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PHYSICS OF FLOW MECHANISM OF SCOUR AROUND SUBMERGED PIPELINES ON AN ERODIBLE BED

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ABSTRACT

Pipelines that are used to convey water, petroleum, gas or any other fluid across a river are generally burried under the bed. Interaction between a pipeline and an erodible bed assumes importance in engineering because of the high cost of laying such pipelines. The pipes may become partially exposed to the action of water currents where a flood causes a general scour in the bed of the river. Also as a direct consequence of rapid urbanization, bridges in close proximity are likely to interfere with such pipelines enhancing their vulnerability to scour. It is agreed that difference in pressures on the upstream and downstream of the pipe initiates piping below the pipeline. Piping together with stagnation eddy combine to undermine the pipeline and mark the onset of scour. Maximum local scour below the pipe is observed when there is a small gap between the pipeline and the undisturbed sediment bed allowing jet like high velocity flow through the gap. As the gap increases, scour depth gradually decreases. For a pipeline placed at bed level, unsteady flow in the form of a hydrograph gives more scour than that for a uniform flow. Column like intermediate supports provided below the pipeline and bridges in close proximity are likely to increase the scour considerably.

Keywords: Pipeline, Flow mechanism, Scouring, Erodible bed, Interference, Piping

1. INTRODUCTION

It is established that piping is the dominant cause of the initiation of the scour in the case of pipelines crossing rivers on erodible beds. Piping and the stagnation eddy combine to undermine the pipeline, and mark the onset of scour. The critical hydraulic gradient associated with the initiation of scour is equal to floatation gradient of the bed sediment, Chiew, (1990). The pressure drops between the stagnation pressure upstream and wake pressure downstream of the pipe induces this hydraulic gradient.

Due to rapid urbanization, bridges in close proximity are on the increase. Under such conditions of close proximity of bridges, if a pipeline has to cross the alluvial bed, various structures will have a bearing on the scouring process of each other. Also, 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 offshore refineries.

Though some work has been carried out on the initiation and mechanism of scouring below pipelines, yet the studies seem inconclusive. No studies are available on the interference effects of such pipelines on existing bridges or pipelines in close proximity. The supports, on which the pipelines are founded, may by themselves become a source of interference. Present work is an attempt to study these aspects.

2. SCHEME OF EXPERIMENTATION

Experiments were conducted in the Hydraulics laboratory of Civil Engineering Department of National institute of Technology, Kurukshetra, India. A recirculating flume 12.25m long, 0.4m wide, and 0.55m deep partly having glass sides was used for the study. Fine sediment of median size, d_{50} = 0.37mm and σ_g = 2.3 collected from a river course nearby was filled in the flume. Detailed scheme of experimentation is shown in Table 1.

Table 1: Scheme of Experimentation

RUN No.	**D (cm)**	**q (m^3/sec/m)**	**h (cm)**	**e (cm)**
1.	4.0	0.0282	15.00	0.00
2.	1.9	0.0356	19.00	0.00
3.	4.0	0.0356	19.00	0.00
4.	6.3	0.0356	19.00	0.00
5.	7.5	0.0356	19.00	0.00
6.	4.0	0.0162	8.50	0.00
7.	4.0	0.0186	10.10	0.00
8.	4.0	0.0247	12.95	0.00
9.	4.0	0.0304	16.24	0.00
10.	4.0	0.2998	13.40	0.00
11.	4.0	0.2998	13.40	1.00
12.	4.0	0.2998	13.40	2.00
13.	4.0	0.2998	13.40	3.00
14.	4.0	0.2998	13.40	4.00
15.	4.0	0.2998	13.40	5.00
16.	4.0	0.0282	15.00	0.00
17.	4.0	0.0282	15.00	1.00
18.	4.0	0.0282	15.00	2.00
19.	4.0	0.0282	15.00	3.00
20.	4.0	0.0282	15.00	4.00
21.	4.0	0.0318	15.80	-1.00
22.	4.0	0.0318	17.08	-2.00
23.	4.0	0.0282	15.00	0.00
24.	4.0	0.0282	15.00	0.00
25.	4.0	0.0282	15.00	0.00
26.	4.0	0.0282	15.00	0.00
27.	4.0	0.0282	15.00	0.00
28.	4.0	0.0282	15.00	0.00
29.	4.0	0.0282	15.00	0.00
30.	4.0	0.0247	14.30	0.00
		0.0299	14.70	0.00
		0.0342	15.20	0.00
		0.0390	16.30	0.00
		0.0327	15.10	0.00
		0.0255	14.50	0.00
		0.0234	14.00	0.00
31.	4.0	0.0299	15.80	0.00
32.	4.0	0.0318	15.00	2.00
33.	4.0	0.0365	16.00	2.00
34.	4.0	0.0299	15.80	-2.00
35.	4.0	0.0299	15.80	0.00
36.	4.0	0.0299	15.00	2.00
37.	4.0	0.0365	16.00	2.00
38.	4.0	0.0299	15.80	-2.00

2. MECHANISM OF SCOURING

3.1 Wet paint impression studies on rigid bed prior to scouring

Before conducting studies on a mobile bed an experiment was carried out on a rigid bed to visualize and study the flow modifications around submerged pipeline with the help of wet paint technique. The flow conditions for the experiment were as follows: Size of pipes D = 4.0cm, Discharge intensity, q = 0.0282 m^3/sec/m, depth of flow, h = 15.00 cm, Velocity, U = 18.80 cm/sec, Froude no., F = 0.155, Clearance, e = 0.

Figure (1a) represents the results of the wet paint study on a 4cm diameter circular pipe. The separation zone is indicated by the removal of paint from around the pipe model. On the pipe, it was observed that the line of separation is an angle of 180^o from the point of contact of the pipe to the rigid bed. At the downstream point of contact of the pipe model with rigid bed, there had been a concentration of the paint, thus indicating a wake zone. Concentration of paint at the downstream end is due to formation of reverse roller, which removes the paint from away of the pipe and deposits it near the pipe.

From the study of flow visualization and flow past a circular pipe held on rigid bed indicates that existence of the vortices on both sides of the pipe for e/D = 0 and these vortices detach from the pipe surface and attach to the base surface.

3.2 Scouring of mobile bed

Mechanism of scouring around pipelines on a mobile sediment (d_{50} = 0.37mm) bed may be discussed with respect to four regions in which the pipe is laid Figure 1(b to f).

Pipeline is fully embedded (Fig 1b)

There is no scour in the vicinity of the pipeline so long as the general scour in the river is not able to expose the pipeline. There is no obstruction caused by the existence of the pipe.

Pipeline is partially embedded (Fig. 1c)

Such a case occurs when a fully embedded pipeline gets exposed due to general scour or otherwise. In this case there is scour at the downstream of pipeline away from the pipe and deposition of sediment near the pipe. The small obstruction near the bed creates an adverse pressure gradient resulting in the separation of flow lines forming a vortex on the upstream front of the pipe. Separation of flow lines also takes place at the crest of the pipeline and a reverse roller is formed in the wake region. This pushes the bed material upstream till the sediment completely chokes the downstream of the pipe and prevents the onset of tunnel scour. In this case, sediment protects the pipeline from vibrations induced hydrodynamically.

Pipeline is resting on the bed (Fig. 1d)

In the initial stage, the above case may be taken to be analogous to a rigid bed when e/D = 0, where D is the diameter of the pipe and e is the gap between the pipe and the bed. In this position vortices are formed on both sides of the pipe and it can be postulated that the cause for the initiation of scour is due to these two vortices and strong suction pressure on the downstream side.

Pipe is above the bed (Fig. 1e and f)

i) When there is small gap (e/D<0.5) between pipe and undisturbed bed (Fig. 1e).

This situation resembles the previous case when pipe is resting on the bed or a small gap has been created by general lowering of stream bed. In this case both vortices; on the upstream and the downstream of the pipe, get detached from the pipe surface and are attached to the bed surface. Suction pressure and high shear stress developed on the bed is thus responsible for jetting of flow resulting in high scour below pipe.

ii) When there is large gap (e/D>0.5) between pipe and undisturbed bed (Fig. 1f).

Equilibrium stage is gradually reached when considerable scour has taken place below the pipe. Under such a situation, the vortices do not reach the mobile bed, thus allowing sufficient flow to pass below the pipeline. There is no pressure difference between the upstream and downstream of the pipe at bed level. Thus the scour decreases as the gap ratio increases.

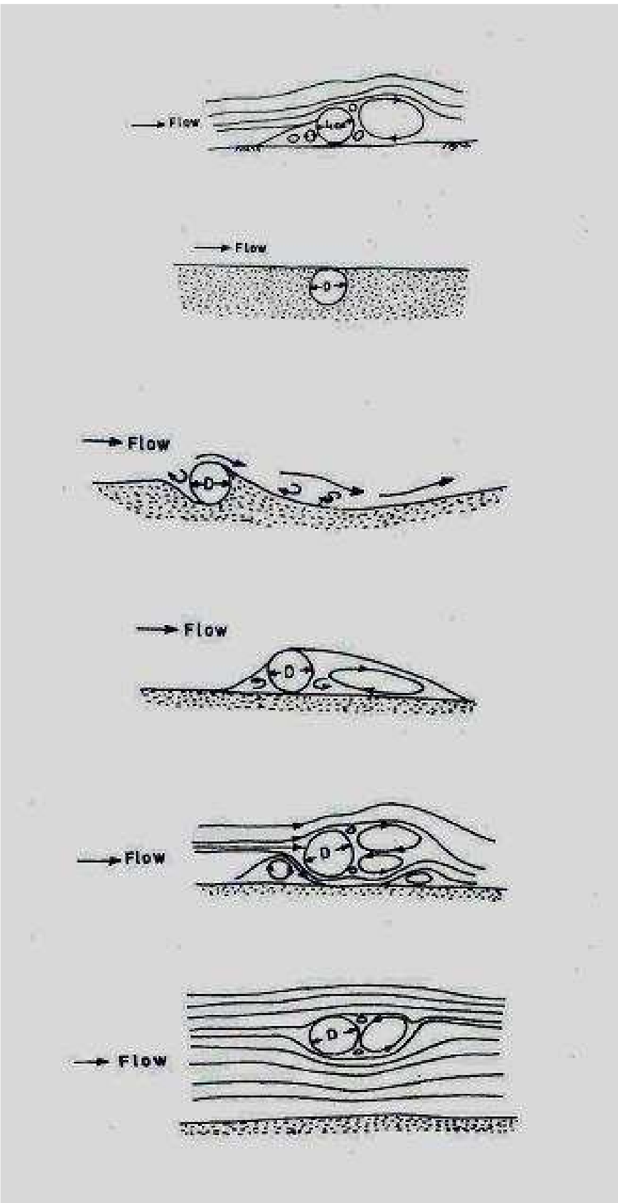

Figure 1(a to f) Flow mechanism around the pipeline for different gap ratios

4. RESULTS AND DISCUSSION

4.1 Effect of size of the pipe

To ascertain the effect of the different diameters of pipe on the resulting scour, a set of experiments with pipes of diameters 1.9 cm, 4.0 cm, 6.3 cm and 7.5 cm, was carried out. The results, Figure (2a), also incorporate the results of a previous study and follow a similar trend. A curve passing through combined data has the form, $H_{sm} = 0.5\ D - 0.0024$. The two linear curves have the same slope but differ on the value of intercept.

4.2 Effect of depth of flow

There seems to be no definite trend of the scour depth with variation of flow depth. The result agrees with the findings of Moncada M and Aguirre Pe (1991). The authors had conducted a series of experiments to illustrate the influence of the blockage effect of the pipe on the flow. A plot of scour depth against depth of flow, both non-dimsionalised with pipe diameter (H_{sm}/D Vs h/D) shows that scour does not seam to depend upon h/D (Fig. 2b).

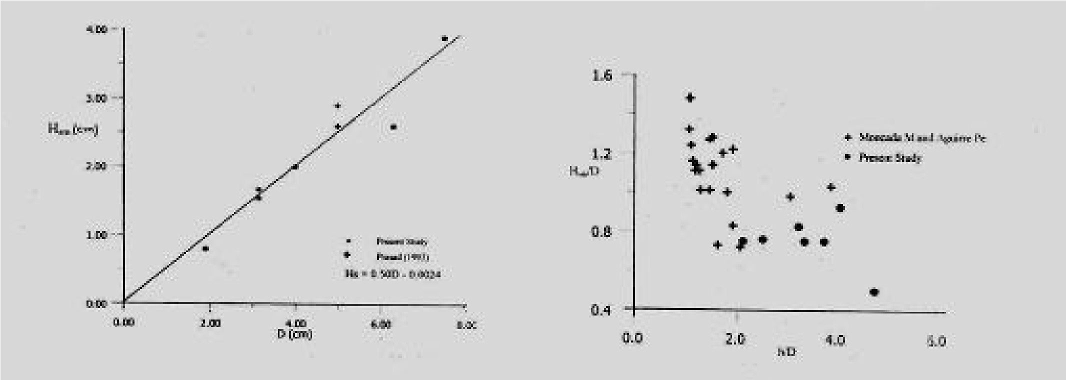

Figure 2(a, b) Effects of diameter D and depth flow h on Scour Depth H_s and comparison with other researchers.

4.3 Effect of location of pipeline in vertical direction in clear water and live bed conditions

To eliminate the effect of depth of flow, the ratio h/D was kept in range of 3-3.5 as suggested by Chiew (1991a,b). Location of pipeline in vertical direction, creating a gap underneath the pipeline, is another parameter, which needed to be explored. Increasing gap below the pipe simulates a situation when a pipe initially placed at the bed level gets fully exposed and then goes on to scour more and more below it.

To study the influence of clearance e, between the pipe bottom and undisturbed bed, a series of experiments under clear water and live bed conditions were carried out and the results have been presented in Figures 3(a) and 3(b).

When the pipe is placed at the bed level, the flow is diverted from above the pipe and it takes sufficient time for the initiation of scour in the form of piping below the pipe. In the second case when the pipe is placed D/4 above the average bed level, then right from the beginning flow lines below the pipe get compressed thus generating relatively higher velocity and shear stress on the bed. The axes of the two vortices upstream and downstream of the pipe shift towards the mobile bed. This is followed by an effort by the flowlines to create larger area of flow below the pipeline. Any increase in the gap beyond D/4 causes lower maximum scour depth that that at D/4. This is true for both clear water and live bed scour conditions.

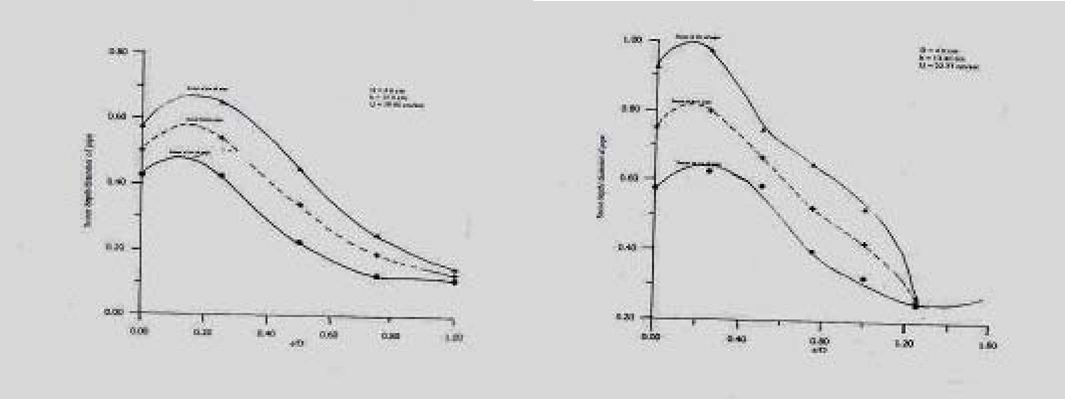

Figure 3 (a, b) Effect of vertical location w.r.t bed level on scour depth (a. clear water, b. live bed)

Figures 4a and 4b give a comparison of effect of pipe position on scour depth below pipeline with Moncada and Aguirre (1999) and Maza (1999) respectively. The trend of present study matches with the results of above said authors. The difference can be attributed to the sediment size. Where sediment size d_{50} is 1.80 mm and 0.72 mm for the study of Moncada and Aguirre (1999), it is only 0.37 mm for present study.

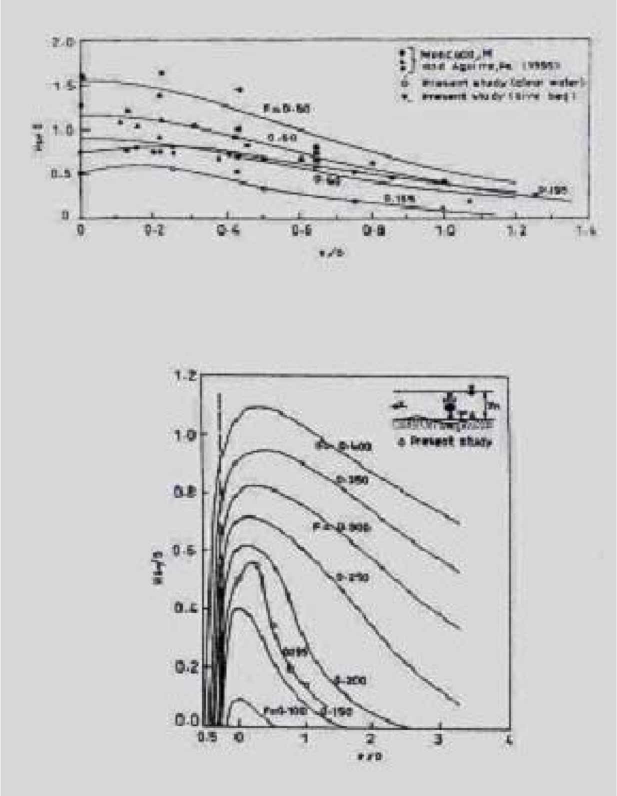

Fig 4 (a) Comparison of effect of gap ratio on dimensionless scour depth (b) Comparison of dimensionless scour depth as a function of e/D and F, Maza (1999)

4.4 Comparison of results

Figure 5 present a comparison of the effect of Froude number on dimensionless scour with other authors. The effect has bean shown for the specific case of location of pipeline at the bed level i.e. e/D = 0. The lone point corresponds to the live bed conditions from the present study (F = 0.195) falls on the extension of the curve. From the figure it may observed that scour depth increases gradually with an increase in Froude number.

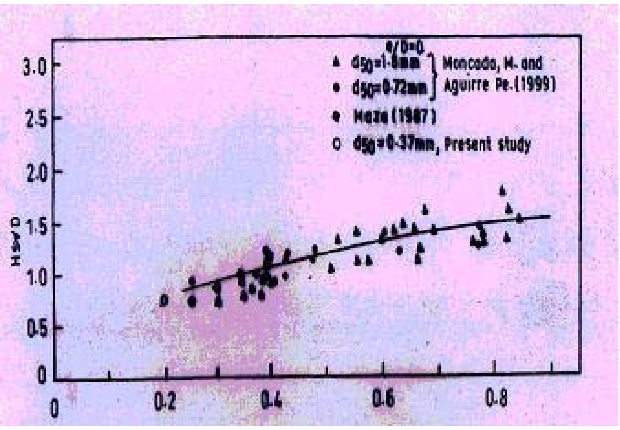

Figure 5 Comparison of influence of Froude no F on dimensionless scour depth H_s/D

Figure 6 shows the effect of Froude number F on dimensionless scour length L/D of the scour hole. The results of the present study have been superimposed on the same figure with the results of earlier researchers. The three curves differ on account of the sediment size. The larger the average size of the sediment more is the length of the scour hole for a given Froude number.

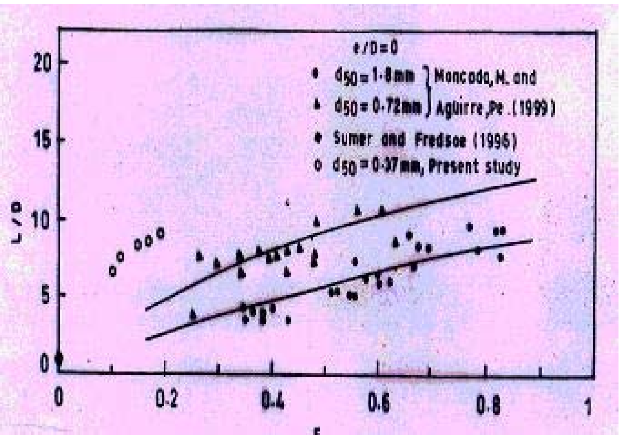

Figure 6 Comparison of influence of Froude no F on dimensionless length L/D

4.5 Hydrographic run

A set of experiments were conducted to ascertain the effect of a high flood combining clear water and live bed scour conditions on local scour below a pipeline. A-time duration of 210 minutes was chosen to get the effect of onset of a flood and its recession. The discharge of the flume was increased in four steps each of 30 minutes duration and thereafter retarded in 3 steps to reach the same initial value.

The experiments were conducted on the same circular pipeline of 4 cm diameter. Observations for the scour depth were taken at regular time intervals. The variation of unit discharge (q), depth of flow (h), velocity (U) and non-dimensionalised scour depth (H_{sdm}/D) with respect to different time intervals is shown by bar charts in Figure 7. The flow conditions and resultant scour depth against time are as at run no. 30 in Table 1. It can be observed from the figure that scour reaches its maximum value in the fourth interval. It may also be seen that till about 30 minutes, no applicable scour was observed. It was owing to the fact that the velocity of flow is below incipient velocity of sediment. After that scour depth was steadily increasing with the velocity. At the peak discharge and hence maximum velocity it was the case of live bed scour conditions with sediment held in mild suspension as well. With further reduction in the discharge, scouring activity seams to have attained an equilibrium stage with maximum scour depth value 0.82 D. There seems to be no appreciable deposition of sediment by suspended or bed load during the recession stage of hydrograph.

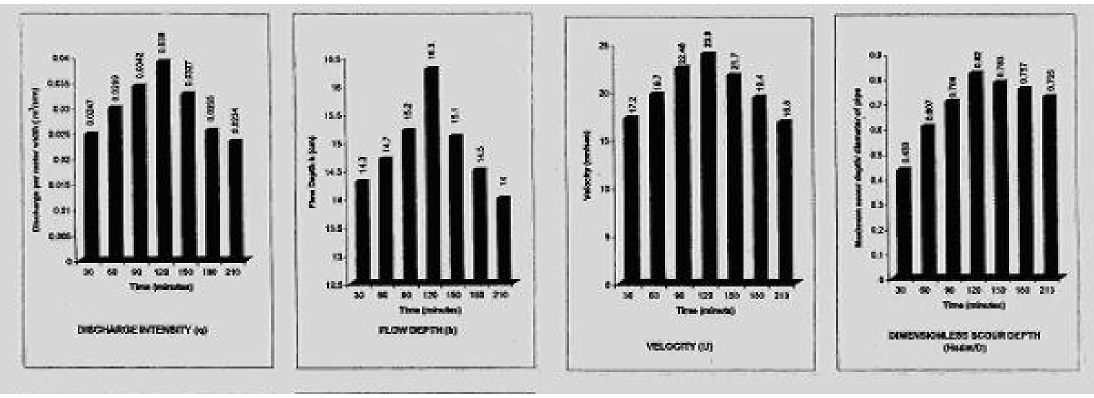

Figure 7 Hydrographic Run

4.6 Effect of interference of pier on upstream or downstream of pipeline

Due to rapid urbanization, bridges in close proximity are on the increase. Under such conditions of the close proximity of bridges, if a pipeline has also to cross the alluvial river, the various structures will have a bearing on the scouring characteristics of each other. To study the effect of such interfering structures, the pipeline was modelled to be passing, firstly from the upstream and then from the downstream of the bridge pier. A set of six such experiments was carried out and the results have been presented in Figures 8(a to f).

Figures 8(a to f) show that as the pipeline is made to move towards the downstream, the scour at the downstream end of the pier is more initially but it goes on decreasing as distance between the pipeline and the pier increases. When distance between pier and pipeline reaches to about four times the diameter of the pier, both the pier and pipeline make their own distinct zones of scour.

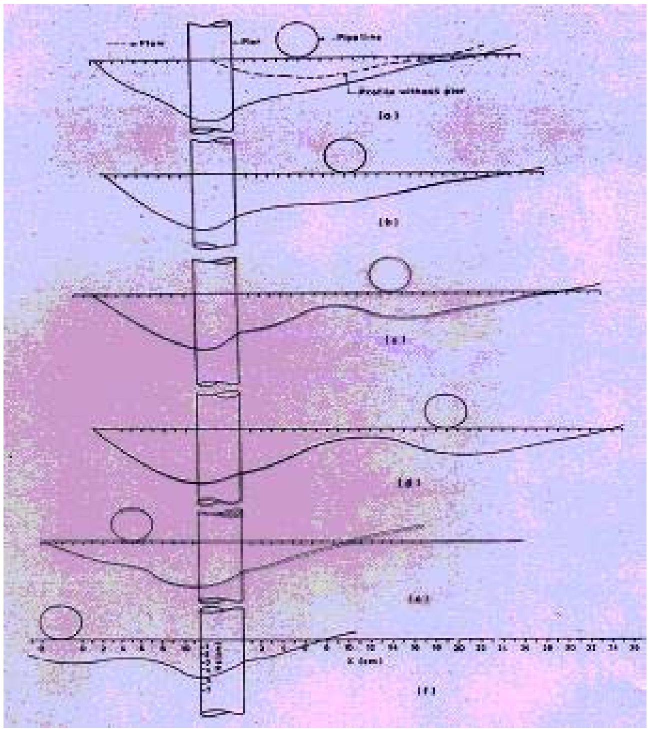

Figure 8 Profile of scour hole for interference of pipe with pier

5 CONCLUSIONS

Following are the main conclusions of this experimental study:

- i) Flow visualization studies with the help of dye injecting and wet paint technique establish the presence of two vortices on either side of the pipeline, which aid in initiating scour.
- ii) Piping is the first visible sign of scour below a pipeline. If the pipeline is half buried, the scour below pipeline is not initiated.
- iii) Both scour depth, H and scour length L of the scour hole increase with an increase in diameter of pipe. Best-fit curve to the data of present study is $H_s = 0.50 - 0.16$.
- iv) Scour depth does not seem to depend on the depth offlow.
- v) The effect of clearance, e between pipeline and undisturbed bed is a basic parameter. The maximum scour depth corresponds to a gap ratio, e/D of 0.250.
- vi) If it is unavoidable to cross the pipeline near a existing pier then it is better to cross the pipeline upstream of the existing pier. The piers and pipelines must at least be separated by 4-5 times the size of the pipe or the pier to avoid their interference.

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