LOCAL SCOUR AROUND HORIZONTAL CIRCULAR CYLINDERS

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الملخص

في ضوء التسارع لإكتشاف الموارد المعدنية في المناطق البعيدة عن السواحل هناك حاجة متزايدة لوضع أجسام ومنشآت في قاع البحار والمحيطات. إن التداخل بين خطوط الأنابيب تحت الماء وقاع البحر القابل للنحر قد جذب الكثير من الانتباه لأهميته في مجال هندسة المناطق البعيدة عن الشواطئ إذ أن النحر تحت الأنابيب البحرية قد يؤدى لتعرية أجزاء منها بحيث تبقى معلقة في الماء مما قد يسبب في انهيارها.

هناك نقطتان يجب مناقشتهما ليتسنى فهم مشكلة النحر وتقييم أبعادها ؛ النقطة الأولى تتعلق بالتقدير المناسب لأقصى عمق للنحر حول الأنابيب والنقطة الثانية هي الآلية التي تتم بها عملية النحر حول الأنابيب والتي هي محور هذه الدراسة.

أظهرت التجارب الكيفية التي يتطور بها النحر الموضعى حول الاسطوانات الأفقية في الرسوبيات غير المتلاصقة، بحيث يمكن القول أن ظاهرة الأنبوبية - أي تسرب الماء عبر رسوبيات القاع بحيث يتم تحريك جزيئات من هذه الرسوبيات الواحدة تلو الأخرى مكونا شبكة تشبه الأنابيب - هي المسبب الغالب لبدء ونشأة عملية النحر، فالظاهرة الأنبوبية تتحد مع دوامة الركود للنحر أسفل الاسطوانة وتبدأ النشأة الأولى (الاستهلال) لعملية النحر.

الميل الهيدروليكي الحرج المرتبط بنشأة النحر يساوى الميل المطلق لرسوبيات القاع، أما الانخفاض في الضغط أسفل الاسطوانة فإنّه يفعّل الميل الهيدروليكي.

وُجد أنه عندما تكون الاسطوانة الأفقية موضوعة فوق سطح الرسوبيات مباشرة دون أي طمر فإن النشأة الأولى للنحر تكون لحظية لكل حالات الدفق التي تم دراستها بينما في حالة طمر الاسطوانة في رسوبيات القاع فإن بدء ونشأة النحر تعتمد على مستوى ميل الضغط (الفرق في الضغط) عبر الاسطوانة بالنسبة لميل الضغط الحرج.

ABSTRACT

In the accelerated exploration of offshore resources there is a growing need to place objects and structures on the seabed. Interaction between a submarine pipeline and an erodible bed has attracted much attention because of its importance in offshore engineering. Scour underneath the pipeline may expose part of the pipe causing it to suspend in the water, if the free span of the pipe is long enough, the pipe may experience resonant flow-induced oscillation, leading to structural failure.

Two Things have to be discussed in order to understand scour and to evaluate its problem, which is an impact effect. The first point is the correct estimation of the maximum scour depth and the second point is the mechanism of local scour around pipelines. The main objective of this study is to elaborate more on the second point.

Experiments have shown how local scour develops around a horizontal circular cylinder in non-cohesive sediments. It has been found that piping is the dominant cause of scour initiation. Piping and the stagnation eddy combine to undermine the cylinder

and mark the onset of scour. The critical hydraulic gradient associated with the initiation of scour is equal to the flotation gradient of the bed sediment.

The pressure drop between the stagnation pressure upstream and wake pressure downstream of the cylinder induces the hydraulic gradient. When the cylinder is just embedded in the sediment, the onset of scour starts immediately under all flow conditions considered; while when there is any embedment in the sediment, the onset of scour will depend on the pressure gradient level with respect to the critical pressure gradient.

KEYWORDS: Offshore structures; Scour; Sediment transport; Critical shear stress; Floating gradient.

INTRODUCTION

In the accelerated exploration of offshore resources there is a growing need to place objects or structures on the sea bed. A sand bottom material is generally in a condition of dynamic stability under currents. When an object is placed in or on the sea-bed the equilibrium may be disturbed and local velocities around the objects are changed and the rate of transported material is changed. This change in the transported material may cause scouring (erosion) or deposition around the structures.

Interaction between a submarine pipeline and an erodible bed has attracted much attention because of its importance in offshore engineering. In connection with the development of oil and gas fields in offshore regions, additional submarine pipelines are being laid on the ocean floor to transmit crude oil to onshore refineries. Design considerations must include an analysis of their stability, particularly if the seabed is composed of non-cohesive sediments.

Scour underneath the pipeline may expose part of the pipe causing it to suspend in the water. If the free span of the pipe is long enough, the pipe may experience resonant flow-induced oscillations, leading to structural failure.

LITERATURE REVIEW

Scour may be defined as the lowering of the sea or river-bed as a result of non-equilibrium sediment transport conditions. Many types of scour exist:

General scour, where the bed level degrades because sediment removal exceeds sediment supply; local scour, where the bed level locally drops, usually caused by local acceleration of the flow around a structure. These types are sub-divided into live bed and clear water scour. Live bed scour occurs where sediment supply equals sediment removal while clear water scour occurs where there is no sediment supply. In general, local scour depths are greater than general scour depths, as pointed out by many investigators, e.g., Melville (1975) and Jain and Fisher (1980).

Two things have to be discussed in order to understand scour and to evaluate the scour problem, which is an impact effect.

The first point is the correct estimation of the maximum possible scour depth and the second point is the mechanism of local scour around pipelines. Based on results from studies of scour at bridge piers and submarine pipelines (Chiew and Melville 1987; Bijker 1986; Abusbeaa 1986), it is well known that the maximum local scour occurs when the structure is subjected to unidirectional current alone and that the undisturbed bed shear stress, τ, equals the critical shear stress, τ_c, for sediment entrainment.

Concerning the first point, estimation of the scour depth underneath pipelines, the research of investigators may be divided into two groups. The first group (e.g. Bijker and Leeuwestein 1984; Kjeldsen at al. 1973; Nalluri and lbrahim 1985) of investigations conducted on scour around submarine pipelines is confined to establishing empirical equations which relate the depth of scour to parameters such as velocity, pipe diameter, grain size, and flow conditions. In most of these experiments the pipe was placed just on top of an initially flat bed. The second group (Chiew 1991) of investigations proposed an empirical function relating the amount of gap flow through the scour hole with the flow depth ratio, h_0/D, making it possible to predict the maximum scour depth at submarine pipelines for given flow and geometric boundary conditions .

Concerning the second point, the mechanics of local scour around pipelines, the findings of previous investigators are as below:

- Bijker and Leeuwestein (1984) identified three basic forms of erosion around a submarine pipeline.

a. Luff erosion, which occurs at the upstream side of the pipe and is caused by an eddy formation upstream of the pipe.

b. Lee erosion, which occurs at the downstream side of the pipe and is caused by reemergence of the main flow over, and the turbulent wake downstream of, the pipe.

c. Tunnel erosion, which occurs under the pipe and is a direct consequence of the increased velocity underneath the pipe compared with the undisturbed velocity.

The onset of scour in this case is due to the action of a three-vortex system.

- Mao (1988) reported the formation of three types of vortices around a submarine pipeline resting on a plane bed as illustrated in Figure (1a). One of the vortices, A, Formed upstream of the pip, the other two vortices, B and C, formed downstream of the pipe.

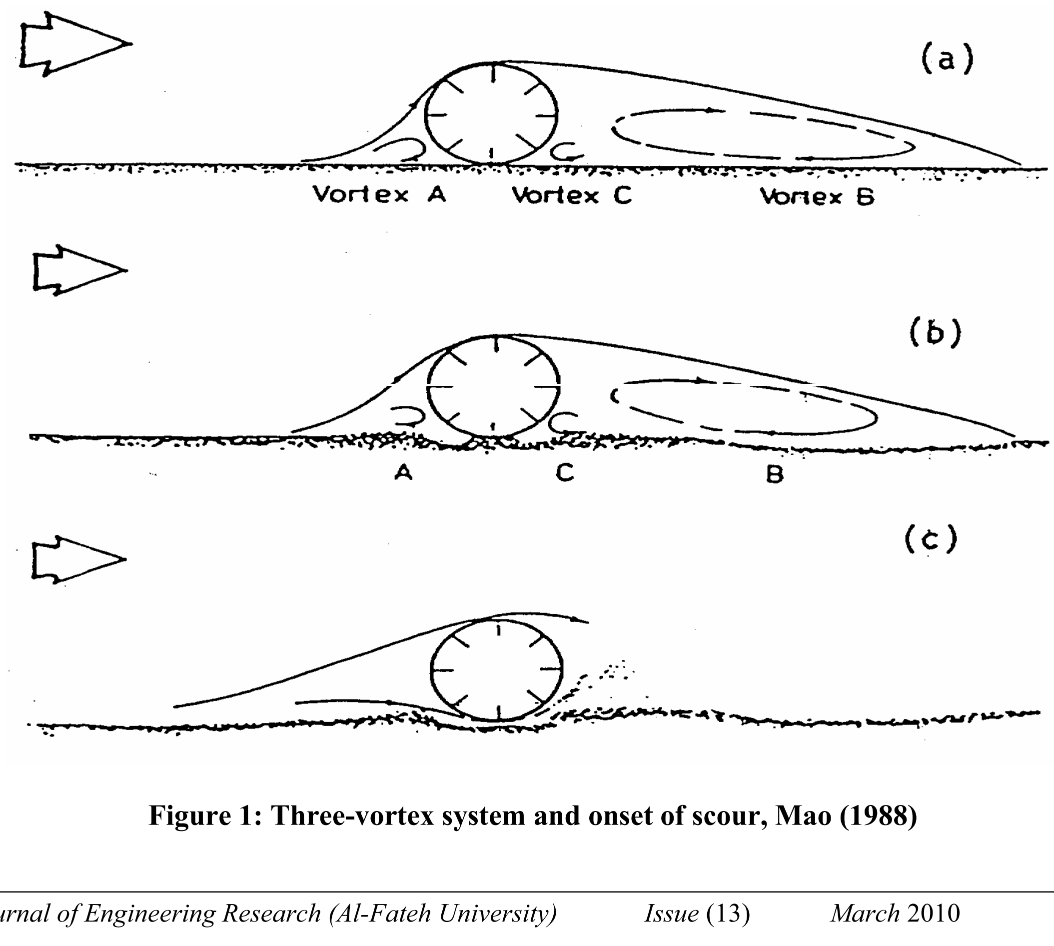

Figure 1: Three-vortex system and onset of scour, Mao (1988)

He deduced a pressure difference between the upstream and downstream sides of the cylinder which may cause seepage underneath it. He stated that "because the permeability of the bed material is rather small, the velocity of ground water flow is too small to move the bed material, it gives the sediment an upward force, inducing instability to the particles so that they are moved away. The onset of scour in this case is due to the combined action of vortices and underflow, which leads to the formation of a small opening under the pipe as more sand particles are carried away.

- Chiew (1990) showed that piping is the dominant cause of the initiation of scour. Piping and stagnation eddy combine to undermine the pipeline, and mark the onset of motion. The critical hydraulic gradient associated with the initiation of scour is equal to the flotation gradient of the bed sediment. The pressure drop between the stagnation pressure upstream and wake pressure downstream of the pipe induces this hydraulic gradient of the bed sediment. When a pipe is just embedded, the onset of scour does not occur if the ratio of the flow depth to pipe diameter exceeds 3.5. Similarly, the onset of scour does not occur for half-buried pipes.

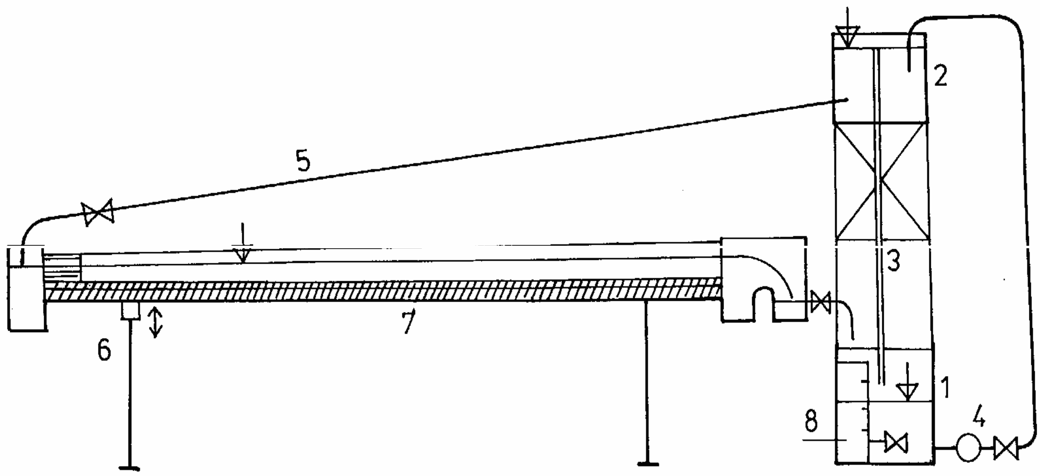

Figure 2: Experimental equipment, schematic diagram

SCOUR EXPERIMENTS AND RESULTS

This part consisted of two series of experiments. The temporal development of the scour was observed using digital video recordings in the first series of experiments. The second series showed the relationship between seepage flow under the pipeline and the onset of scour. The first series included observations of the temporal development of the scour hole under various flow conditions. Video recordings were used to obtain better views of the scour process especially during the initial stages. The experiments in this series were conducted in the flume shown in Figure (2). The flume is 5.5m long, 0.25m wide and 0.25m deep glass walled with an adjustable bed slope. Water is delivered from a main tank (2), where it is kept at a constant level by an overflow tube (3), by pipe (3) to the flume (7). In order to measure the flow rate a level gauge (connected to an electric timer) is installed in a separate clamping chamber (8) of the collecting tank (1).

The bed adjusting device (6) allows to a achieve bed slopes up to 4%. A maximum of about 5 liters/sec. could be attained. Several guiding and stabilizing device exist in the inlet structure which assure quasi-uniform entrance flow. In the end section of the channel a gate is installed to change the water depth.

The measuring reach (1.3 m) was located at 3.15 m from the entrance section in order to assure the establishment of fully developed flow. All measurements were taken at the mid-span of the measuring section.

For each test, a cylinder that extends the entire width of the flume was used to represent the pipe. The cylinder, fixed at both ends, placed in different positions from the top of the sediment. The cylinder diameters used are 30 and 50mm with two types of sand as shown in Table (1). The velocity of flow for all tests was kept just below the critical velocity for the onset of sediment entrainment.

Table 1: Average pressure gradient at failure

Sediment type	D_{50} (mm)	Gs Specific gravity	n porosity	D Cylinder Diameter (mm)	e Depth of embedding (mm)	e/D	Difference In water level at failure (mm)	Average pressure gradient at failure (mm)	i_f Floating gradient
Sand i	0.30	2.62	0.41	50	15	0.30	60	1.035	0.97
Sand i	0.30	2.62	0.41	50	20	0.40	71	1.035	0.97
Sand i	0.30	2.62	0.41	50	28	0.60	86	1.017	0.97
Sand ii	0.60	2.62	0.43	30	9	0.30	36	1.035	0.92
Sand ii	0.60	2.62	0.43	30	15	0.50	48	1.019	0.92
Sand ii	0.60	2.62	0.43	30	24	0.80	65	0.978	0.92
Sand ii	0.60	2.62	0.43	50	10	0.20	47	1.014	0.92
Sand ii	0.60	2.62	0.43	50	15	0.30	58	1.001	0.92
Sand ii	0.60	2.62	0.43	50	25	0.50	79	1.006	0.92
Sand ii	0.60	2.62	0.43	50	35	0.70	96	0.969	0.92

Piping may occur underneath a submarine pipeline if the pressure gradient across the pipe can induce a large enough upward flow of ground water at the downstream side. When this occurs, the threshold of sediment entrainment will decrease substantially and scour will start. The initiation of scour was investigated by artificially creating a static gradient across the 50 mm and 30 mm diameter cylinders. The cylinders were placed in a glass box that was 300 mm long, 200 mm wide and 800 mm deep. The box was divided into two equal compartments by placing a watertight partition at its center **(**Figure 3**)**.The same sediment used in previous tests was placed below the pipe. Both the compartments were initially filled with water to the top. Thereafter, the water in one of the compartment was siphoned out, whereas the water level in the other compartment was maintained at its original level, thus creating a pressure gradient across the cylinder. The mod of failure of the sediment and the critical pressure **(**water level**)** difference at failure were noted. The experiment was repeated with different embedment ratios e/D, where e is the depth of the cylinder embedded in the sediment. The pressure gradient is the ratio of the pressure difference between the water level and the length of the arc of contact between the sediment and the buried cylinder.

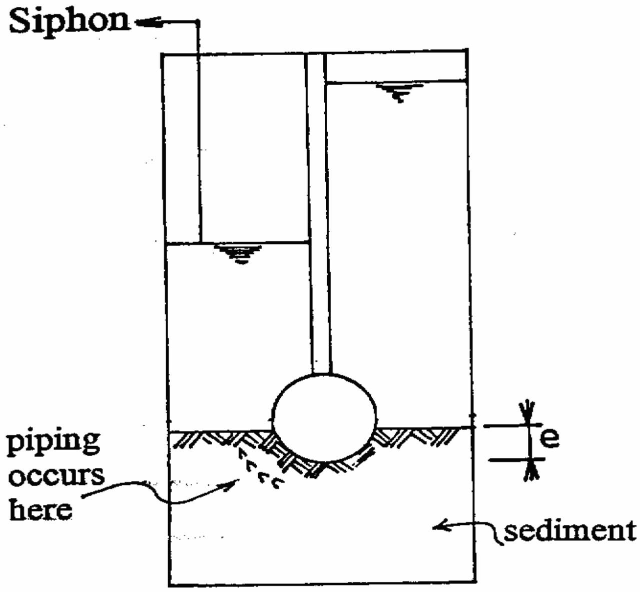

Figure 3: Apparatus for investigating the onset of scour using a static pressure gradient

DISCUSSION

Temporal development of a scour hole with submarine pipelines

The video recordings of the temporal development of the scour hole from an initially flat bed showed that tunnel scour began at the downstream side of the cylinder. The bed sediment appeared to be ejected from the bed, revealing that piping could be the cause of failure. Once the sand grains on the downstream side of the cylinder were lifted off the bed, they were carried downstream by the flow. At the same time, the stagnation eddy on the upstream side of the cylinder created a small depression, and the sand barrier was quickly breached leading to the formation of a tunnel under the cylinder. In the tunnel, sediment particles were entrained, and vigorous sediment transport occurred in the early stages. The sand that eroded from the tunnel formed a bar downstream of the scour hole, with time, the sand bar propagated downstream and lee erosion, caused by the turbulent wake and reattachment of the main flow over the cylinder, began to dominate. Scour continued until equilibrium was reached, i.e., when the temporal shear stresses and turbulent agitation (disturbance) near the bed were no longer able to transport bed material from the scour hole.

The sediment particles just downstream of the cylinder, where the scour hole (tunnel scour) is believed to occur, appear to lose their stability, much as sediment do that have reached the quick condition. A quick phenomenon normally occurs if an upward flow of water through a sand layer produces seepage forces large enough to offset the water through a sand layer produces seepage forces large enough to offset the weight of the sediment. A greater flow may even lift the sand grains on the surface. In general, erosion of this kind starts (for cohesion-less sediment) when the floatation gradient i_f is exceeded: $i_f = (1-n)(G_S-1)$, where n= Porosity ; and G_s = specific gravity (Bowels 1984).

In piping failures as hydraulic structures, such as dams, the difference between the water levels in the reservoir upstream and the tail water downstream causes the hydraulic gradient. For a submarine pipeline, the pressure gradient is induced by the formation of a stagnation pressure upstream and comparatively low pressure in the separation zone downstream of the pipeline. If the exist pressure gradient exceeds the flotation gradient of the bed sediment, piping occurs. When the sediment at the downstream end of the pipe has reached the quick condition, the weight of the sand particles reduces and soil particles are dislodged and eroded. this erosion process is a progressive phenomenon: As the grains are eroded, the threshold of sediment entrainment reduces with a corresponding increase in the pressure gradient. With the reduction of the threshold of sediment entrainment, the upstream eddy (Vortex A in Figure 1) easily excavates the sediment. Both piping and the stagnation eddy combine to breach the sand barrier underneath the pipe, leading to the formation of tunnel scour.

For cylinders which just placed on top of the sediment bed undermining (tunnel scour as described above) occurred almost as soon as the flow was started, regardless of the values of flow depth ratios (h_0/D).

Figure (4) shows the progress of the scour hole for this case, whereas if there is any embedment (1-2 mm) thickness, score does not occur for all the cylinders and flow conditions tested. These findings are not in accordance with the previous investigators (Chiew 1990, Mao 1988) where the condition for onset of scour was that **e**/D <0.5 and/or $h_0/D<3.5$

Figure (5 a, b and c) shows that no scour occurred even though $h_0/D < 1.0$. In prints d and e of this Figure, the discharge was stopped and the flow depth decreased gradually creating a tunnel scour underneath the cylinder.

Figure (6) clarifies the case where there was no scour occurring under all the flow conditions tested with $h_0/D <1$ and $e/D < 0.5$.

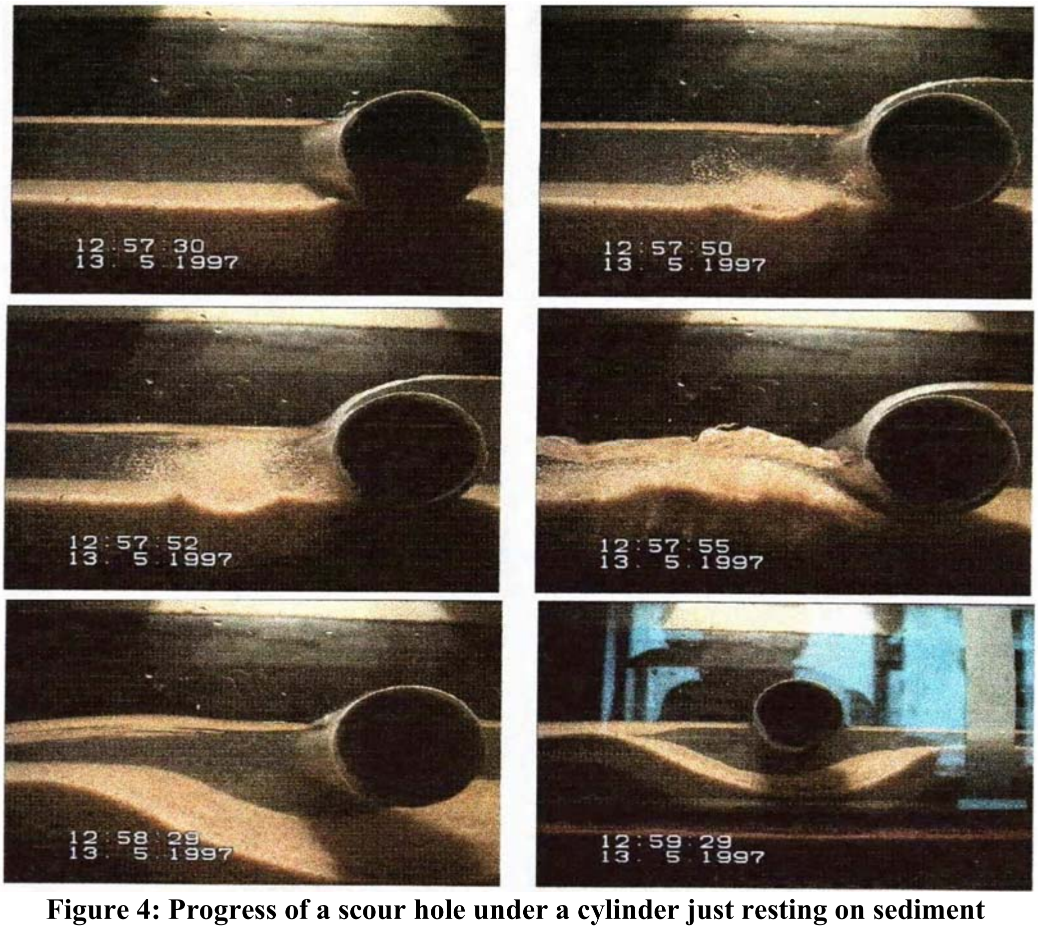

Figure 4: Progress of a scour hole under a cylinder just resting on sediment

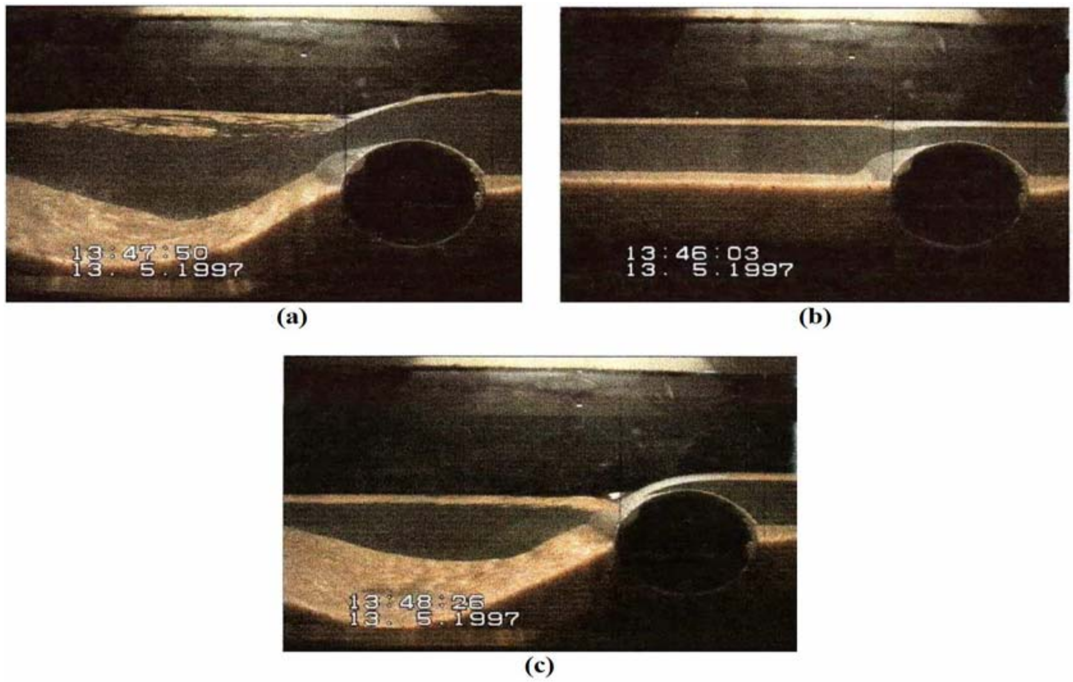

Figure 5: No scour hole in prints a, b, and c for $h_0/D<1.0$, However a scour hole has developed in prints d and e when flow is stopped

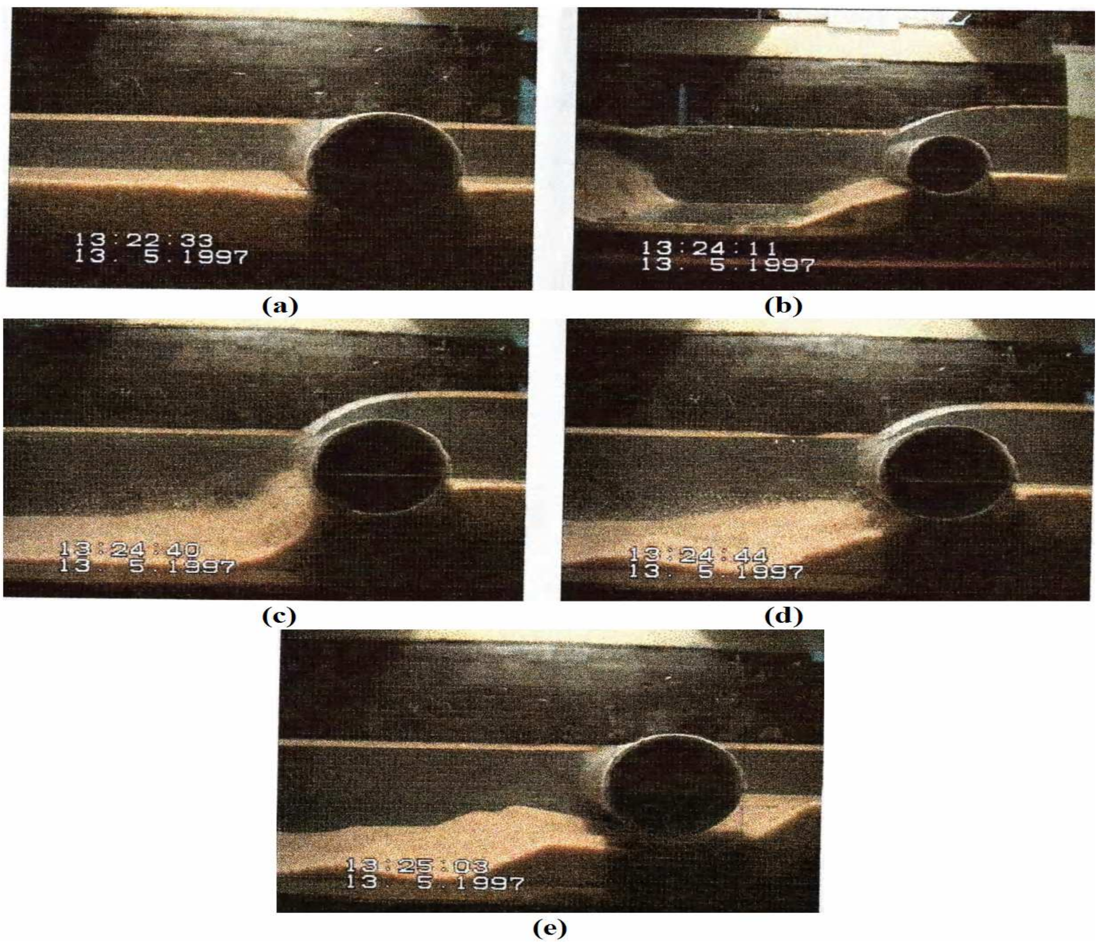

Figure 6: Lack of scour for $h_0/D<1.0$ and $e/D<0.5$

Static pressure gradient

Experimental series II was designed to explore piping and its role in causing scour at submerged pipelines. The purpose of this series was to determine the critical pressure gradient at which tunnel scour occurs. The results would show that the flotation gradient formula, $i_f=(1-n)(G_s-1)$, normally used in soil mechanics to determine the occurrence of piping, can also be applied to scour around pipelines (Table 1).

The sequence of prints (fringes) of Figure (7) showed clearly the outputs of one case of the second series of tests, the progress of the piping action underneath the cylinder. The bed was initially flat and as the difference in water levels between the two compartments increased the piping began with an elevation in the bed (print b) and a rupture (liquefaction) formation (print c) and went on until the stage of this rupture. It should be noted that all scour holes were symmetric along the longitudinal direction, x-axis, with maximum scour at the mid-span of the channel due to the effect of the side-wall of the channel

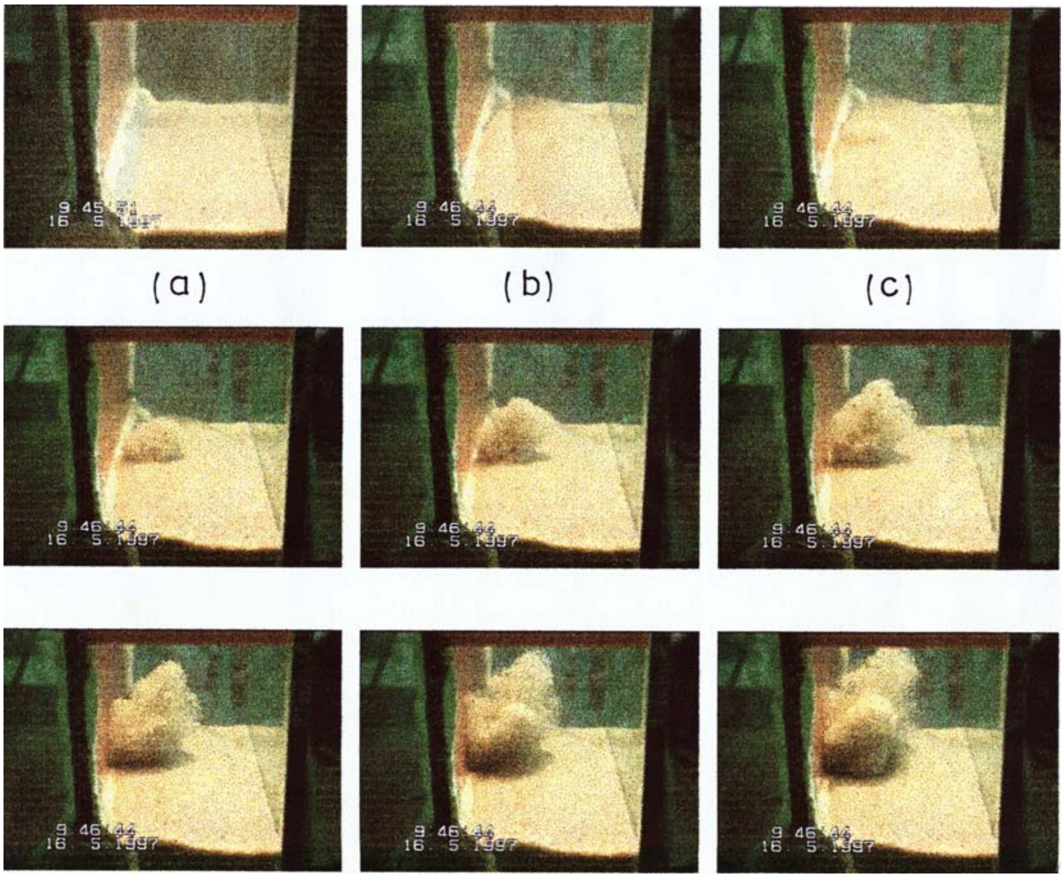

Figure 7: Progress of a tunnel scour due to piping action

CONCLUSIONS

- For a cylinder just embedded in a flat bed, the study shows that tunnel scour occurs immediately as the flow starts regardless of the flow depth ratio and this is due to the infiltration of flow through the underneath side of the cylinder where the length of circumference of the cylinder in contact with the sand bed is very short causing a high pressure gradient across the cylinder. If there is any embedment in the flow bed then the tunnel scour will occur only under certain conditions of flow depth ratio.

- The study shows that the onset of scour at horizontal cylinder is primarily caused by piping. Piping occurs when the hydraulic (exit) gradient at the cylinder exceeds the flotation gradient of the bed sediment. The upward flow of water associated with piping offsets the weight of sediment and reduces the threshold of sediment entrainment. This phenomenon helps the upstream stagnation eddy to breach the sand barrier underneath the cylinder causing the onset of tunnel scour. The hydraulic gradient is induced by the stagnation pressure upstream and a low pressure in the separation zone downstream of the cylinder. The pressure gradient is greater for unidirectional flow over a cylinder when the ratio of flow depth cylinder diameter is small because choking effects. The choke causes a large backwater buildup of the cylinder and creates an even higher pressure gradient than one expects for conditions when the h_0/D ratio is large .The magnitude of the pressure gradient is thus related to the h_0/D ratio, which accounts for cases when tunnel scour does not occur.
- Piping scour will take place whenever the floating gradient is exceeded which can be achieved by the effect of hydrostatic pressure difference between both sides of the cylinder and or by the action of the wake at the downstream side of the cylinder.

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