REVIEW OF PIPELINE-SEABED INTERACTION

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1   Abstract

The objective of this mini-report resulting from the senior project of the first author was to provide a brief description of the process of pipeline scour as it pertains to the larger topic of object-seabed interaction. This description begins with the simple case of two-dimensional scour beneath a fixed pipe. Next, the parameters that characterize scour depth are examined and an empirical formula to predict scour depth is given. The consequences of embedment on two-dimensional scour are also detailed. The two-dimensional case is then expanded to three- dimensional scour behavior and a formula is given to approximate the span length of a scour hole. The phenomenon of pipe vibration in both regular and irregular waves is also discussed.

It should be stated that this mini-report is intended to introduce some of the available literature on the complicated problem of pipeline-seabed interaction to those who are not familiar with this problem, including the authors of this report before the mini- project was initiated. This report should, nevertheless, be of some use in initiating studies on the little understood problem of object-seabed interaction.

2   Introduction

A seabed-structure interaction workshop sponsored by the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) was held in New Orleans in November, 1991 . The major concern of this meeting was Mine Countermeasures Warfare. Among the issues given importance was the "prediction of mine burial, impact penetration, and sand wave burial on the seafloor." The scour and burial of a small body on the seafloor is a topic with civilian implications, as well. Among these is the fate of marine pipelines and individual armor units protecting coastal structures (e.g., quarrystone at the toe of a breakwater).

The subject of fluid-sediment-object interaction is a very difficult topic and is not well established. Most of the research done on this topic has been in the areas of pipeline scour or self-burial and scour around a vertical pile. Pipeline-seabed interaction is probably the more relevant of the two topics because much of the past research examined the dynamic relationship between the seabed and pipe. Whereas piles are generally treated as fixed rigid structures, vibration and sagging is an important consideration in pipeline research. If an object placed on the seafloor does not penetrate the sediment upon initial impact deeply enough to become fixed, its fate will be more like that of a pipeline laid on the seafloor. This mini-report therefore reviews the topic of pipeline-seabed interaction as it pertains to discrete object- seabed interaction.

3 Two-Dimensional Scour Beneath a Fixed Pipe

Scour beneath a pipeline occurs because of the disturbance in flow due to the presence of the pipeline. The equilibrium scour profile for a fixed pipe placed on an erodible bed and subjected to a steady transverse current is characterized by a steep upstream slope and a more gentle downstream slope (Sumer and Fredsøe 1990). Bijker and Leeuwestein (1984), Jensen et al. (1990) and Chiew (1990) identified the stages in the scour process for a pipe under this flow condition. It is agreed among the researchers that erosion is the result of a local increase in the sediment transport capacity of the flow and that deposition occurs when this transport capacity drops below a critical value. However, there is a discrepancy as to what driving force initiates the scour process. Jensen et al. (1990) observed that in the first stage, an upstream eddy formed just in front of the pipe and a large separated region formed behind it. Fig. 1 shows the progression of scour observed by Jensen et al. Bijker and Leeuwestein (1984) denoted the action of this upstream eddy as luff erosion.

Mao, as quoted by Chiew (1990), observed a similar upstream eddy as one of three vortices arising near the pipe as shown in Fig. 2. Unlike Jensen et al., Mao identified a small downstream second eddy just under the pipe, which started the scour process. Its action, in conjunction with the small upstream stagnation eddy, was thought to form a tunnel. Mao also suggested that the pressure difference between upstream and downstream caused seepage which contributed an added upward force. This force was not enough to move the sediment, but was thought to offset some of its weight.

Like Mao, Chiew (1990) observed scour beginning on the downstream side of the pipe. The scour was characterized by the ejection of bed particles which were then carried by the downstream flow. A small depression also formed on the upstream side as a result of the stagnation eddy. However, the small downstream vortex was observed to be not strong enough to initiate scour. Chiew (1990) postulated that the onset of tunnel scour was caused by piping, which occurred when the hydraulic gradient beneath the pipe exceeded the flotation gradient of the bed sediment. Piping helped the upstream stagnation eddy to breach the sand barrier under the pipe and caused the onset of tunnel scour. The hydraulic gradient was a result of the high stagnation pressure upstream and low pressure downstream in the separation zone. Therefore, both Chiew and Mao indicated that in its early stage, scour was a result of the combined action of vortices and underflow.

The second phase in the scour process is tunnel erosion, which occurs in the space under the pipe and results from the increased velocity in the flow contraction (Bijker and Leeuwestein 1984). Tunnel erosion occurs after the sediment support under the pipe is breached. The flow velocity in the tunnel approaches that of the fluid above the pipe. Jensen et al. (1990) suggested that the tunnel was the result of the upstream vortex, which disappeared after the tunnel was formed. On the other hand, Mao and Chiew (1990) found that the tunnel was formed by the joining of the upstream and downstream scour holes. All researchers observed a bar formed by the scoured material from the tunnel which moved downstream with time. Chiew (1990) noticed the height of this bar to be half of the pipe diameter.
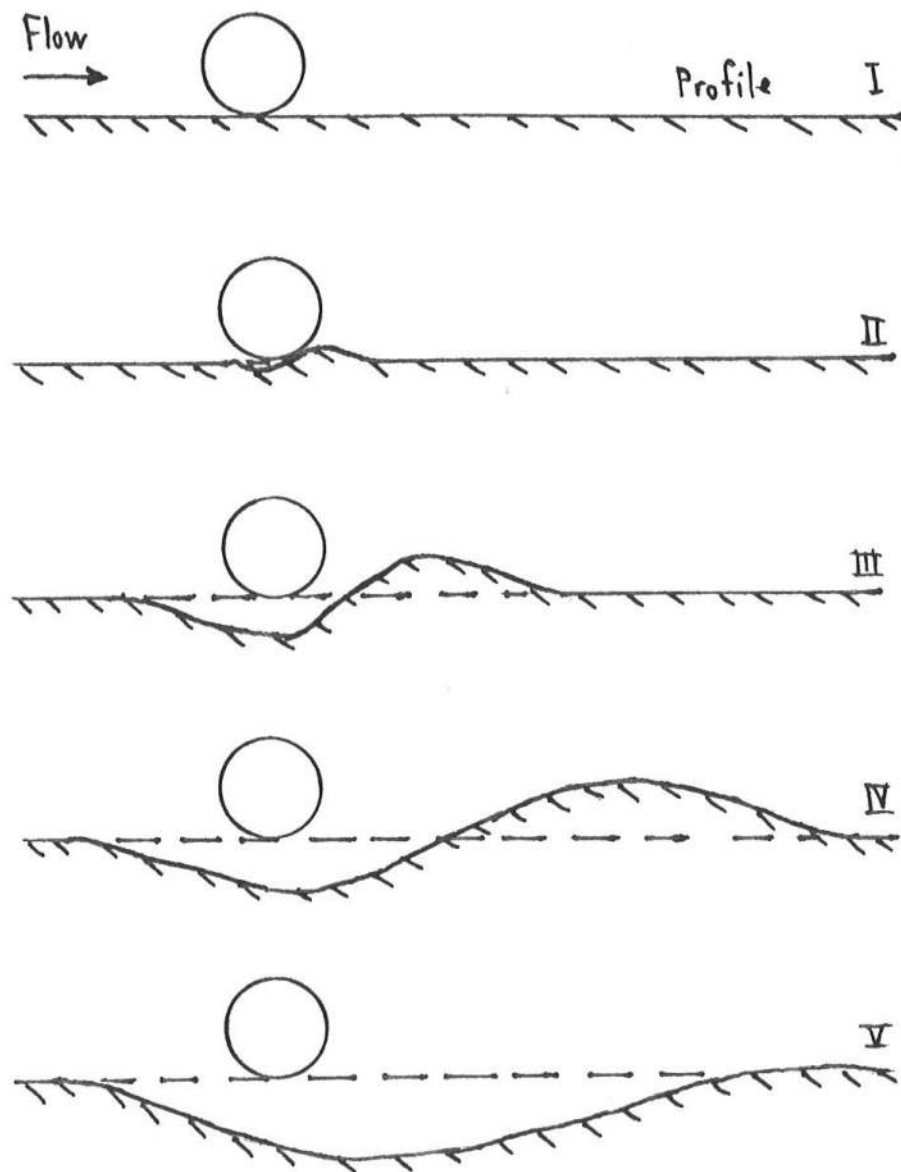
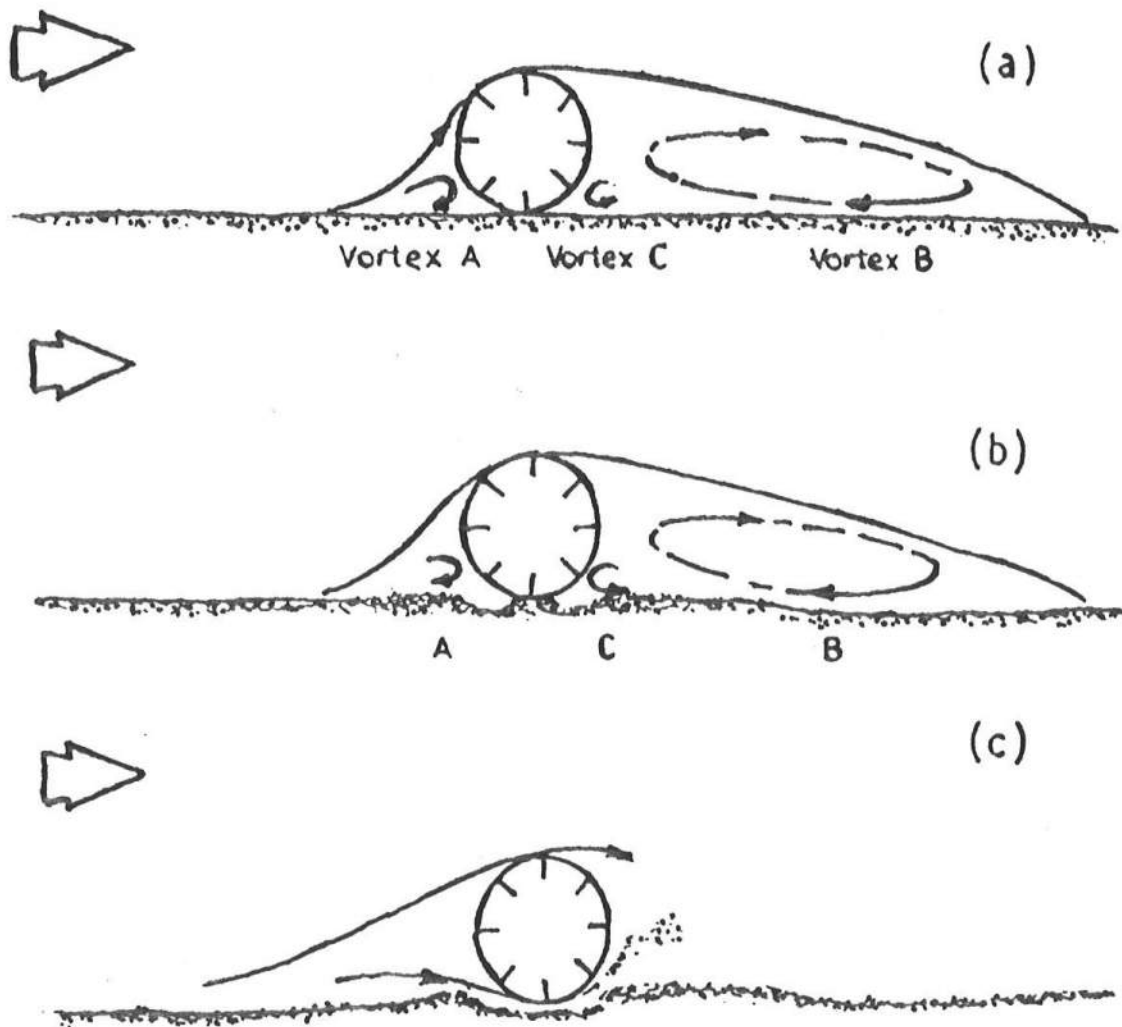Figure 1: Progression of the two-dimensional scour profile (Jensen et al. 1990).

(a)

Vortex A   Vortex C   Vortex B

(b)

A   C   B

(c)

Figure 2: Three-vortex system and onset of scour observed by Mao (Chiew 1990).

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Eventually, as the tunnel is enlarged, the top and bottom laminar boundary layers which develop over the cylinder surface separate, roll up into vortices, and cause vortex shedding. Sumer, Jensen, Mao, and Fredsøe (1988) found that vortex shedding in the lee wake leading to an organized wake flow was established in the first 5% of the total time to equilibrium. Mao (Chiew 1990) identified this as the third type of vortex, and Bijker and Leeuwestein (1984) named its action lee erosion. At this stage, the vortex street is the dominant scour mechanism. Sumer, Jensen, Mao, and Fredsøe (1988) performed experiments on an elevated pipe with the Shields parameter θ kept well below the critical value for incipient sediment transport, so that effects other than vortex shedding were kept to a minimum. The Shields parameter is defined as:

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

where U_f is the undisturbed bed shear velocity, g is the gravitational acceleration, s is the specific density of the sediment, and d is the diameter of the sediment particle. The undisturbed bed shear velocity was estimated using the Colebrook-White formula:

$$V/U_f = 8.6 + 2.5\, ln(D/2k_b) \tag{2}$$

where V is the flow velocity at the center of the pipe, D is the pipe diameter, and k_b is the bed roughness which is usually taken as 2.5d (Sumer and Fredsøe 1990). Sumer, Jensen, Mao, and Fredsøe (1988) observed that scour occurred downstream of, rather than just below the pipe, which suggested that scour was a result of the lee wake. Also, using dye, it became apparent that sediment transport occurred only when a vortex shed from the lower edge of the pipe swept the scour region. The Shields parameter was easily raised three to four times when this bed-side vortex swept the sediment. The scour frequency was found to be in agreement with the Strouhal number St which is defined as the normalized frequency at which vortices are shed. This further supported the theory that scour resulted from vortex shedding. The gentle slope of the downstream scour profile was a direct consequence of the extended wake. The downstream side of the pipe eroded more heavily because of the additional turbulence and high instantaneous velocities that resulted from the vortex street. If the pipe does not sag into the scour hole, the transport capacity is reduced as the scour depth increases because of the increasing space between the pipe and the trench bottom (Bijker and Leeuwestein 1984).

Sawamoto and Kikuchi, as quoted by Tsuzuchi, Horikawa, and Watanabe (1988), thought that the pattern of vortex shedding could be classified using the Keulegan-Carpenter KC number defined as:

$$KC = 2\pi a/D \tag{3}$$

where a is the amplitude of the oscillatory water motion and D is the pipe diameter. For KC values greater than 8, asymmetrical vortices appear. This complicates calculations such as prediction of the forces acting on the pipe. The behavior of the vortices in the wake was found to be in good agreement with a discrete vortex model. This model proved useful in gross description of the wake flow (Jensen et al. 1990). Sumer, Jensen, Mao, and Fredsøe (1988) showed that the Cloud-in-Cell (CIC) discrete vortex model predicted general characteristics of the organized wake flow behind the pipe. The application of the CIC method to sediment

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transport calculations also indicated that the time averaged bed shear stress was not a suitable parameter to work with in mathematical model studies of lee wake erosion.

As the scour profile reached equilibrium, the velocity under the pipe became slightly lower than that above the pipe. Vortex shedding became nearly symmetrical and the flow behaved almost like that of a pipe suspended at an equivalent distance above a plane bed (Jensen et al. 1990). At equilibrium the net sediment transport underneath the pipe became zero.

4   Scour Depth

Sumer and Fredsøe (1990) suggested that equilibrium scour depth for pipes in a steady flow was a function of the relative roughness of the pipe, the Reynolds number Re, and the Shields parameter θ. The effects of the relative roughness and Reynolds number appeared downstream of the pipe. However, if the pipe is hydraulically rough, which is often the case for pipes covered with marine growth, wake flow is practically unaffected by the Reynolds number (Achenbach and Heinecke 1981). Some influence of the Reynolds number was observed for hydraulically smooth pipes. In this case, there was a slight decrease in scour depth for Reynolds numbers corresponding to the transition from subcritical to supercritical flows because vortex shedding became less pronounced. However, the Reynolds number did not qualitatively affect the scour results because vortex shedding was maintained for all flow regimes (Sumer, Jensen, Mao, and Fredsøe 1988).

In his wind tunnel experiments, Schewe (1983) found that the Strouhal number St increased markedly as the flow regime changed from subcritical to transitional or supercritical regimes. In the case of scour around pipelines, this implied that the sediment would be exposed to the vortex action at a different rate for subcritical flows.

When a pipeline is subjected to tidal flows or waves, it experiences the effect of the downstream wake on both sides of the pipe. Sumer and Fredsøe (1990) suggested that scour profiles under these conditions could be characterized by the Keulegan- Carpenter KC number. They found that for KC values of less than five there was no organized wake formation. Above this value, as KC increased, the scour hole profile became longer with a gentler slope. As the slope became more gentle, the region below the pipe was less protected. This resulted in an increase of the flow velocity below the pipe and a corresponding increase in scour. For KC values exceeding approximately 300, the scour depth S remained practically constant. For pipelines exposed to wind waves, KC values are usually less than about 80. Sumer and Fredsøe proposed the following empirical formula based on the KC number to predict the scour depth, S, under a pipe placed on an erodible bed:

$$S/D = 0.1\, KC^{1/2} \tag{4}$$

The influence of the pipe on equilibrium scour depth decreases with increasing pipe clearance. The interval of the maximum influence of the lee wake on the bed was $e/D \simeq$ 0.3-0.7 where e is the pipe elevation and D is the pipe diameter. Vortex shedding was greatly

suppressed for e/D values of less than 0.2. Unless the KC number is large, no scour may occur for e/D values of greater than 1 (Sumer and Fredsøe 1990). For the large KC values possible in experiments, scour may occur for e/D values as high as 3.

5 Pipe Embedment

Embedment of the pipe causes an important change in the scour behavior. Bijker and Leeuwestein (1984) found that as embedment depth e^* was increased, scour depth S decreased. For an embedment to pipe diameter ratio of between about 0.5 and 0.7, no scour was observed, although they could not specify the exact flow conditions.

In another experiment to determine the effects of embedment on scour as shown in Fig. 3, Chiew (1990) observed no tunnel scour at a flow velocity 95% of the critical shear velocity for an e^*/D value of 1/16 when the ratio between the still water depth y_o and the pipe diameter D was greater than 3.5. As mentioned earlier, Chiew thought that piping was responsible for initiating tunnel scour. He found that the hydraulic gradient necessary to induce piping existed because of the choking phenomenon which is caused by a backup of water that occured for small y_o/D values. In prototype situations, y_o/D values are much greater than those in the laboratory experiments, which would suggest that tunnel scour may not occur in the field. This is contrary to field observations. As an explanation, Chiew postulated that the pressure gradient under prototype conditions could reach the critical value necessary for piping because of the large pressure and velocity fluctuations resulting from turbulence in the wake. This large wake turbulence can normally not be accurately reproduced in model tests. For an e^*/D value of 1/2, no tunnel scour occurred for any water depth tested. For this case, the measured pressure gradient was always less than the flotation gradient of the bed sediment, thereby prohibiting piping. Instead, reverse flow within the lee wake pushed bed material upstream which piled on the downstream side of the pipe, thereby preventing tunnel scour as shown in Fig. 4. The resulting scour hole occurred about 5 to 6 pipe diameters downstream of the pipe. This accumulation of sediment also protected against hydrodynamically induced vibration.

## 6 Three-Dimensional Scour Beneath a Fixed Pipe

The three-dimensional pattern of scour in the experiment of Fredsøe (1988) consisted of a series of scour holes along the length of a pipeline interrupted by supporting segments of sediment. The length of these holes was important for calculating the mode of vibration and was shown to be governed by the stiffness length L_s defined as (Fredsøe et al. 1988):

$$L_s = (EI/w_p)^{1/3} \tag{5}$$

where E is the modulus of elasticity for the pipe, I is the moment of inertia of the pipe cross-section, and w_p is the weight of the pipe in the fluid per unit length. Scour beneath
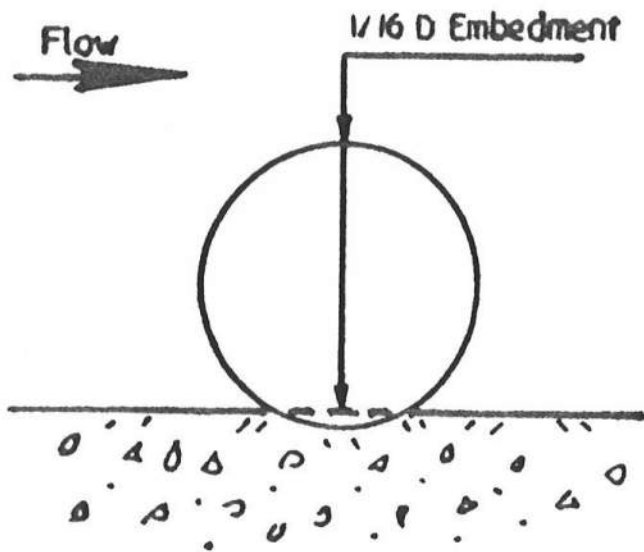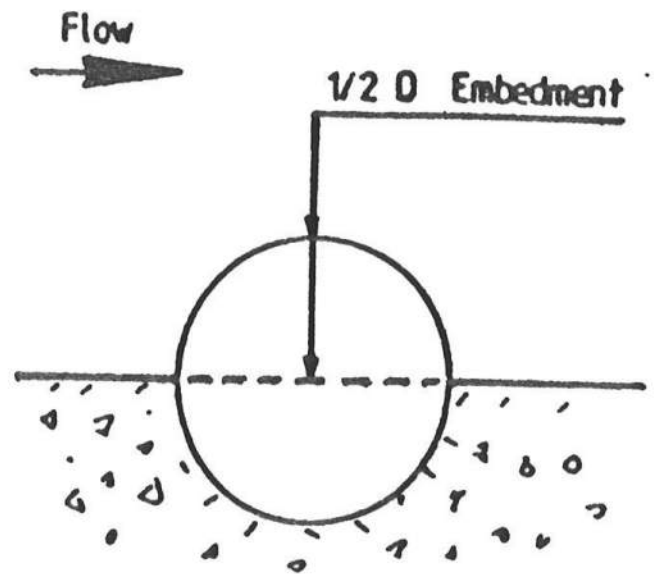
Figure 3: Definition sketch for embedment experiments (Chiew 1990).
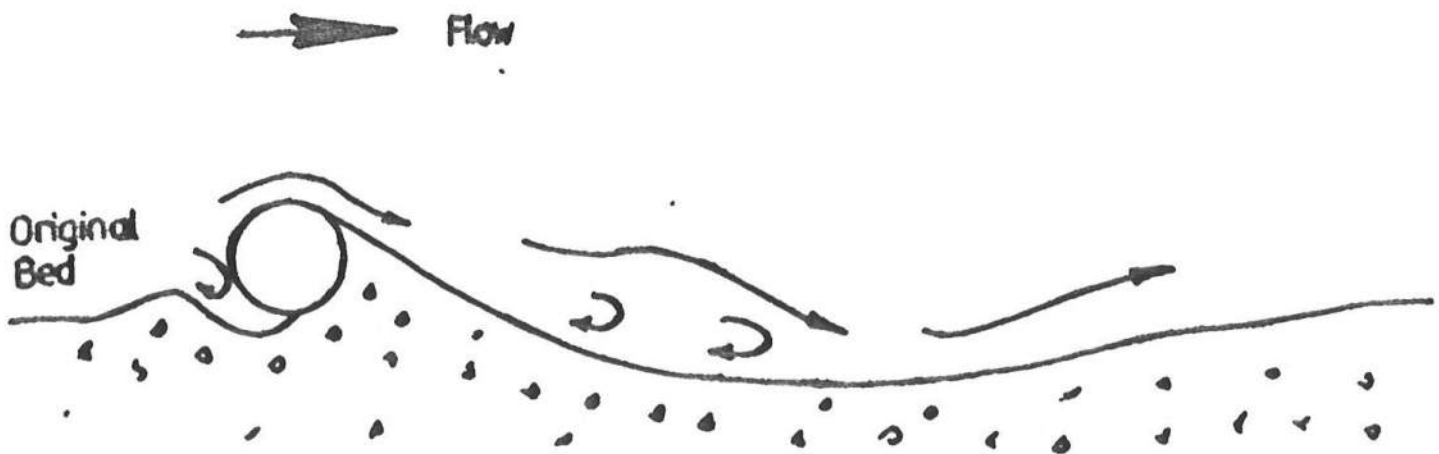

Figure 4: Scour pattern when tunnel scour did not form (Chiew 1990).

ffthe pipe was observed to start in a narrow region and spread along the pipe's length with time. The pipe may eventually sag and rest on the bottom of these holes after which backfilling and self-burial may occur. If sagging does occur, there is a deposition of sand downstream of the pipe. This is because the pipe becomes partially protected against the flow as sagging progresses. The result of this protection was found to be a decrease in the near bed flow velocity, and therefore the sediment transport capacity downstream of the pipe. A sagging pipe caused a slightly deeper scour hole than a fixed pipe because of the increase in near-bed flow velocities at the early stages of sagging. The span length L of the scour hole was suggested to be expressed as

$$L = (1/a)^{1/4} \, S^{1/4} \, L_s^{3/4} \tag{6}$$

in which S is the scour depth and a is a constant characterizing the nature of the end conditions of the pipeline span where a was 1/384 for hinged ends and 5/384 for fixed ends. If the scour hole depth is approximated by the pipe diameter D and the value of a is taken to be 3/384, which is the average of the two possibilities, Eq. 6 may be simplified as

$$L = 3.4 \, D^{1/4} \, L_s^{3/4} \tag{7}$$

This equation proved to be insensitive to end condition uncertainties of the pipeline span and to the actual scour depth of the sagging pipe (Fredsøe et al. 1988).

7   Pipe Vibration In Regular and Irregular Waves

Pipe behavior in cross flows is further complicated when pipe vibration is taken into account. Sumer and Fredsøe (1989) performed vibration experiments with KC numbers equal to 10 and 40 on pipes with e/D values ranging from -0.8 to 2 where a negative value denoted the pipe sagging into a scour hole. For $KC = 10$ in regular waves, the frequency response remained constant regardless of pipe position. The forcing frequency of cross-flow vibrations was twice the wave frequency irrespective of the mechanism driving the vibration.

However, for $KC = 40$, three different frequency responses were observed for the three e/D regions tested. For positive e/D and low reduced velocity V_r values, the frequency ratio N was between 10 and 11 where the reduced velocity was defined by:

$$V_r = U_m / (D f_n) \tag{8}$$

where f_n is the natural frequency of the pipe and U_m is the maximum velocity of the oscillating flow described by:

$$U = U_m \cos(\omega t) \tag{9}$$

where $\omega = 2\pi f_w$, f_w is the frequency of the oscillating flow, and t is time. As V_r was increased, N decreased (Sumer and Fredsøe 1987). For this arrangement the source of vibration was thought to be vortex shedding. For e/D values between 0 and -0.5 the frequency ratio was 2. In this situation vortex shedding was suppressed by wall proximity and downstream blockage

by part of the trench. The close proximity to the bed created a lift force on the pipe which oscillated at twice the wave frequency. For the e/D interval between -0.5 and -0.8, the vibration behavior was nearly the same as that for positive e/D values. This was supposed to result from the disappearance of the lift force due to the protection offered by the scour hole and reappearance of vortex shedding. In general, the pipe vibration amplitude increased with increasing V_r and peaked when the cross-flow vibration frequency f_w was approximately equal to the natural frequency f_n of the pipe. Also, amplitudes for the tests at $KC = 40$ were smaller than those tests at $KC = 10$. This may have resulted from a significant decrease in the lift force as the KC number was increased from 10 to 40 (Sumer, Fredsøe, Gravesen, and Bruschi 1989). Another important note is that small impacts occurred between the pipe and bed when V_r was increased to 7 or 8 in the near wall tests. Considerable impact between the pipe and trench sides resulted when V_r was increased further.

In addition to the cross-current vibrations, Sumer and Fredsøe (1989) conducted experiments for in-line vibrations in regular waves. They reported two kinds of in-line motions existing simultaneously. The first was a periodic movement which occurred at the wave frequency and was caused by the total in-line force. The second motion was a high frequency in-line motion thought to result from effects such as vortex shedding. In the case of a flexibly mounted cylinder placed near a wall in a steady current, the cross-flow and in-line vibrations occurred at the same frequency. In waves, the additional presence of a flow reversal during each period created one more mode in the in-line vibration as compared to the cross-current vibration. For the experiment conducted at $KC = 10$, large amplitude in-line vibrations occurred at the natural frequency of the pipe only for V_r values of approximately 3.5. For $KC = 40$, large in-line vibrations occurred at the natural frequency over the entire V_r range. As the value for V_r was increased, so the amplitude of the vibration increased.

During their experiments on vibrations in irregular waves, Sumer and Fredsøe (1989) defined the Keulegan-Carpenter number as

$$KC = U_{mo}/(Df_{wo}) \tag{10}$$

where f_{wo} is the frequency corresponding to the spectrum peak and U_{mo} is the significant velocity amplitude. Given the same KC values, the vibration amplitudes was observed to be slightly larger in the irregular waves than in the regular waves. The vibration frequency was the same for both regular and irregular waves for negative e/D values but differed for positive e/D values. This was thought to be caused by the different mechanisms driving the vibrations in each regime. For $(e/D) < 0$, the vibration was supposed to be driven by a lift force oscillating at twice the wave frequency f_w. Therefore, the pipe vibrated at the frequency $f = 2 f_w$, regardless of whether the waves were regular or irregular. For $e/D > 0$, the vibration was a result of vortex shedding. In irregular waves, the pipe vibrated at its natural frequency whenever the vortex shedding frequency was close to the natural frequency. In regular waves, the vortex shedding frequency was constant and the pipe vibrated at that frequency.

The in-line vibrations were observed to be practically the same for both regular and irregular waves. Sometimes the vibration amplitude was larger in irregular waves because

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the velocity amplitude reached values high enough to give rise to the resonant in-line pipe movement.

Scour trenches have an effect on the cross-current vibrational behavior of pipes. In general, if the pipe was placed in the trench, the amplitude and frequency of the vibration were greatly reduced. The presence of a trench had no effect on the in-line vibration of the pipe. The trench had no effect on either type of vibration if the clearance of the pipe was greater than twice the pipe diameter (Sumer and Fredsøe 1989).

Sumer, Mao and Fredsøe (1988) investigated the interaction between pipe vibration and scour. A vibrating pipe was found to cause extra erosion resulting in larger scour depths and widths. This effect was most pronounced for pipes slightly above the static bed and ceased to exist for gaps larger than one pipe diameter. Vibrations were found to be dominated by vortex shedding even when the pipe was placed close to the original undisturbed bed. The development of vibrations began only after the initiation of full vortex shedding. Development of an organized vortex street occurred only after the dune made from the scoured material traveled a minimum distance downstream from the pipe. When this specific distance was reached, the upper and lower boundary layers interacted to form the vortex shedding necessary to induce vibration.

Sumer, Mao, and Fredsøe (1988) identified three types of erosion that took place during pipe vibration. The first was fixed pipe erosion resulting from the presence of the pipe wake. This type of erosion was augmented by the vibrating pipe. The second type of erosion occurred on the upstream face of the scour hole as the pipe moved away from the bed. Under this condition the fluid velocity near the bed exceeded the value at which bed load transport occurs. The final type of erosion was the suspension and entrainment into the flow of sediment just below the pipe as the pipe moved toward the bed. The last two types of erosion were caused by the periodic motion of the pipe and occurred at opposite phases. The final scour depth was found to depend on the gap ratio e/D and the pipe category (fixed or vibrating). The scour depth was only weakly dependent on the Shield parameter. The range of V_r defined by Eq. 8 for appreciable amplitudes changed significantly with the separation between the pipe and bed. As the gap ratio increased, the V_r value at which the maximum vibration occurred decreased. However, the maximum amplitude remained practically unchanged for all gap ratios. The vibration was initiated earlier for larger gaps.

8 Discussion

Pipeline scour is a little understood phenomenon. Disagreement exists among researchers concerning even the relatively simple occurrence of two-dimensional scour. The role of underflow as a driving force in the initial stages of scour is considered essential by Chiew (1990). However, Bijker and Leeuwestein (1984) and Jensen et al. (1990) do not regard underflow as a factor in their experiments. This fundamental disagreement leads to a discrepancy in the cause of tunnel scour. Obviously, the exact mechanisms of tunnel scour are not thoroughly understood. Almost nothing is known about generalizing results from the tunnel scour under

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a pipe to an object of arbitrary shape on the seafloor. Flow around the ends of an object may take on great significance. In pipeline experiments, the end conditions are inconsequential because the pipe is treated as being infinitely long. Additionally, if an object on the seafloor is not long and thin, it will probably not vibrate in a cross-current. Therefore, the geometry of an object must be very important. The reason why scour around pipelines was examined in this report is because, with the exception of end condition effects, the behavior of the pipe encompasses a majority of the possible behaviors of an object on the seafloor. Obvious exceptions are overturning and skidding, since in all of the experiments, the pipe experienced no translational or rotational motion.

The most important parameter when quantifying the reaction of a pipeline appears to be the Keulegan-Carpenter number, KC. The KC number was used to classify the pattern of vortex shedding and to develop an empirical formula to predict scour depth. The KC number was an important parameter in the experiments on pipe vibration in regular and irregular waves (Sumer and Fredsøe, 1987, 1989). However, the most important parameters in the pipe vibration experiments were the reduced velocity of the flow defined by Eq. 8 and the pipe clearance to water depth ratio. In general, the effect of the Reynolds number was found to be only slight for hydraulically smooth pipes and insignificant for hydraulically rough pipes (Achenbach and Heinecke 1981).

Object-seabed interaction is a dynamic occurrence in which the object, flow, and sediment continuously alter each other's behavior. The use of approximations and idealizations may be necessary to perform a feasible experiment but, due to the extremely complex nature of this type of problem, unrealistic assumptions may yield results which are totally useless for practical engineering purposes. It is therefore necessary to keep in mind the overall and realistic picture when investigating object-seabed interaction.

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