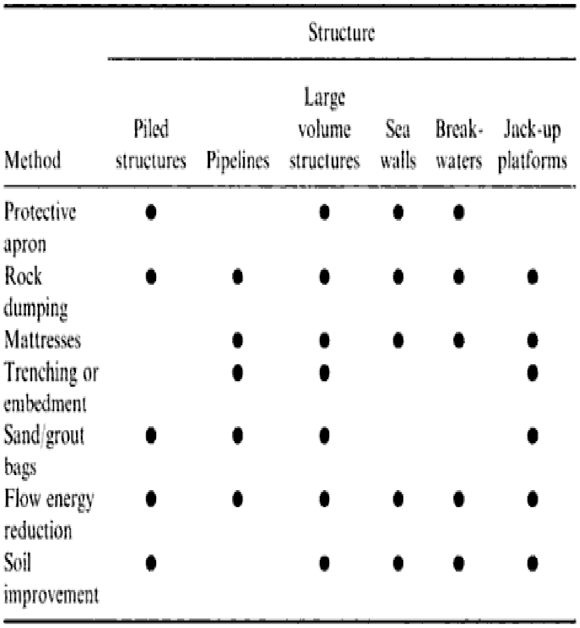
Underwater pipeline protection is of major concern for the Oil and Gas operating companies. They carry high pressure crude oil, gas, and products and hence their health is of major concern. Given the amount of threat present in the underwater pipeline, the following protection measures are employed as shown in fig. 10.

Rock and Gravel Dumping

Rock and gravel dumping provides a protective layer of rip-rap around the pipeline. Various installation techniques have been employed from the surface vessels, namely:

- From a side-dumping barge or vessel with individual stones falling to the sea bed,
- From a split-hopper barge as one big mass,
- From a barge through a pipe to reduce the fall velocity of the rock and improve placement accuracy.

The type of material required and the amount of material required is determined by the site location and hence the method of deployment depends on it. The material used to form the protective layer must offer sufficient resistance to withstand the flow induced forces (enhanced shear stress, vortex action). The stability of the local sea bed material can be calculated based upon knowledge of the local flow field around the pipeline.



Method	Structure					
	Piled structures	Pipelines	Large volume structures	Sea walls	Break-waters	Jack-up platforms
Protective apron	●		●	●	●	
Rock dumping	●	●	●	●	●	●
Mattresses		●	●	●	●	●
Trenching or embedment		●	●			●
Sand/grout bags	●	●	●			●
Flow energy reduction	●	●	●	●	●	●
Soil improvement	●		●	●	●	●

Fig.9: Various protection measures and their areas of application.

Mattresses

Prefabricated mattresses have been used in bed protection or preparation schemes. These mattresses can be installed in a controlled manner as compared to the rock dumping method. Mattresses are often used to provide the much needed protection to pipelines but it can also be adopted for other sea bed structures. One of the major advantages of using mattresses is that they are flexible and can be laid to suite the local bed contours.

The various types of protective mattress used for pipeline protection are:

- Fascine mattress: it synthetic filter fabric strengthened with synthetic or natural fascines, usually overlain by rock dump material
- Block mattress - it continuous array of concrete blocks held together by cables and laid on the sea bed or individual blocks held in it pattern on the sea bed by synthetic nails
- Cell mattress -- mesh baskets filled with sand or gravel, large rocks in large wire mesh also called gabion baskets
- Concrete mattress - the mesh baskets of the cell mattress are filled with underwater concrete instead of ballast
- Stone asphalt mattress - a synthetic filter fabric ballasted with it stone and asphalt mixture
- Ballast mattress -- a heavy synthetic fibres woven mattress is double folded at both sides and tilled with sand or gravel.

Fig10. Mattress

Whilst the rock rip-rap is held in place due to its own weight and resistance between the rock and the underlying layers. The mattresses are often held in place by the use of soil pins or anchors. The resistance to pull out presented by the soil fixings, or the tensile strength of the material joining the mattress to the anchor, is designed to resist the uplift and drag due to hydrodynamic forces. Poorly designed fixings have historically been the most common cause of failure of these types of protection devices. Steps are often taken to fill any unevenness in the bed beneath the structure and this provides additional protection from scour.

Trenching (Pipelines) Or Increasing Structure Embedment

Trenching of pipeline or increasing the structure embedment in the sea bed provides the much needed sheltering from wave and current forces which cause scour. This increases the pipeline stability and also the margin of safety against the undermining by scour as a result of greater soil-structure interaction.

The trenching of pipeline into the sea bed not only provides protection from the scour activity but it also reduces the hydrodynamic load on the pipeline thereby adding stability to it. The increased embedment of the pipeline results in reduced flow fields around it when compared to pipeline resting on initial bed level. When trenching or increased embedment of pipelines are not feasible in harsh environmental conditions it may be necessary to stabilize them with anchors.

In a region of active sediment movement or sand waves, sea bed needs to be ploughed flat prior to the installation. This causes the sand waves to reform and migrate over the pipeline resulting in changes to the pipeline cover over time, thereby providing cheap and effective way of protecting and stabilizing a pipeline. The embedment process can be enhanced with the use of a spoiler placed along the top of the pipe.

Sandbags

Sandbags are used to stabilize the scour holes. They are effective only for short period as they get undermined quickly and require significant diver time to install them.

Sand bags or grout filled bags are also used to underpin pipeline free spans. In order to provide protection to the pipeline and bed stabilization, they need additional protective covering of gravel or mattresses.

The service life of the sandbag clusters is estimated to be 1 to 2 years.

Flow Energy Dissipation Devices

Over the years the most attractive method for reducing the scour has been the Flow energy dissipation method. This method tackles the source of the scour itself. It is commonly used on dam or barrier overflow spillways. This method reduces the flow energy around the base of the pipeline and hence reduces the potential for sediment transport (scour) and thereby enhances the local deposition of sediment.

Various forms have been deployed in varying field conditions to great success.

- At breakwaters through the installation of a field of wave energy dissipating blocks placed on the sea bed in front of a breakwater. However the local interaction of these blocks with the sea bed and their long-term stability should be considered.
- The installation of mats studded with neutrally buoyant fibres, i.e. artificial seaweed. These fronds are installed to mimic and simulate natural seaweed, i.e. fixed at the bed, or they hang down from a support frame. The seaweed causes the water flow to slow down through them. This action results in settling of suspended sediment to the bed where continued deposition leads to formation of a bank.

The major operational difficulties with artificial seaweed mats are to ensure that the fibres become fully open, otherwise they have minimal effect, and to ensure that the foundation anchors and strops have adequate strength. The fibres are only just neutrally buoyant and fouling can reduce their effectiveness. Whilst this material is successful for erosion control by currents it is less successful at controlling wave induced scouring and shoreline erosion.

4. Conclusions

In this study, the main emphasis has been given to understand the mechanism of scour process for underwater pipeline. It is observed that local sour beneath underwater pipeline gets fully developed in very short interval. The process of three dimensional scour is quite complex in nature and further developmental study need to be done. The study can be extended to examine the scour process in arctic region (ice scour) and scour process in hilly or mountain terrains under various boundary conditions. The empirical relations need to be further developed to enhance its applicability in various conditions.

Monitoring of scour process in real –time has been a challenge and very small, expensive methods are available in the market. Development of low cost technique with high reliability and enhanced monitoring capabilities are the need of the industries.

Linking the scour potential for any underwater pipeline with a risk matrix to understand its impact on the integrity of pipeline is the future study scope.

Appendix

SAMPLE CALCULATION

Case Study

Given Data:

D = 1 m ; e = 0.05 m ;

n = 0.43 and s = 2.65.

U_m= 1.3 m/s; T_w = 10 s;

Wave height of H = 2 m.

The water depth is h = 10 m.

Sand size, d_{50} = 0.5 mm

Mean current velocity, V= 0.6 m/s (the current being perpendicular to the pipeline).

$E_{concrete} = 2 \times 10^{10}$ N/m^2, $E_{steel} = 2.1 \times 10^{11}$ N/m^2.

$\rho_{steel} = 7.8 \times 10^3$ kg/m^3, $\rho_{concrete} = 3 \times 10^3$ kg/m^3,

$\rho_{oil} = 0.8 \times 10^3$ kg/m^3 ,and $\rho_{water} = 1 \times 10^3$ kg/m^3.

Solution:

Calculation of Critical velocity for the onset of scour:

In case of a steady current:

The critical velocity (measured at the top of the pipeline) is given as

$$U^2_{cr} = 0.025\exp[9(e/D)^{0.5}]gD(1 - n)(s - 1)$$

$$= 0.025 \times \exp\ [9(0.05/1)^{0.5}] \times 9.81 \times I \times (1 - 0.43) \times (2.65 - 1) = 1.73$$

U_{cr} = 1.3 m/s.

In case of Wave:

The Keulegan-Carpenter number is given as

$$KC = \frac{U_m T_w}{D}$$

= 13

From Fig 8, Thus for KC = 13 and e/D = 0.05/1 = 0.05,

The critical velocity is found to be

$$\frac{U^2_{m,cr}}{gD(1-n)(s-1)} = 0.08$$

$U_{m,cr}$ = 0.86 m/s.

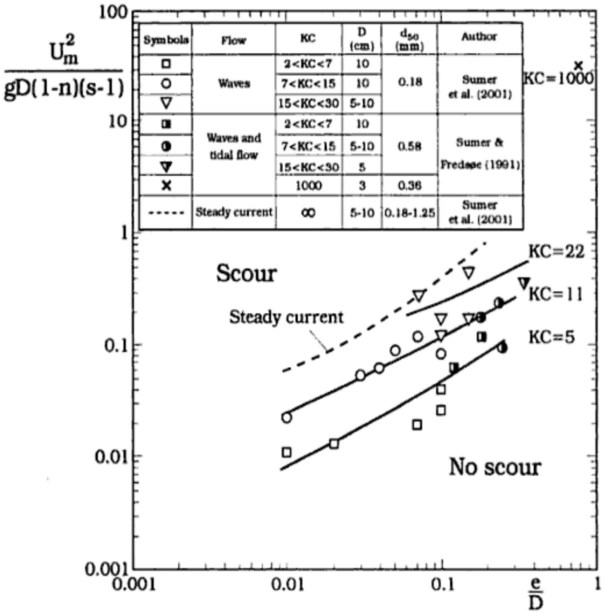


Fig.11 Onset of Scour. Experimental results.Sumer et al. (2001)

We can see that $U_m = 1.3$ m/s > $U_{m,cr} = 0.86$ m/s, so scour will occur.

Calculation of scour depth in Waves:

1. Calculate the deep-water wave length (L_o):

$$L_o = \frac{gT_w^2}{2\pi}$$

$$= (9.81\text{x}10^2)/\ (2\ \pi) = 156\text{ m}$$

2. Calculate the parameter h/Lo

$$h/\ L_o = 10/156$$

$$= 0.064$$

3. From the wave tables for sinusoidal waves (Appendix II)

sinh(kh) = 0.733 for $(h/L_o) = 0.064$

4. Calculating the amplitude of the orbital motion of water particles at the seabed, assuming that the small-amplitude sinusoidal wave theory is applicable.

$$a = \frac{H\ \cosh(k(z+h))}{2\ \sinh(kh)} = \frac{H\ \cosh(k(-h+h))}{2\ \sinh(kh)}$$

$$= (2/2)\text{ x }(1/0.733)$$

$$= 1.36\text{ m}$$

Here z = the vertical distance measured from the mean water level

z = -h (the seabed).

The maximum value of the velocity at the bed is given as

$$U_m = \frac{\pi H\ \cosh(k(z+h))}{T_w \sinh(kh)}$$

$$= 0.86\text{ m/s}$$

5. Check for the sinusoidal theory is applicable

$$U\text{ (the Ursell parameter)} = \frac{HL^2}{h^3}$$

Where L, the wave length,

$$L = L_o \tanh(kh).$$

From the wave tables (Appendix II)

Tanh(kh) = 0.591 for $(h/L_o) = 0.064$

Therefore

L = 156 x 0.591 = 92 m

then $U = HL^2/h^3$

$= 2*92^2/10^3$

U= 17

Which is only slightly larger than 15. Therefore we may assume that the sinusoidal theory still is applicable.

6. Calculate the Kalgan-Carpenter number (at the seabed)

$$KC = \frac{2\pi a}{D}$$

$$= 2*3.14*1.36/0.3$$

$$= 28.5$$

7. Predict the scour depth:

$$S/D = 0.1\sqrt{KC} = 0.1\text{ x}\sqrt{28.5} = 0.53$$

or

$$S = 0.53\text{ x }0.30 = 0.16\text{ in}$$

8. Calculate the Shields parameter (check for validation):

$$\theta = \frac{U_{fm}^2}{g(s-1)d} = \frac{\frac{f_w}{2}U_m^2}{g(s-1)d} =$$

Where f_w, is calculated from

$$f_w = 0.035Re^{-0.16}$$

$$= 0.004$$

Here, Re = aU_m/v, the wave-boundary-layer Reynolds number.

As seen, the Shields parameter, θ = 0.46, is larger than the critical value, $\theta_{cr} = 0.05$

i.e., the bed is live; therefore the equation used to calculate the scour depth is valid.

Calculations for Lengths of pipeline span which can produce deflection:

Consider that the deflection formula

$$U_{max} = \alpha\ p L^4 / EI$$

Here, $\alpha = 3/384$ for pipeline freely supported on sea bed

p = the intensity of the distributed load per unit length of the pipe,

E = modulus of elasticity, and

I = the inertia moment

The modulus of elasticity values are

$E_{concrete} = 2 \times 10^{10}$ N/m^2, and $E_{steel} = 2.1 \times 10^{11}$ N/m^2.

The product EI:

$$EI = E_{conerete}\ I_{concrete} + E_{steel}\ I_{steel}$$

$$= E_{concrete}\ (\pi/64)(D_1^4 - D_2^4) + E_{steel}\ (\pi/64)(D_2^4 - D_3^4)$$

$$= 2 \times 10^7 \text{Nm}^2$$

The intensity of the distributed load:

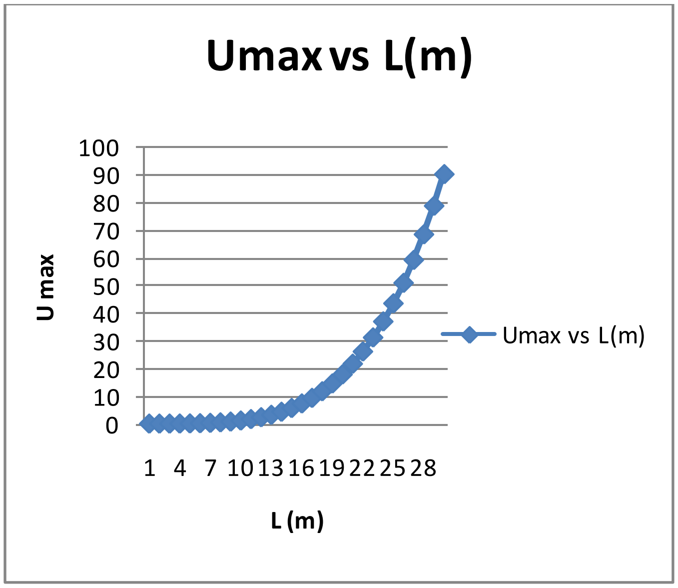
$$P = [(\pi/4)\ (D_2^2 - D_3^2)\ \rho_{steel} + (\pi/4)\ (D_1^2 - D_2^2)\ \rho_{concrete} + (\pi/4)\ D_3^2 \rho_{oil} - (\pi/4)\ D_1^2\ \rho_{water}] \times 1$$

$$= 1243 \text{ N/m}$$

In which the densities of steel, concrete, oil, and water are taken as

$\rho_{steel} = 7.8 \times 10^3$ kg/m^3, $\rho_{concrete} = 3 \times 10^3$ kg/m^3, $\rho_{oil} = 0.8 \times 10^3$ kg/m^3 ,and $\rho_{water} = 1 \times 10^3$ kg/m^3, respectively.

The maximum deflection is calculated and plotted versus the span length.



As seen, while the deflection is almost nil for a span length of 10-15 m, it grows explosively for span lengths larger than 20 m.

Calculation of propagation velocity of scour, C:

1. Calculate the undisturbed bed friction velocity

$$U_f = V / [2.5\{\ln (30h/k_s) - 1\}]$$

$$= 0.6/[2.5 \times \{\ln ((30 \times 10)/ (2.5 \times 0.5 \times 10^{-3})) - 1\}]$$

$$= 0.021 \text{ m/s}$$

2. Calculate the undisturbed Shields parameter

$$\theta = U_f^2/[g(s-1)d_{50}]$$

$$= 0.055$$

3. Pick up the value of α

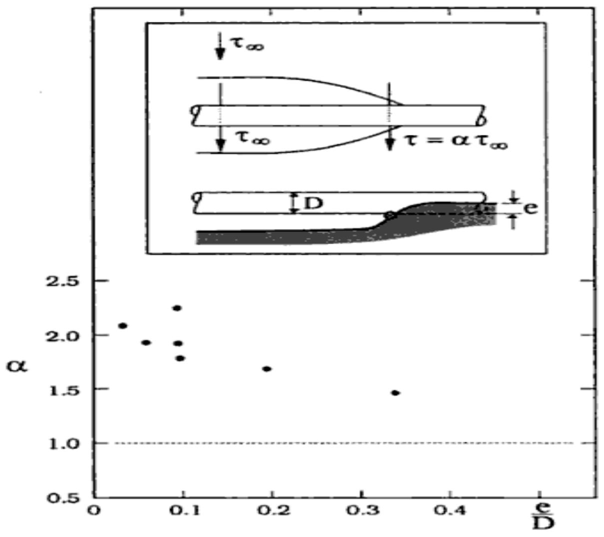


Fig.12 : Amplification in the bed shear stress Hansen et al.(1991)

From figure 19, corresponding to e/D = 0.05/1 =0.05, namely α = 1.8.

4. Calculate the sediment transport rates on flat seabed and in the corners of the scour hole from Eq:

$$q_\theta = 8\sqrt{[(s-1)gd^3_{50}(\theta - 0.047)^{3/2}]}$$

Flat seabed : $\theta = 0.055$,

Thus $q_\theta = 2.6 \times 10^{-7}$ m^2/s

Corner area : $\theta_{c0} = \alpha\theta$

$= 1.8 \times 0.055 = 0.099$,

$q_{c\theta} = 4.3 \times 10\text{-}15$ m^2/s

5. Calculate C:

$$C = (q_{c0} - q_\theta) / e\ (1- n)$$

$$C = \frac{(4.3 \times 10^{-6}) - (2.6 \times 10^{-7})}{0.05 \times (1-0.4)}$$

$= 0.000135$ m/s $= 0.48$ m/h

Nomenclature

e	clearance between pipeline and the seabed; self-burial depth of pipeline; burial depth of pipeline
D	pipeline diameter
d_{50}	sand size
Fr	Froude number
g	acceleration due to gravity
H	wave height
h	water depth
I	inertia moment
K	bulk modulus of elasticity of water
KC	Keulegan-Carpenter number
L	pipeline span length
Lo	deep-water wave length
n	porosity
p	the intensity of the distributed load per unit length of the pipe,
q,	bed –load sediment transportation rate
Re	Reynolds number
RE	wave-boundary layer Reynolds number
S d	equilibrium scour depth
s	specific gravity of sediment grains
T	time scale of scour or time scale of self-burial of pipeline
T_w	wave period
U	undisturbed flow velocity at the top of pipeline in current
U_{cr}	critical value of U (see above for U) corresponding to the onset of scour below pipeline
U_f	bed shear velocity
U_{fm}	maximum value of bed shear velocity in waves
U_{max}	maximum value of undisturbed orbital velocity at the bed
V	mean flow velocity (cross-sectional-/depth-averaged velocity)
z	vertical distance measured from the mean water level
θ	Shields parameter
θcr	critical value of the Shields parameter.

References

[1] Joko Nugroho, Dhemi Harlan and Hendra Achiari, "Preliminary Study on Scouring at Parallel River Crossing Pipelines"- , Vol. IV No. 1, (June 2008).

[2] B. Mutlu Sumer and Jorgen Fredsoe, "The Mechanism of Scour in the Marine Environment"- Advance Series on Ocean Engineering, Vol.17, p. 5-138, (2005).

[3] Transportation Research Board of the National Academies, "Portable Scour Monitoring Equipment"- NCHRP Report 515.

[4] George W. Annadale, "Scour Technology-Prediction and Management of Water Erosion of Earth materials", TMH Publication, p. 23-343,(2006).

[5] Marc Nikles, Fabien Ravet, "Fiber Optic Distributed Temperature and Strain Sensing for integrity monitoring of Subsea Umbilicals, Risers and Flowlines"- 2nd Optoelectronics for the Oil and Gas Industry Technical Meeting, Aberdeen, Slides 1-44(Nov 4 2010).

[6] Richard Seeger, "Pipeline Route and Depth-of-Cover Survey Considerations"- Pipeline and Gas Journal, September 2011, Vol. 238 No. 9.

[7] Marc Nikles, "Long-distance fiber optic sensing solutions for pipeline leakage, intrusion and ground movement detection", Proceedings of SPIE, Vol. 7316, p.731601-01-13 (2009).

[8] Yung Bin Lin, Kuo Chun Chang, Jihn Sung Lai and I- Wen Wu, "Applications of Optical Fiber Sensor on Local Scour monitoring" – IEEE Journal of, p. 832-835 (2004).

[9] "Artificial Seaweed Frond Mattresses"- Subsea Protection System product Leaflet.

[10] "Plastics keep corrosive currents at bay"- New Scientist, Issue No. 1578 Weekly, p. 44, (17 September 1987).

[11] Jørgen Fredsøe, Rolf Deigaard, " Mechanics of Coastal Sediment Transport"- Advanced series on Ocean Engineering, Vol. 3, p. 350-351, (1994).