LIVE-BED SCOUR AROUND PIPELINE EXPOSED TO UNIDIRECTIONAL WATER FLOW

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ABSTRACT:

The results of laboratory experiments on live-bed scour of cohesionless bed sediment at pipelines placed on or near the bed and exposed to unidirectional water flow are presented. Different shapes of pipe cross section were used to study the effect of the geometry on the local scour. The experiments coverd a range of Froude number from 0.30 to 0.457. The main particle size of bed sediment is kept constant at d_{50}=0.34mm. Observations include the shap of scour hole, scour depth and scour hole width.

KEY WORDS: Live-bed , pipeline and a tilting flume.

NOTATIONS:

A, a, B, b, c, k, m and n are variable constants,
D = diameter of circular pipe,
d_s = sediment size,
F_e = Froude number
g = the gravitational acceleration,
L = Side length of square pipe,
L_s = diagonal length of rhombus pipe,
Q = flow discharge,
V = Mean velocity,
Y_o = flow depth,
Y_s = maximum scour depth,
W_s = width of scour hole,
ρ = Water density, and
μ = absolute viscosity of water

INTRODUCTION:

Prediction of the behavior of submarine pipelines on an erodible bed depends on understanding the mechanics of local scour around submarine pipelines resting on an initially flat bed composed of uniform cohesionless sediment and accurate estimate of the scour depth is important in the design of the submarine pipelines. Two types of scour according to the approaching flow velocity and size of sediment entrianment are available. The first type is the clear-water scour, which occurs when the bed material upstream of the scour area is at rest. The second is the live-bed scour, which occurs when there is a general bed load transport by stream.

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It is important to distinguish between these two types of scour because the development of the scour hole with time and the relationship between scour depth and the approaching flow velocity depending upon the type of scour (clear-water or live-bed) that is occurring. The fundamental cause of the erosion around a pipeline in local increases in the transport capacity of the flow around the pipeline, while deposition takes place where this capacity decreases [2]. Many investigators among whom were (Ali [1], Bijker [2], Chiew [5], Hulsbergen [7], Ibrahim and Nalluri [8], Laursen [10]) studied this problem to stand on the main factors affecting this problem and to determine the practical solutions of it.

Bijeker and Leeuwestein [2] stated that the scour depth at submarine pipelines depends on the undisturbed flow velocity, pipe diameter, flow depth, height of pipe above bed level and grain size.

Sumer et al [13] studied the interaction between vibrating pipe and erodible bed. The experimental scour profiles were given for two different stages of scour process for a pipe: one for the early stage and one for the equilibrium for fixed and vibrating pipe. The development of the scour depth with time lead to the conclusion that the value of scour depth relative to the pipe diameter is approximately constant after t=100-200 minutes from the beginning of tests.

Breusers [3] reported that scouring depth increases with the velocity V until the velocity approaches the critical velocity V_c at which the bottom-transport in the undisturbed area starts. Further increase of velocity gives practically no further increase in scouring depth because this depth depends more on the ratio of transports than on the absolute values.

Chabert and Engeldinger [4] stated that as the approaching velocity exceeds the critical velocity, the scour depth will decrease to about 10% less than the maximum scour depth at the critical velocity. Thereafter, the scour depth remains constant irrespective of further increases in velocity.

Chiew and Melville [6] studied the relationship between the local scour depth and mean approaching velocity. The variations of equilibrium scour depth with approaching velocity showed that the depth of scour decreases at velocities just above the threshold until it reaches a minimum at about twice the threshold velocity. Thereafter, it increases again until a maximum is reached at the transition flat bed condition. At still higher velocity, the equilibrium scour depth decreases due to the formation of antidunes.

Although much effort has recently been given in studying the erosion phenomena below pipelines, no study is yet available investigating to what extent the variation of pipelines cross section influence the development of scour process. Therefore, the present study investigates the effect of pipeline cross section under unidirectional flow on the scour profile and the equilibrium scour depth for live-bed scour stage.

EXPERIMENTAL SET-UP

The experiments were conducted in a tilting flume having a cross-section of 30 cm x 30 cm with a 13.50 m in length, which incorporates transparent test section of 10 m in length. The flume used in the present work is illustrated in Fig. (1). The water depth could be adjusted by means of tailgate installed at the flume end. The flow rate was measured by means of nozzle meter. A movable sand bed was used for the experiments. The depth of the sand layer was 10 cm and extended 3.0 m in length. The movable sand bed was located at a distance 3.0m downstream the entrance section of the flume as in Fig. (1). Therefore, a false bed with 10cm depth was furnished for the first 3.0m of the flume length at the upstream and for the last 4.0 m of the flume length downstream with 10 cm depth .The false bed constructed from a gravelly material with 9.0 cm thickness and covered with 1.0 cm cement mortar for the U.S. and D.S. parts of the false bed.

Three shapes of a smooth aluminum pipe cross section, circular, square and rhombus were used to simulate pipeline . The diameter of circular pipe was changed as 15, 25 and 35 mm, the side length of square pipe was varied as 15, 25 and 35 mm and the diagonal length of rhombus pipe was varied as 21.20, 35.30 and 49.50 mm. All cylinders were kept perpendicular to the longitudinal axis of the flume. To prevent the cylinder from sagging into the scour hole, it was hanged by two bars fixed to a heavy carriage resting on the flume rails as shown in Fig. (2).

The sand feeder as shown in Fig. (3) is designed to inject sand at a required rate. It is composed of a steel hopper 90x45 cm with vertical sides discharging onto conveying belt driven by a motor at a variable speed.The wet-sand feeder is supported on the upstream end of the flume to inject the sand into the false bed, 120 cm before the beginning of the test section.

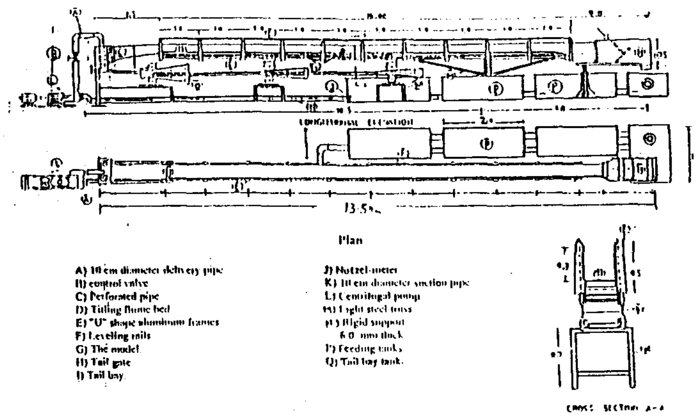

Fig. (1): Tilting flume

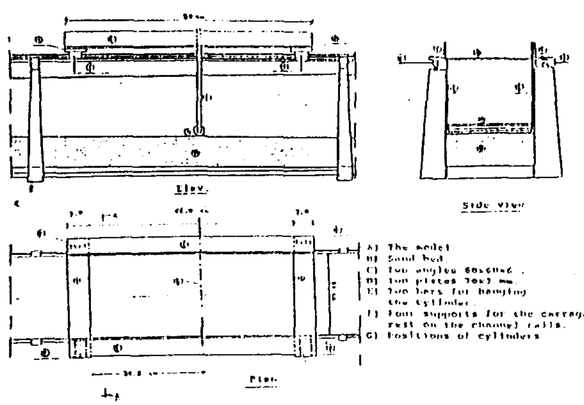

Fig. (2): Pipe model with hanging mechanism.

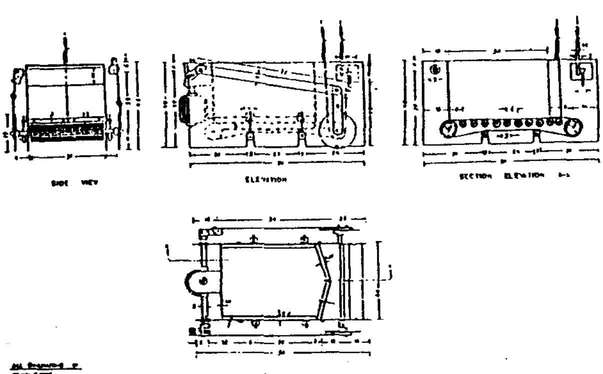

Fig. (3): The Wet-Sand Feeder Apparatus

SERIES OF TESTS:

The procedure of performing the experiments was as follows: -

1- The intake valve of the feeding pipeline connected to the nozzle-meter was opened slowly to give the required value of discharge by adjusting both the intake valve and the water manometer reading.

2- The downstream tailgate was adjusted to obtain the required water depth at the location of the cylinderical model.

3- The wet sand feeder was operated to feed the wet sand to the flume in order to fix the bed surface level during the test.

4- Then, the cylinder that was clamped to the carriage outside the flume was dropped gently into the water until becomes in contact with the sand level.

5- After a period from 6.0 to 8.0 hrs. the water depth at the cylinder location was gradually increased by means of tail gate to stop the process of scouring, then the cylinder was lifted and hence the bed profile could be measured. Accordingly, the maximum scour depth and its location relative to the centerline of the cylinder could be recorded.

6- For the same cylinder diameter, the procedure was repeated for water depths covering Froude numbers from 0.306 to 0.457.

7- The cylinder model was varied and the steps from 1 to 6 were repeated.

8-The steps from 1 to 7 were repeated for cylinders with square and rhombus cross-sections.

THEORETICAL DERIVATION

The method of dimensional reasoning can serve best in the absence of the theoretical approach which seems in our problem very complicated. The variables used for dimensional analysis are chosen to represent all parameters involved in the problem under consideration. Fig. (4) shows the variables used in the analysis. The general functional relationship for these variables is given in the following form;

$$Y_s \text{ or } W_s = \varphi(V, Y_o, D, d_s, \rho, \mu, g) \qquad \text{......(1)}$$

Applying the Buckingham's "π" theory, in which Y_o, V and ρ are selected as repeated variables representing the geometrical dimensions, flow characteristics and fluid properties, respectively, results in the following non-dimensional groups;

$$W_S / Y_O \text{ or } Y_S / Y_O = \varphi\left(\frac{Y_O}{D}, \frac{\rho V Y_O}{\mu}, \frac{V}{\sqrt{g Y_O}}, \frac{D}{d_S}\right) \quad \text{.......................................(2)}$$

The term $\frac{V}{\sqrt{gY_o}}$ is the Froude number " F_e" and the term $\frac{\rho V Y_o}{\mu}$ is the Reynolds number " R_e". The flow over sand bed exposed to erosion is considered hydrodynamically rough surface and hence the viscous effect can be neglected [10], [1]. Besides, the experimental results of Nalluri and Ibrahim [8], Ali [1] for the flow around submarine pipelines didn't show any between interdependency scour depth and Reynolds number R_e. In the present study, Reynolds number is nearly constant at average value of (6.2×10^4) for live-bed scour. Thus, equation (2) reduces to;

$$W_S / Y_O \text{ or } Y_S / Y_O = \varphi\left(\frac{Y_O}{D}, F_e, \frac{D}{d_S}\right) \text{.......................................(3)}$$

Chiew and Melville [6] found that the relative water depth (Y_o/D) has negligible influence when its value exceeds 3.0. Thus for $Y_o/D > 3.0$, equation (3) reduces to;

$$W_s/Y_o \text{ or } Y_s/Y_o = \varphi\,(F_e, D/\,d_s); \qquad \text{.........................(4)}$$

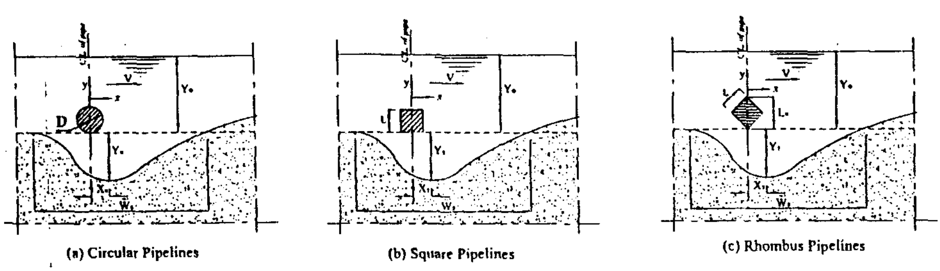

Fig. (4): Variables covered by the tests

RESULTS:

Experiments were conducted for various combinations of cross-section shape, cross section size and Froude number. To bring clarity, the observed results are presented herein to show their effects on the scour hole profile, scour depth, and scour hole width.

1-Scour Hole Profile:

Figures (5) to (7) illustrate the effect of variation of Froude number on the scour hole profile keeping the relative pipe size constant. The value of F_e varies from 0.306 to 0.457 for the three types of pipes (circular, square and rhombus). It is clear to notice that the scour hole profile depends mainly on F_e. The maximum scour depth and the hole width increase by increasing F_e. Apparently, for live bed, the sand particles to a long distance are transported downstream of the scour hole and the height of the accumulated sand hump is relatively small in the range of higher F_e value (F_e>0.36).

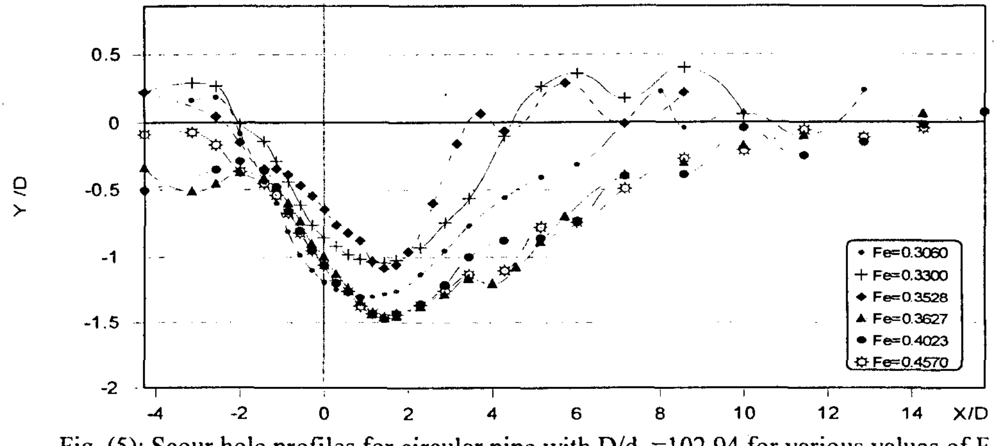

Fig. (5): Scour hole profiles for circular pipe with D/d_s =102.94 for various values of F_e.

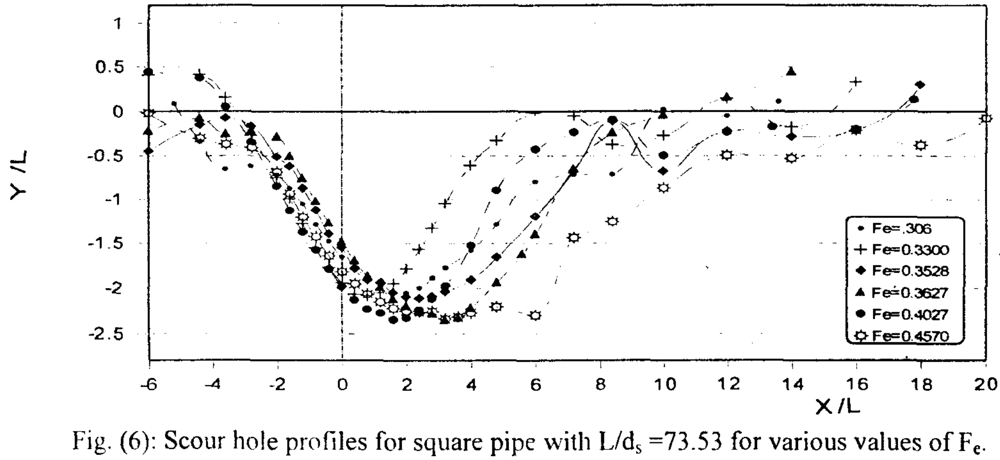

Fig. (6): Scour hole profiles for square pipe with L/d_s =73.53 for various values of F_e.

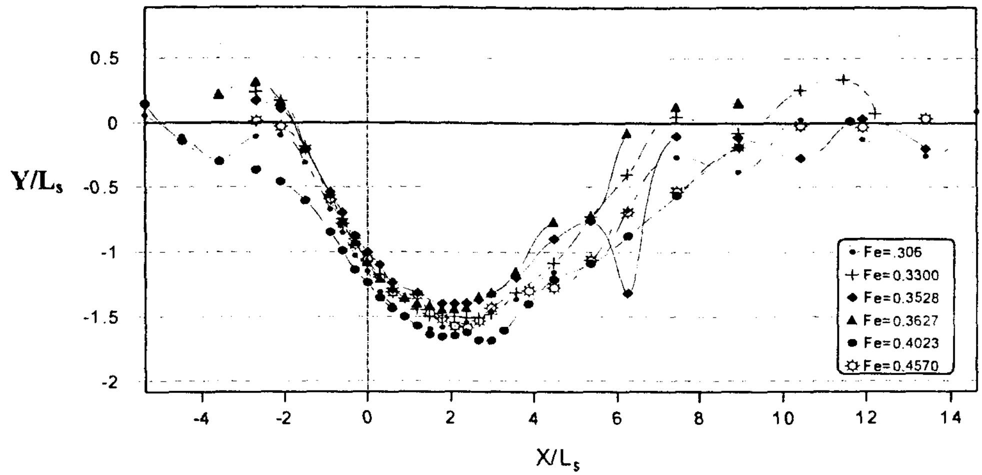

Fig. (7): Scour hole profiles for rhombus pipe with L_s/d_s =103.98 for various values of F_e.

(2)- Effect of the pipe shape on the scour hole: -

Figures 8 and 9 illustrate the scour hole profiles for the three types of pipes, where (Di) is the internal diameter of the pipe. In Figs. 8 and 9, the Froude number is kept constant at a value of 0.3627. In all these figures, the maximum depth of scour is attained for the square pipe. However, the maximum width of scour hole occurs with the rhombus pipe. The profile of the scour hole is dependent as well on the pipe shape.

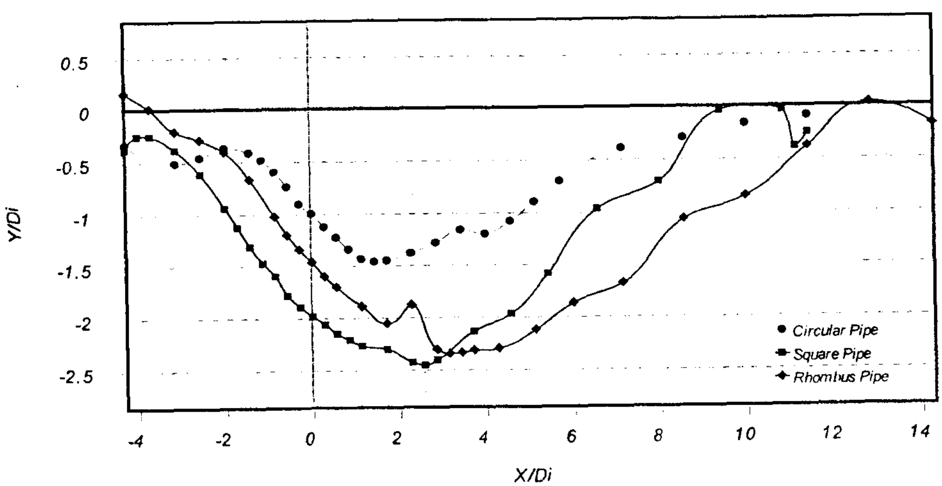

Fig. (8): Scour hole profiles for pipes with various cross sections and F_e = 0.3627 with Di=3.5 cm.

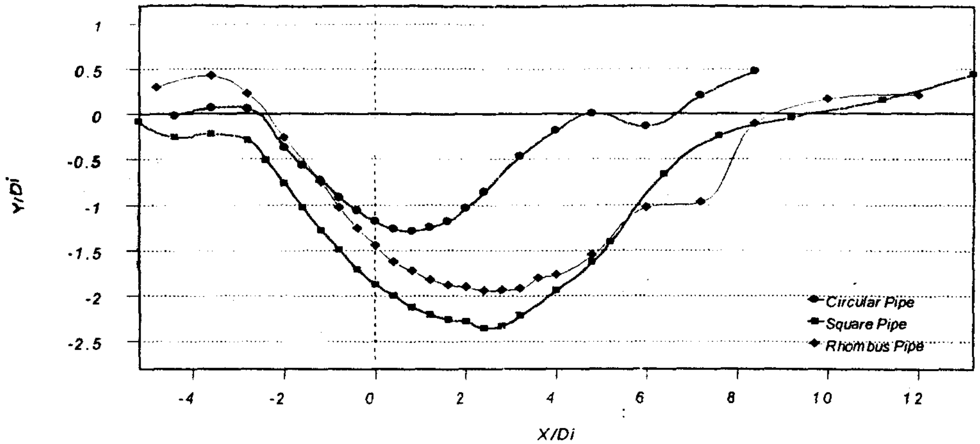

Fig. (9): Scour hole profiles for pipes with various cross sections and F_e = 0.3627 with Di=2.5 cm.

Fig. (9): Scour hole profiles for pipes with various cross sections and F_e = 0.3627 with Di=2.5 cm.

(3)- Scour Depth:

i)- For circular pipes:-

Fig. (10) illustrates the variation Y_s/Y_o with F_e for the three values of the relative pipe diameters (D/d_s). The data illustrates that, the relative maximum scour depth Y_s/Y_o depends on the Froude number and the relative pipe diameter. The maximum relative scour depth (Y_s/Y_o) increases with the increase of Froude number keeping the value of (D/d_s) as constant. Also, for constant value of F_e, the value of (Y_s/Y_o) increases with the increase of D/d_s value. The relationship between Y_s/Y_o and F_e takes the following form:

$$Y_s/Y_o = a \times F_e^{\,b} \qquad \text{...(5)}$$

Where a and b are coefficients depending on the relative pipe diameter (D/d_s). The value of a and b may be given in the form;

$$a = 0.0006667 \times (D/d_s)^{1.39426} \qquad \text{........................ (6)}$$

and

$$b = -1.159187 + 0.0144266 \times (D/d_s) \qquad \text{........................ (7)}$$

ii)- For square pipes:-

In similar way, the data of Y_s/Y_o are plotted against F_e as in Fig. (11). It is obvious to see that, the value of (Y_s/Y_o) increases with the increase of F_e value. For constant value of F_e, the maximum relative scour depth increases with the increase of L/d. value The relation between (Y_s/Y_o) and F_e may be expressed as.

$$(Y_s/Y_o) = c \times F_e^{k} \qquad \text{.......................................(8)}$$

where c and k are constants depending on the relative pipe side length. The function for each coefficient in isolation may be given by;

$$c = 8E\text{-}5 \times (L/d_s)^{2.133041} \qquad \text{.......................................(9)}$$

and

$$k = -0.861503 + 0.0168533 \times (L/d_s) \qquad \text{.................................(10)}$$

iii)- For rhombus pipes:

The variations of the maximum relative scour depth Y_s/Y_o with Froude number are shown in Fig. (12). As for the circular and square pipes, the value of Y_s/Y_o increases by increasing both the Froude number F_e and the relative diagonal length L_s/d_s. The functional relationship may be given by the following equation;

$$Y_s/Y_o = m \times (F_e)^{n} \qquad \text{.... ....(11)}$$

where m and n are variable constants depending on the relative pipe diagonal length (L_s/d_s). Value of m or n may be expressed as a function of (L_s/d_s) as;

$$m = 0.044656 \times (L_s/d_s)^{0.6074416} \qquad \text{..................... (12)}$$

and

$$n = 0.821611 - 0.00277 \times (L_s/d_s) \qquad \text{................ (13)}$$

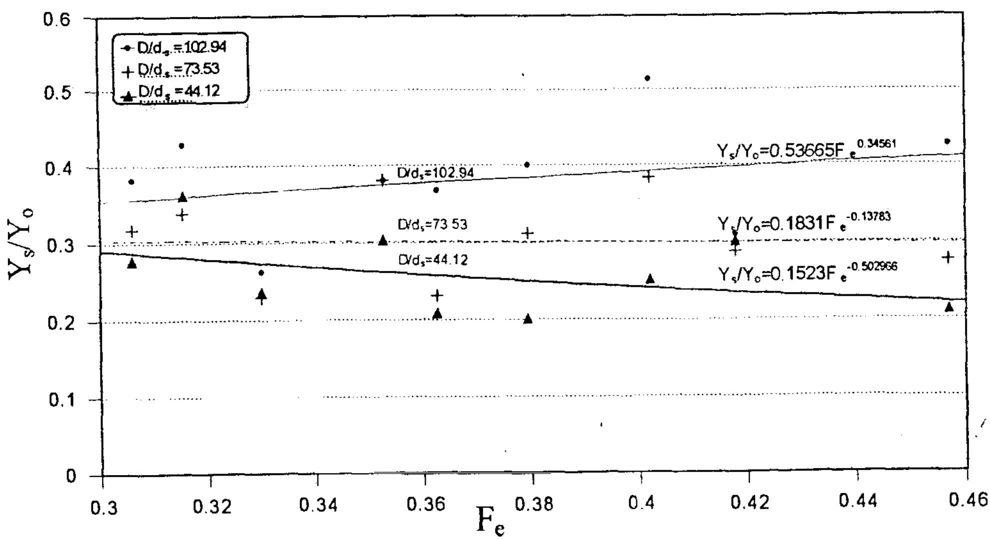

Fig. (10): Relationship between Y_s/Y_o and F_e for circular pipes with different diameters.

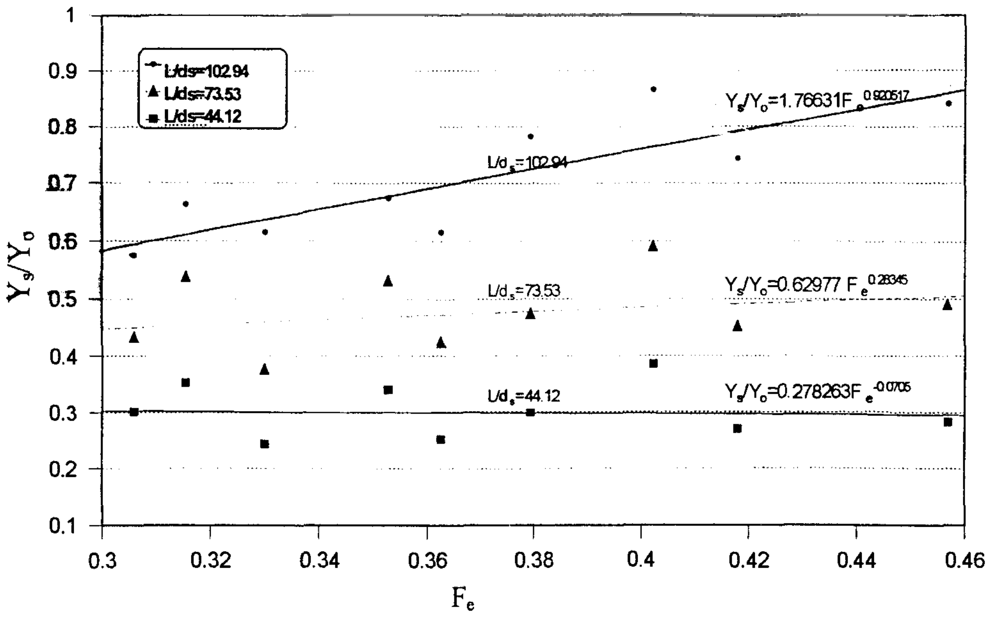

Fig. (11): Relationship between Y_s/Y_o and F_e for square pipes with different side lengths.

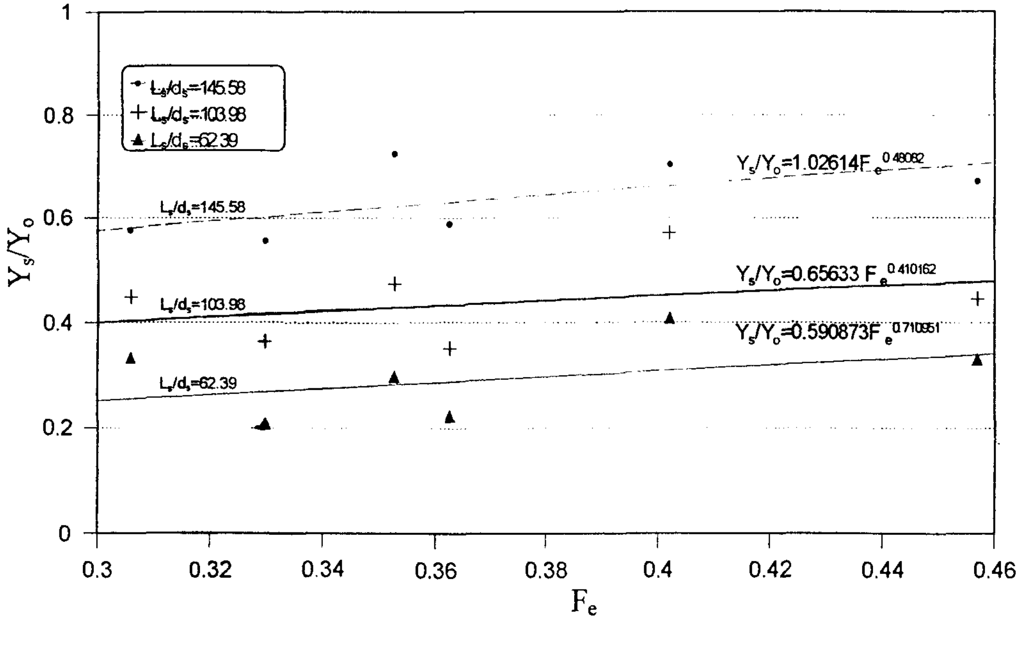

Fig. (12): Relationship between Y_s/Y_o and F_e for rhombus pipes with different diagonal lengths.

(4)- Scour Hole Width:

The experimental results of the relative width of the scour hole W_s/Y_o versus Fe for constant value of relative pipe size are plotted in Figs. (13, 14, 15). The above mentioned figures show that, the relative width of scour hole increases with the increase of Froude number F_e. The data are clustered around a curve, which may be expressed in the form;

$$W_s / Y_o = A \times F_e^B \quad \text{...(14)}$$

where A and B are coefficients depending on the pipe cross sections. The values of A and B are summarized in Table (1) for circular, square and 'rhombus pipes.

Table (1): Values of the coefficients A and B in Eqn. (14)

Coefficient	Circular Pipes	Square Pipes	Rhombus Pipes
A	5.6768	10.1204	6.3834
B	0.60991	0.9872	0.44853

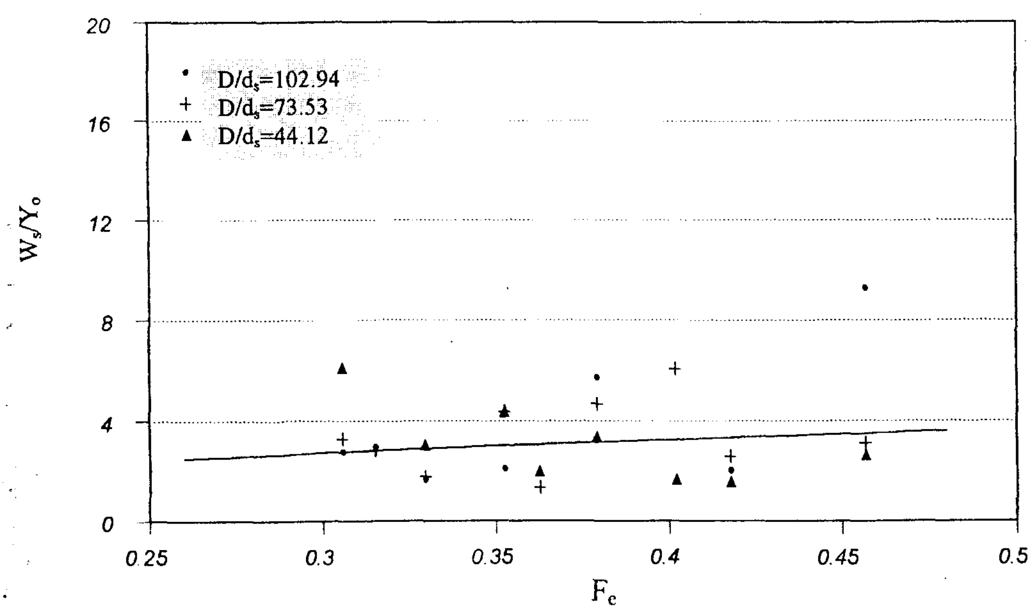

Fig. (13): Relationship between W_s/Y_o and F_e for circular pipes with different diameters.

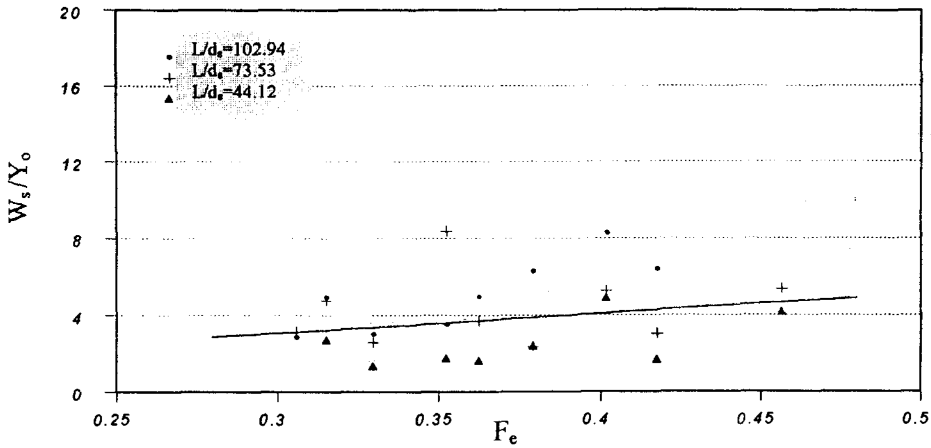

Fig. (14): Relationship between W_s/Y_o and F_e for square pipes with different side lengths.

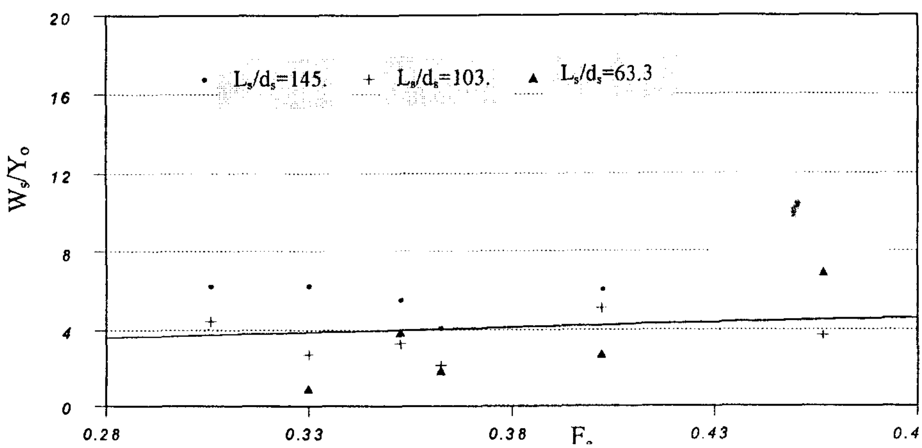

Fig. (15): Relationship between W_s/Y_o and F_e for rhombus pipes with different diagonal lengths.

(5)- The Maximum Scour Depth in the Two Stages of Scour (Clear-Water and Live-Bed) :-

The relationship between the maximum scour depth relative to the size of pipeline and Froude number "F_e" for circular; square and rhombus pipes are plotted in Figs. (16), (17) and (18), respectively. The range of Froude number is from 0.15 to 0.457,[11]. For all pipe cross section the maximum relative scour depth Y_s/D increases with the increase of F_e until the critical value of F_e at which the value of Y_s/D decreases gradually with the increase of F_e. This agrees fairly well with previous findings of Raudkivi [12] and others [3, 4 and 6]. In general, the maximum scour depth in case of live-bed scour is relatively less than that for clear water scour.

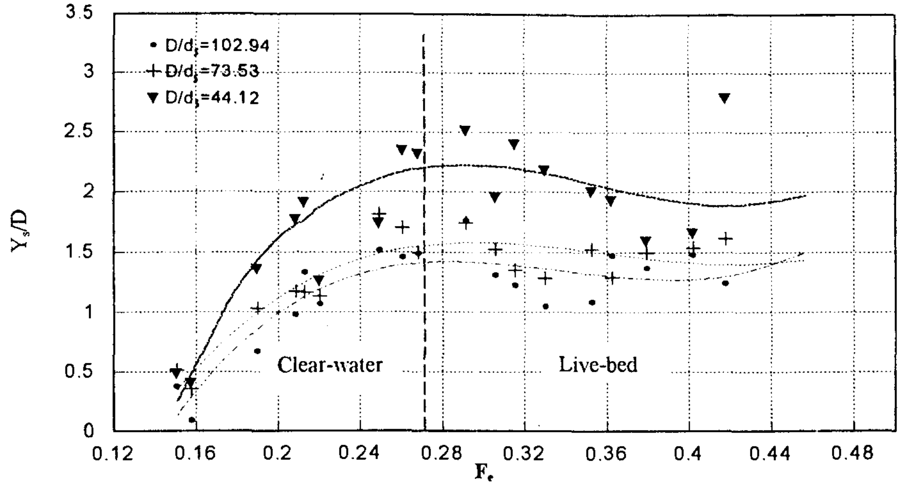

Fig. (16): Variation of the maximum relative scour depth Y_s/D with F_e for circular pipes.

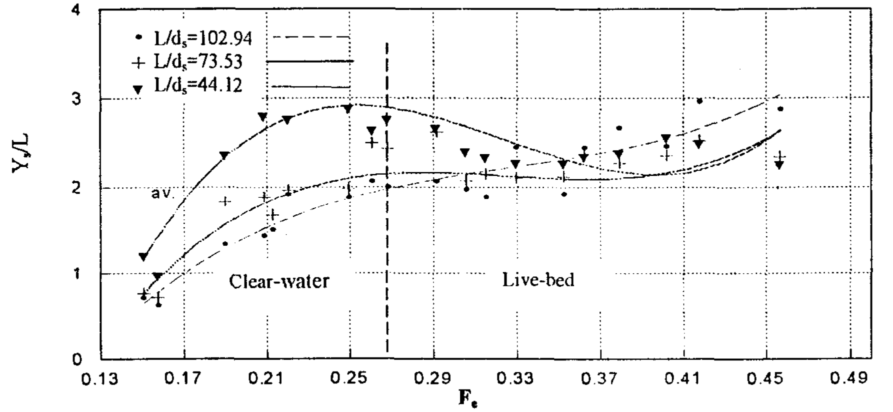

Fig. (17): Variation of the maximum relative scour depth Y_s/L with F_e for square pipes.

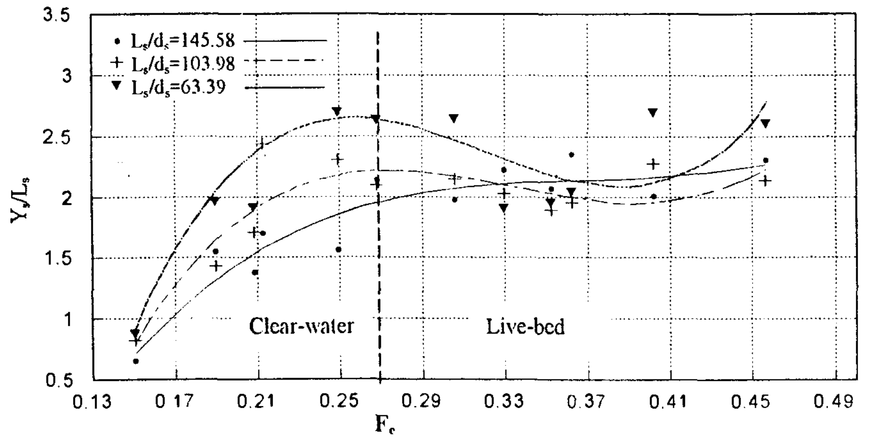

Fig. (18): Variation of the maximum relative scour depth Y_s/L_s with F_e for rhombus pipes.

Conclusions

The main conclusions drawn from the present study can be summarized as follows:

1-Froude number (F_e) has a great effect on the maximum scour depth, the width of scour hole, and also the location of maximum scour depth from the axis of the pipe.

2-For all pipe cross sections (circular, square and rhombus), the maximum scour depth of the scour hole relative to flow depth is increased by the increase of pipe dimension relative to the sediment size d_{50}.

3- The width of scour hole increases with the increase of Froude number and are not affected by the variation of relative pipe size.

4- For all pipe cross sections, the maximum relative scour depth Y_s/D increases with the increase of F_e until the critical value of F_e at which the value of Y_s/D decreases gradually with the increase of F_e.

5-From the present analysis, the relationship between the ratio of maximum scour depth to the flow depth (Y_s/Y_o) and Froude number with the relative pipe size for different shapes of pipeline cross sections takes the following form;

$$Y_s/Y_o = a \times (F_e)^b$$

in which a and b are variable constants depending on the pipe cross section and the size of pipe cross section relative to sediment size where:

Coeff.	Circular Pipe	Square Pipe	Rhombus Pipe
a	$0.0006667\times(D/d_s)^{1.392}$	$8E\text{-}5\times(L/d_s)^{2.13304}$	$0.04466\times(L_s/d_s)^{0.60744}$
b	$-1.159+0.01443(D/d_s)$	$-0.8615+0.014427\times(L/d_s)$	$0.8216-0.00277\times(L_s/d_s)$

6-The relationship between the relative scour width (W_s/Y_o) and Froude number may be expressed as;

$$W_s / Y_o = M \times F_e^N$$

where M and N are coefficients varying with the variation of pipe cross sections as:

Coefficient	Circular Pipe	Square Pipe	Rhombus Pipe
M	5.6768	10.1204	6.3834
N	0.60991	0.9872	0.44853

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