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LOCAL SCOUR NEAR OFFSHORE PIPELINES

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ABSTRACT

The stability of off-shore structures will depend on the extent of local scour due to the action of currents and waves, in addition to geotechnical factors.

The present investigation of local scour treats model tests with scour from a uniform flow near pipelines resting on the bottom and pipelines more or less buried. Two different flumes with uniform flow perpendicular to the longitudinal axis of the pipes were used for the experiments. The following mean flow velocities were used: V = 0.25 m/s, 0.35 m/s and 0.45 m/s. The mean diameter of the bed material was 74 μ. Thirty-two experiments including 4 diameters D = 6.0 cm, 11.0 cm, 22.5 cm and 50.0 cm were carried out.

On the basis of these model experiments the following has been estimated for a uniform flow: 1) The development with time of the scouring process. 2) The different scour patterns near the pipes when they are resting on the bottom and when they are more or less buried in the sand. 3) Possibilities with relevant parameters to extend the observed results for use on prototypes. If test facilities is available the experience gained will be used in a further work investigating scour from waves and scour from a combination of currents and waves.

1. INTRODUCTION

The process of local scour is caused by a construction placed as an obstruction in a unidirectional or oscillating flow. This process has been observed to start as a creation of a strong vortex ahead of the construction.

The turbulent energy in this vortex then starts the eroding action on the bottom. If the energy in the vortex is weak a stable situation can occur, where the amount of material transported into the scouring pit equals the amount of material transported out of the pit. If the energy is strong the construction might be undermined and the material can be transported under the construction and deposited behind it in more calm water.

If the construction is fixed, then after some time a stable situation will occur with a flow under the construction and a scour pit where material transported into it and material transported out from it are in balance.

A great number of model tests for local scour near different types of constructions exists, but only a few of these treat local scour near pipelines. (1)

Field observations are limited, and difficult to obtain. (2)

Nevertheless it is believed that model tests give a good possibility to study the general development of the scouring process.

Several investigators have tried to evaluate more general model laws from model tests.

CHITALE 1941 (3) expressed the local scour near a bridge pier as a function of the overall Froude number for the flume. SHEN, SCHNEIDER and KARAKI 1969 (4) investigated bridge piers using a pier Reynold number as an important parameter. COLEMAN 1971 (5) used an Euler number and a pier Froude number to characterize the scour.

Several investigators have in their developments used a critical parameter to characterize the situation, where grains on the undisturbed bottom start to move.

BREUSERS 1971 (6) used the critical mean flow velocity. STRAUB 1934 (7) and GILL 1972 (8) used a critical shear stress, while CARSTENS (1) used a critical sediment number.

LAURSEN 1963 (9) investigated scour associated with a long contraction, and generalized this solution to the case of abutments and piers.

He introduced, in addition, a distinction between scour where material transport takes place and scour where no material transport occurs, "clear water scour".

NINOMIYA, TAGAYA and MURASE 1972 (10) used a critical friction velocity in their scaling of scour, and stated that the overall Froude number the friction angle, and settlement characteristics for a non-fixed construction must be kept equal in a model and a prototype, if the scour development shall be equal.

2. MODEL ARRANGEMENT

The experiments were carried out in two permanent flumes of different sizes. The biggest one was 33 m long, 1.0 m wide and 2.0 m deep. To obtain the desired flow velocity in the big flume it became necessary to decrease its cross section. This was done by dividing the flume lengthwise. The width of the flume became then 0.50 m. The smaller one 26 m long, 0.6 m wide and 0.75 m deep. In the flumes silty sand was used as bed material with a specific gravity $\gamma_s = 2.74$ and grains with a sieve diameter $d_{50} = 0.074$ mm. The model arrangement in the big flume is shown in Fig. 1.

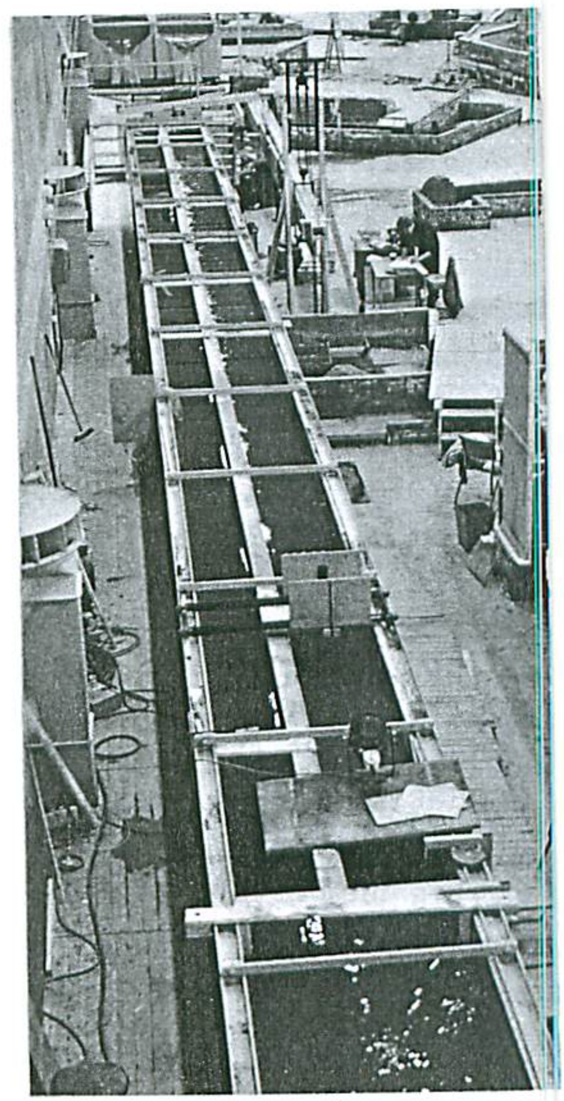

Fig. 1. Model arrangement in big flume.

The pipelines tested in the little flume were 0.06 m and 0.11 m in diameter, respectively. In the big flume investigations were undertaken for pipelines with diameters 0.11 m, 0.225 m and 0.50 m.

Measurements of scour profiles in cross-sections fig. 4 and velocity profiles showed that wall effects, even for the diameter 0.50 m could be neglected.

At the beginning of the investigation the tests were performed with four pipelines of equal size in the flume at the same time. In these cases pipeline no. 1 was completely buried, pipeline no. 2 was three-fourths buried, pipeline no. 3 half buried and pipeline no. 4 rested upon the bottom at the beginning of the test series. The pipelines were in all cases placed with the longitudinal axis perpendicular to the flow direction. The pipelines were fixed so that movements horizontally and vertically were not possible.

In order to obtain a uniform velocity profile in the flumes, filters were placed in the upstream part of the flume, and a logaritmic velocity profile was obtained by measurements.

It must be emphasized that none of the flumes were of the recirculating type. Material was feed at the upstream end, and removed at the downstream end. In some cases it was necessary only to have one or two pipelines placed in the flume, in order to have the material balance established in the flume upstream of the first pipeline.

The distance between the pipelines were checked by velocity measurements, and kept long enough to obtain a regular logaritmic velocity profile upstream of each pipeline.

3. TESTS AND TEST RESULTS

The tests were carried out for three different mean flow velocities. In the little flume the following mean velocities were used:
V = 0.20 m/s, 0.36 m/s and 0.52 m/s. In the big flume the velocities V = 0.25 m/s, 0.35 m/s and 0.45 m/s were used.

The measurements taken during the investigation are summarized in Table 1.

TABEL 1.

SUMMARY OF MEASUREMENTS AND PROFILES

Diameter	D=11 cm	D=6 cm	D=50 cm	—	—	D=11/22,5 cm
Run	1 2 3	4 5 6	7 8 9 10 11	12 - 23	24 - 29	30 31 32
MEASUREMENTS:						
I. Scour profiles	x x x	x x x	x x x	-	-	x x x
II. Photo's scour profiles	x x x	x x x	x x x	-	-	- - x
III. Velocity profiles	x	x	x x x x x			
IV. Photo's flow picture			x x			
V. Turbulence profiles			x x x x			
VI. Pressure distribution profiles	x x x		x x x x x			x x x
VII. Bed load measurements					x	
VIII. Initial motion observations				x		

Only a selection of the performed measurements are presented here. For details concerning this investigation reference is given to KJELDSEN and GJØRSVIK (11) and to BRINGAKER (12).

3.1. Measurements of scour profiles

The depths of scour were measured with a point - gauge type instrument to the extent that the contour lines of the scour profiles coul be drawn. The flow was stopped each time the measurements were take At the beginning of each time the measurements were taken rather frequently. As the rate of scour decreased the measurements were taken at an interval of 4 hours. All tests continued until differences in scouring depth could not be registrated and this was define as the equilibrium condition.

Fig. 2 shows the scour profile obtained with a pipe diameter D = 0.5 m and a mean flow velocity V = 0.35 m/s. Fig. 3 shows a photo of equilibrium scour pit taken from above.

To a certain extent it also became necessary to make measurements in

RUN 8.

MEAN VELOCITY V = 0.35 m/s
PIPE DIAMETER D = 0.50 m
WATER DEPTH h = 1.43 m

FLOW DIRECTION

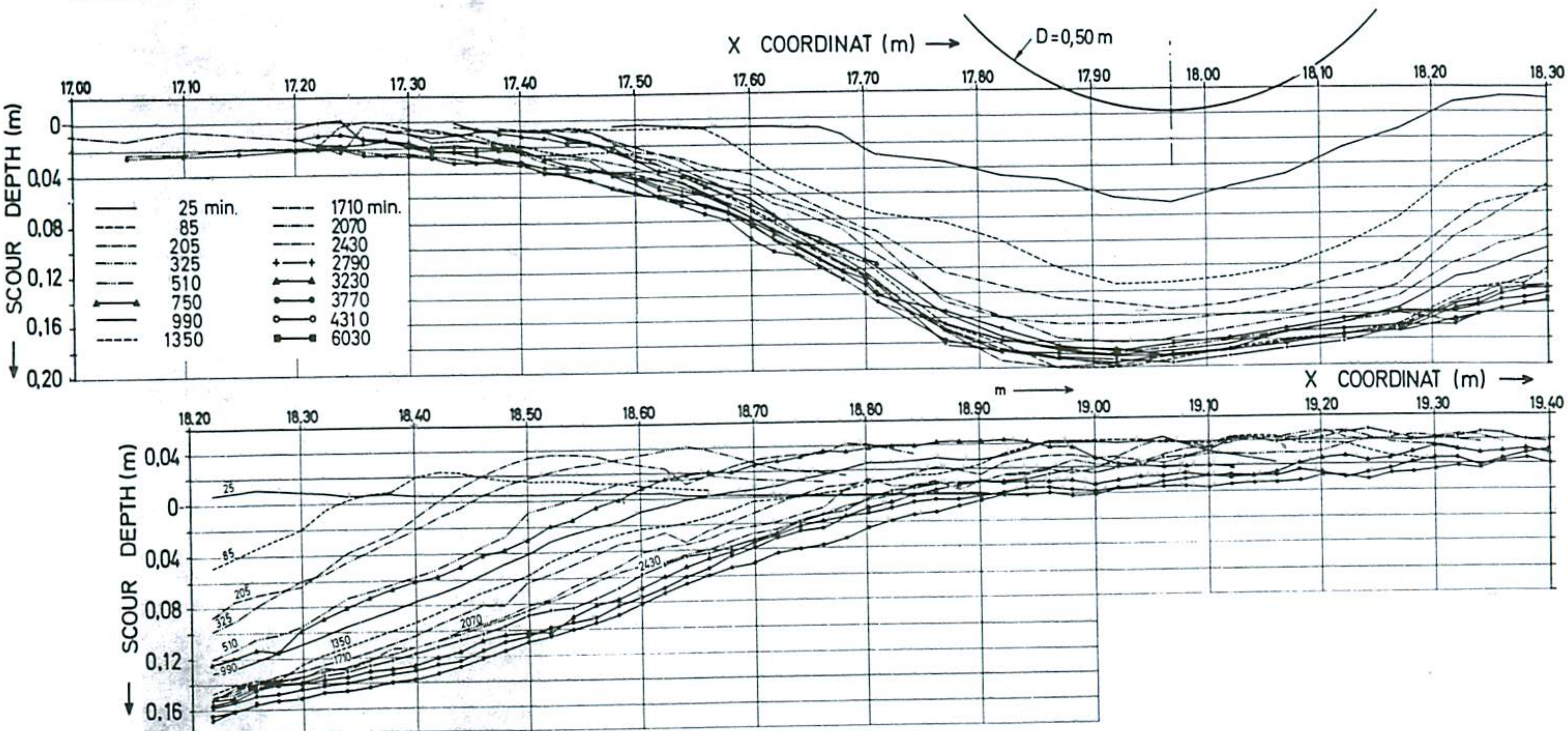

FIG. 2 SCOUR PROFILES AT PIPELINE NO. 4 (RESTING ON BOTTOM)

the cross-section. These measurements made it possible to observe potential wall effects. The cross-sectional profiles in Fig. 4 shows the situations right below pipeline no. 4 after approximate equilibrium was reached.

It appears from the diagrams that the wall effects have been rather insignificant during the performed tests. In particular, this is the case for the three smallest pipe diameters. But also for the biggest one the wall effect is small and mainly restricted to the boundary layer along the walls.

The development of the scouring process is illustrated in Fig. 5, where the scour depths are shown as functions of time at two characteristic sections near the pipe.

An example of the scour development near pipeline 2 and 3 is shown in Fig. 6.

Here the scour pit is shown behind pipeline 2 where three quarters of the diameter was buried.

As a conclusion, Fig. 7 is presented and the final development for the different pipelines are as follows:

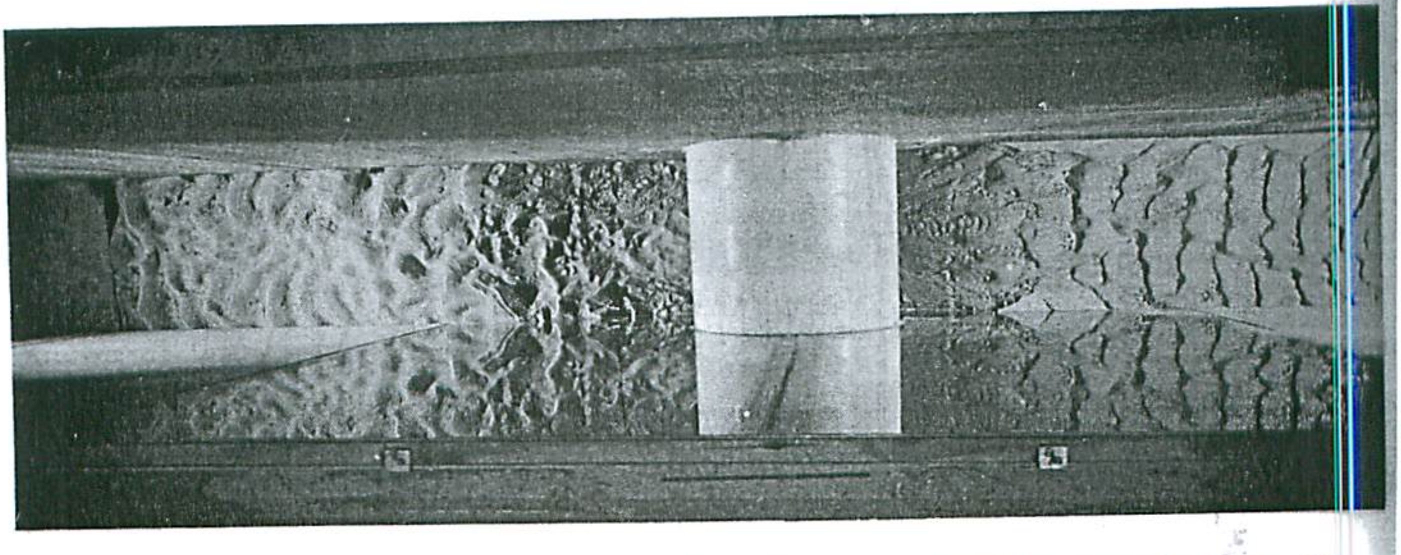

Fig. 3. Final Scour Profile for Pipeline initially resting on the Bottom. (D = 0,50 m, V = 0,25 m/s inflow from right side).

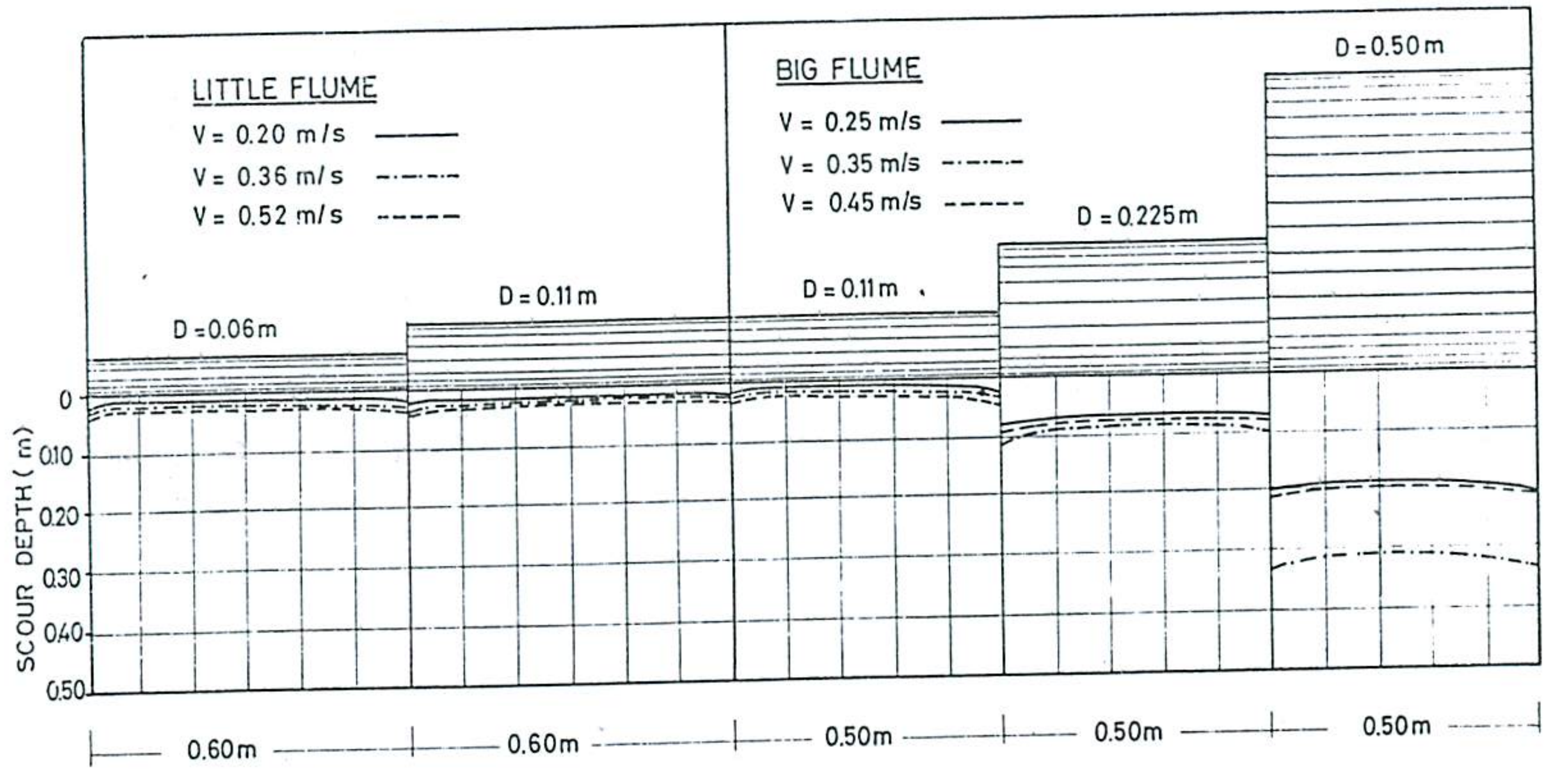

FIG. 4 CROSS SECTIONS SCOUR PROFILES

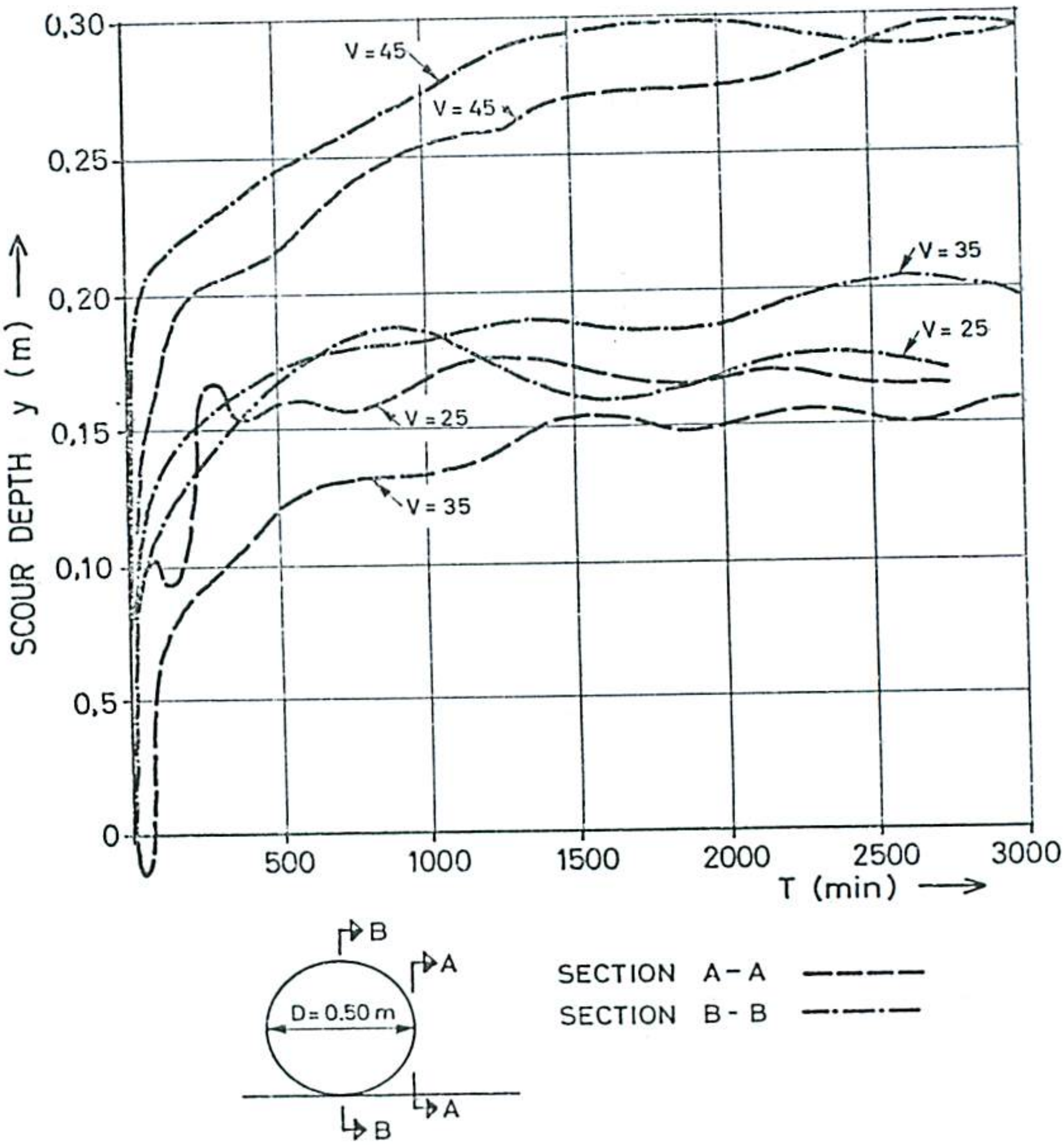

FIG. 5. DEVELOPMENT OF SCOUR FOR PIPELINES INITIALLY RESTING ON THE BOTTOM

RUN 8

MEAN VELOCITY V = 0,35 m/s
PIPE DIAMETER D = 0,50 m
WATER DEPTH h = 1,43 m

FLOW DIRECTION

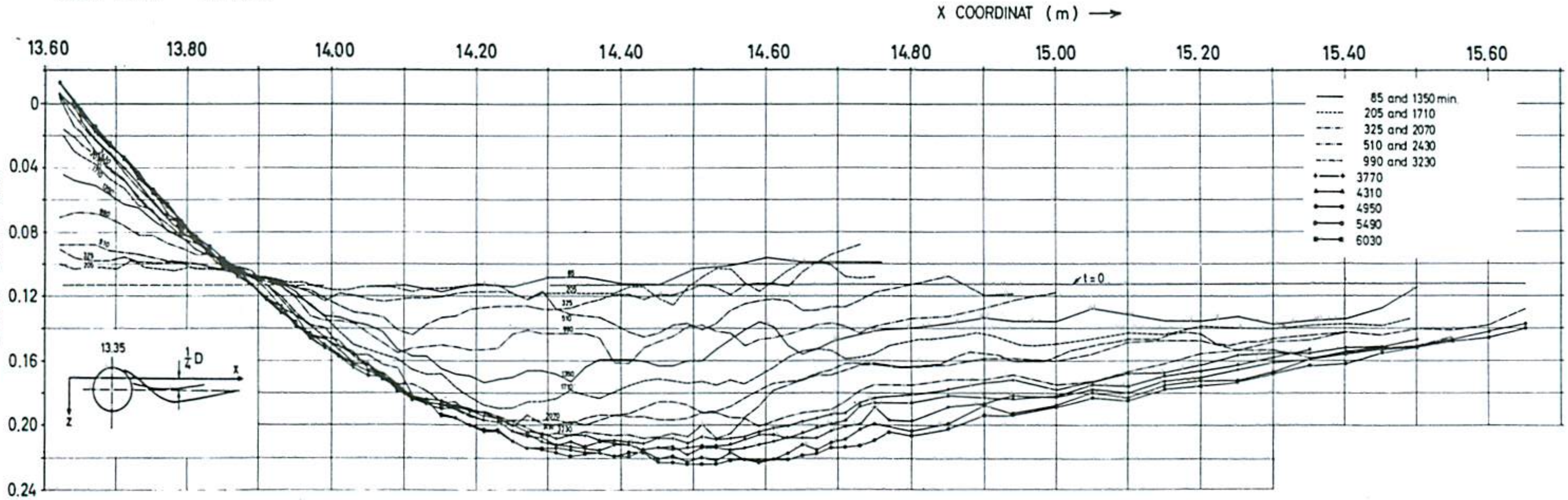

FIG. 6. SCOUR PROFILES AT PIPELINE NO. 2
(THREE QUARTERS OF DIAMETER BURIED.)

Results pipeline no. 1. - At the completely buried pipeline no erosion took place during the performed tests.

Results pipeline no. 2. - In examing the results of the pipe where three quarter of the diameter was buried it was found that the common scour pattern which arose at pipeline no. 2 for different diameter sizes is as shown in Fig. 7.

It appears that sedimentation of material took place both upstream and downstream from the pipeline. At a certain distance downstream from the pipe - depending on the mean flow velocity and the diameter size - an extended scour hole was developed.

Results pipeline no. 3. - The results obtained at the half buried pipeline shows the same tendency of scour pattern as those obtained at pipeline no. 2. Fig. 7 illustrates the common situation which appeared at pipeline no. 3 during the performance of the investigation.

Results pipeline no. 4. - All performed tests with the pipeline touching upon the bottom at the beginning of the test series, showed that the pipeline became undermined. In all cases the undermining took place immediately after the current was started. Fig. 7 illustrates the common scour pattern which arose at pipeline no. 4 during the performance of the investigations.

An examination of the results obtained for pipeline no. 4 indicates that the scouring depth, in the present case, depends on the flow velocity. Further, it is obvious that the erosion rate is highest at the beginning of the tests. In addition, the results indicate that the final scour depth is first reached directly below the pipeline.

3.2. Measurements of bed load

To check the amount of material transported as bed load during the test serie, six individual tests were undertaken without pipelines under which the bed load was registrated.

Here the same mean velocities were used, as in the scouring tests V = 0.25 m/s, 0.35 m/s and 0.45 m/s.

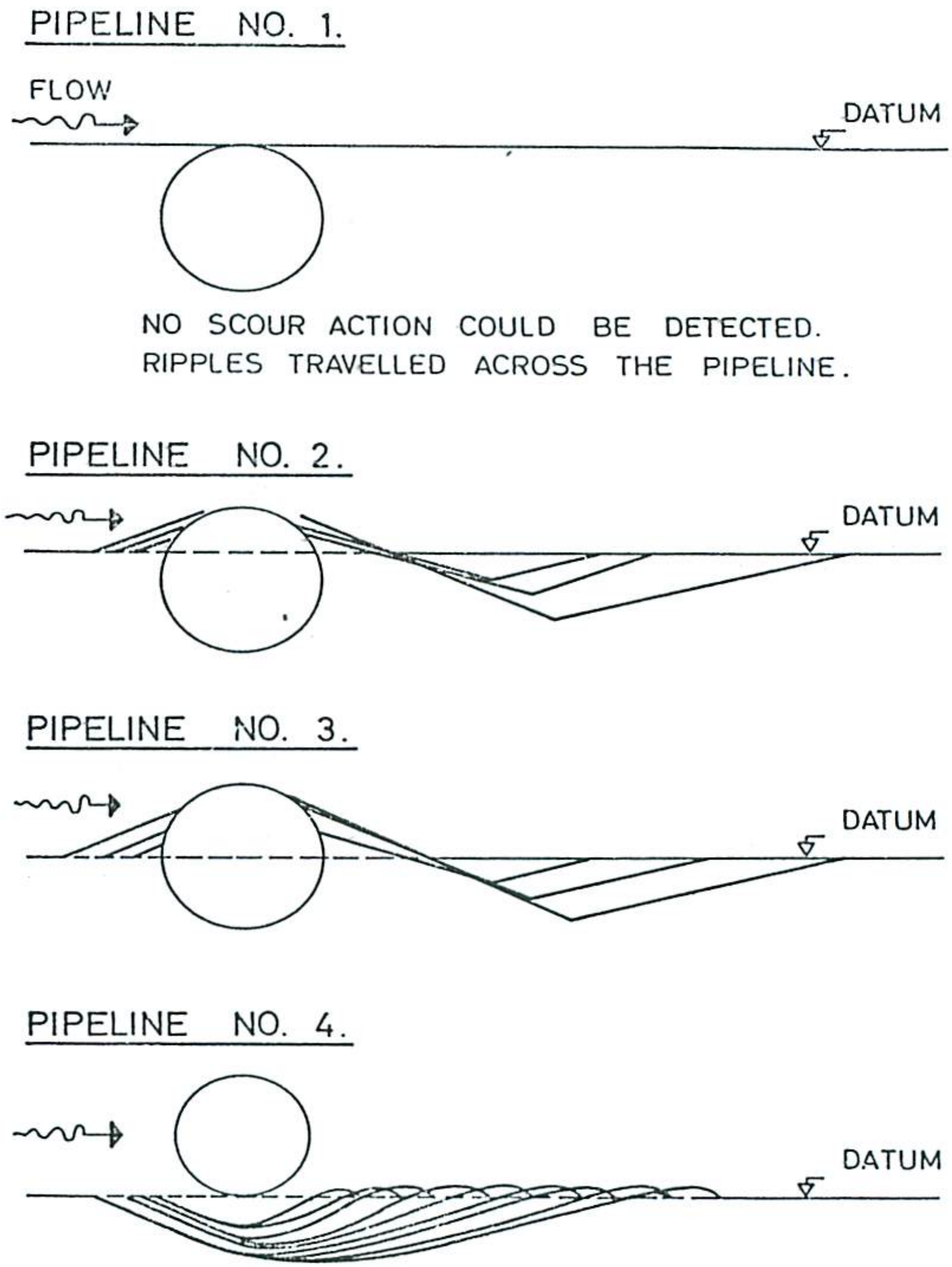

FIG. 7. SCOUR DEVELOPMENT IN PRINCIP.

Two tests were run with each velocity.

The bed load measurements were performed using three samplers with different widths (Δb = 0.5 cm, 1.0 cm and 2.0 cm). To observe potential wall effects each sampler was devided in three sections.

The measurements were undertaken as a guide only. Some scatter in the results occured mainly because of travelling ripples across the samplers.

Summing up the results from all sections in all samplers and taking the mean of these, the result shown i fig. 8 occured. Here the dry weight of material transported per meter of flume per minute (q_B), is plotted as a function of the mean velocity (V) for each test.

It appears from the diagram that the amount of bedload increases rather fast as the mean velocity increases. Further it is of interest to observe that the lengthening of the curve nearly coincide with Shields critical velocity for incipient motion.

No earlier measurements for this fine material has been found, and no bed load formulae have been evaluated. More tests will be necessary but still the data gives some indication of the amount of transported bed load.

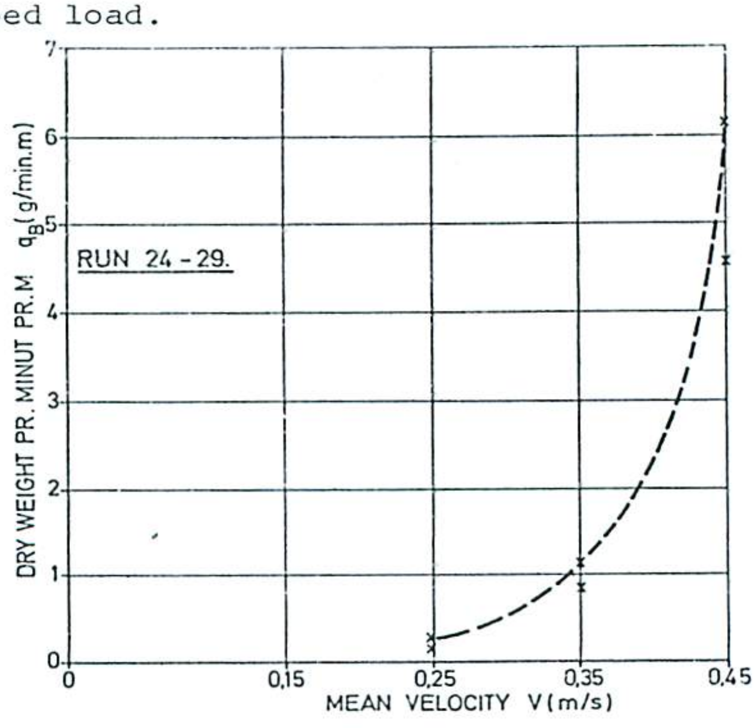

FIG. 8 BED LOAD AS FUNCTION OF MEAN FLOW VELOCITY.

3.3. Measurements of flow velocity and turbulence

As an example of the turbulent flow picture under pipeline 4, Fig. 9 is shown.

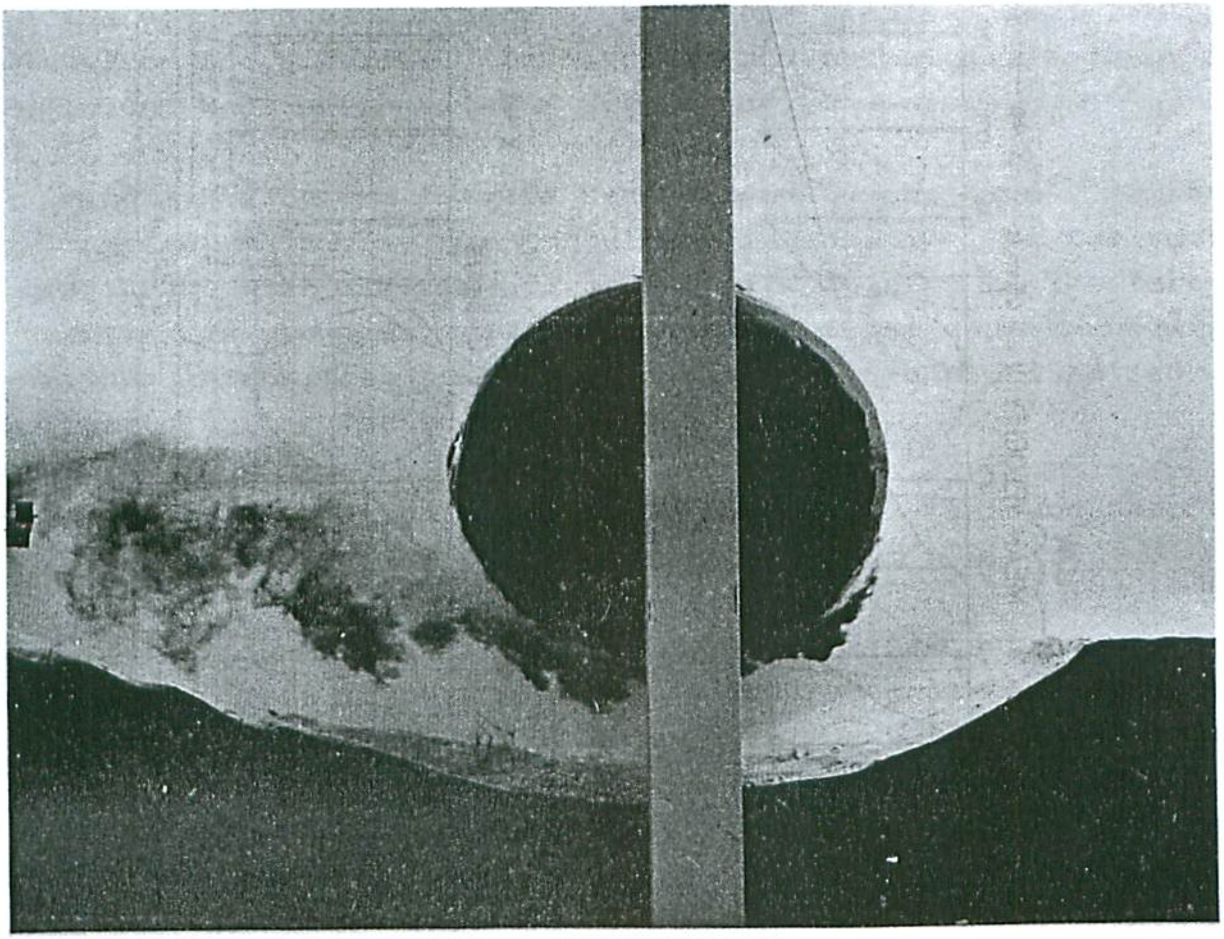

Fig. 9. Flow Picture and Scour Development for Pipeline initially resting on the Bottom. (D = 0.50 m, V = 0.25 m/s).

The picture is taken after a stable situation has occured, using coloured dye for visualisation.

A large number of flow velocity measurements were undertaken during the tests. The purpose was partly to ensure that a uniform flow profile in the flume was obtained, and partly to track the flow pattern near to the pipelines. Most of the flow velocity measurements were performed by using a new ultrasonic flow-meter. The flow velocity measurements were not performed before the scour profile at pipeline no. 4 approcimately had reached equlibrium. The obtained flow velocity profiles from one of the measuring series are shown in Fig. 10. Here the mean flow velocity is V = 0.45 m/s, the pipe diameter D = 0.50 m and the water depth h = 1.43 m.

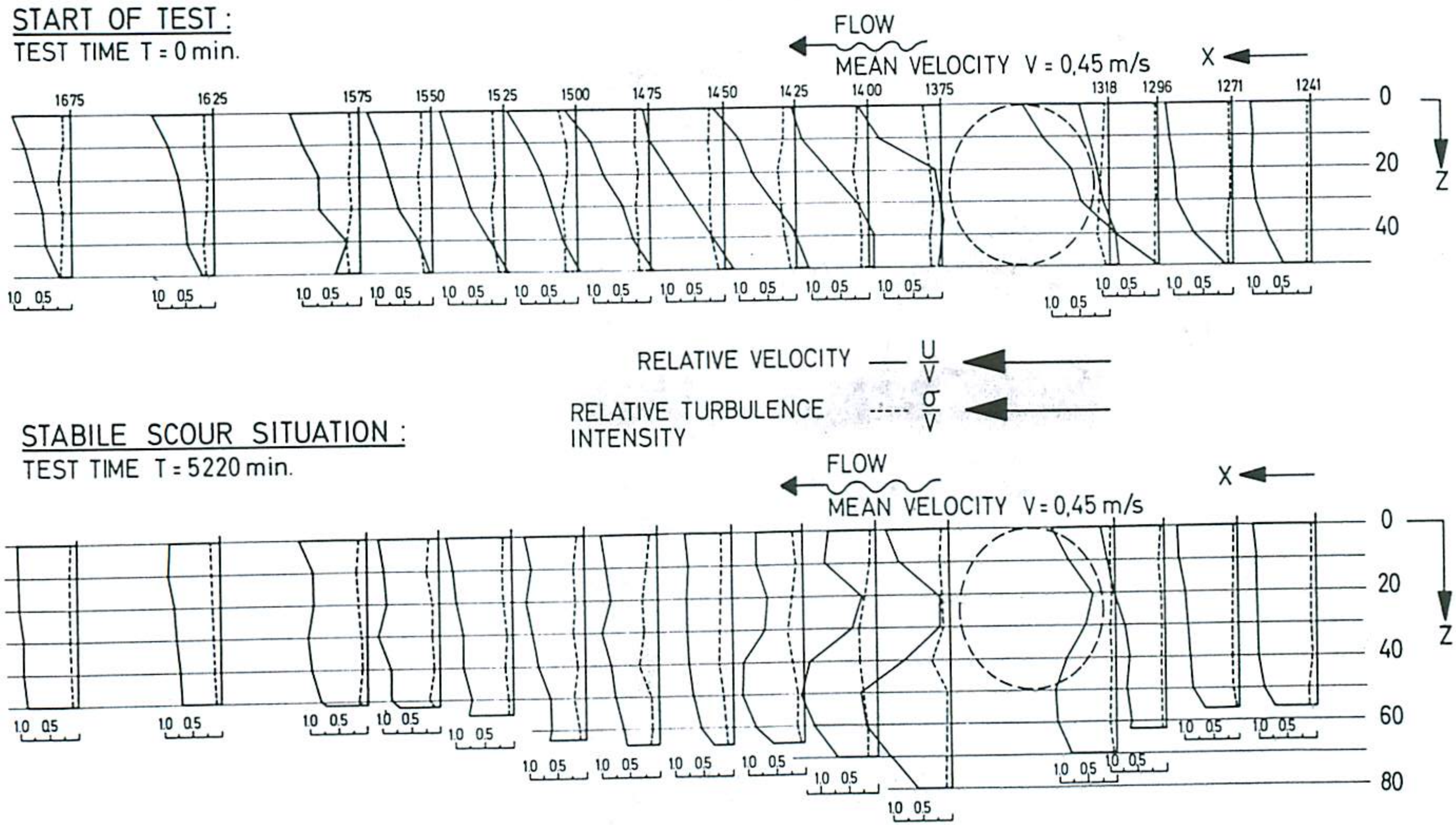

FIG. 10 RELATIVE VELOCITY AND TURBULENCE INTENSITY PROFILES.

The flow velocity merasurements showed that the flow velocity profiles were nearly uniform at a certain distance upstream from the pipelines. Further, the disturbing effect can be seen. This is particularly the case for pipeline no. 4, when the flow is separated from the bottom at a distance of about one pipeline diameter upstream from the pipeline. Downstream from the pipeline there is a turbulent wake which extends five to six diameters.

The velocity measurements were recorded on a tape, and a digital sampling from this gave the turbulence intensities, as the root mean square of the veloctiy fluctuations. In Fig. 10 the turbulence intensities is shown as well. It seems that the zone for maximum turbulence intensities just ahead and behind the pipeline is transferred during the scour action.

At the start of the test the maximum turbulence is found near the top of the pipeline just downstream.

In the established situation the flow picture is changed, and the maximum turbulence intensity seems to occur downstream of the lower part of the pipeline.

This is in accordance with what could be expected.

At the start of the test, separation of eddies from the pipeline will occur form the upper part, during the test separation will occur from the upper part and the lower part as well, and in the established situation the strong flow under the pipe will cause the eddy separation to dominate near the lower part of the pipeline.

From the logaritmic velocity profiles obtained an effective velocity is calculated for each test situation as follows:

$$V_{eff}^{2} = \frac{1}{D} \int_{o}^{D} u(z)^{2}\, dz \qquad (4)$$

and this is used in reduction of data for drag and lift coefficients.

Here D is the pipe diameter, u is the horizontal velocity and z a vertical coordiante measured from the bottom. The use of equation (4) is similar to the work of JONES (13).

3.4. Measurements of drag and lift coeeficients

The pressure profile around the pipeline was measured with a water manometer.

Twelve probes from the surface of the pipeline and one probe from still water level was mounted on the manometer.

From this, forces on the pipelines in different scour situations could be evaluated.

The measurements were only taken as a guide. From the data, lift and drag coefficients could be evaluated.

The data showed some scatter and were very dependent on the distance from the pipeline to the bottom of the scour pit. Therefore in Fig. 11 only lift and drag coefficients are presented when the situation was nearly stabilized.

The figure shows lift and drag coefficients as function of Reynolds number based on effective velocities. If y is the scour depth measured from the bottom of the pipeline, and D is the pipe diameter, the ratio y/D varies from 0.35 to 0.79.

This ratio is shown marked on the figure for each point.

The data show, that when the underflow under the pipe is very strong, the lift is negative, which is in accordance with (14).

4. ANALYSIS OF SCOUR DATA

As mentioned in Section 1, earlier model laws evaluated for different situations were studied, and some calculations were done trying to estimate scour depths by modifying these laws in different ways.

For the pipe, initially resting on the bottom no correlations were obvious and therefore following COLEMAN (5), a dimensional analysis was carried out.

The equlibrium depth of scour is expected to be a function of the

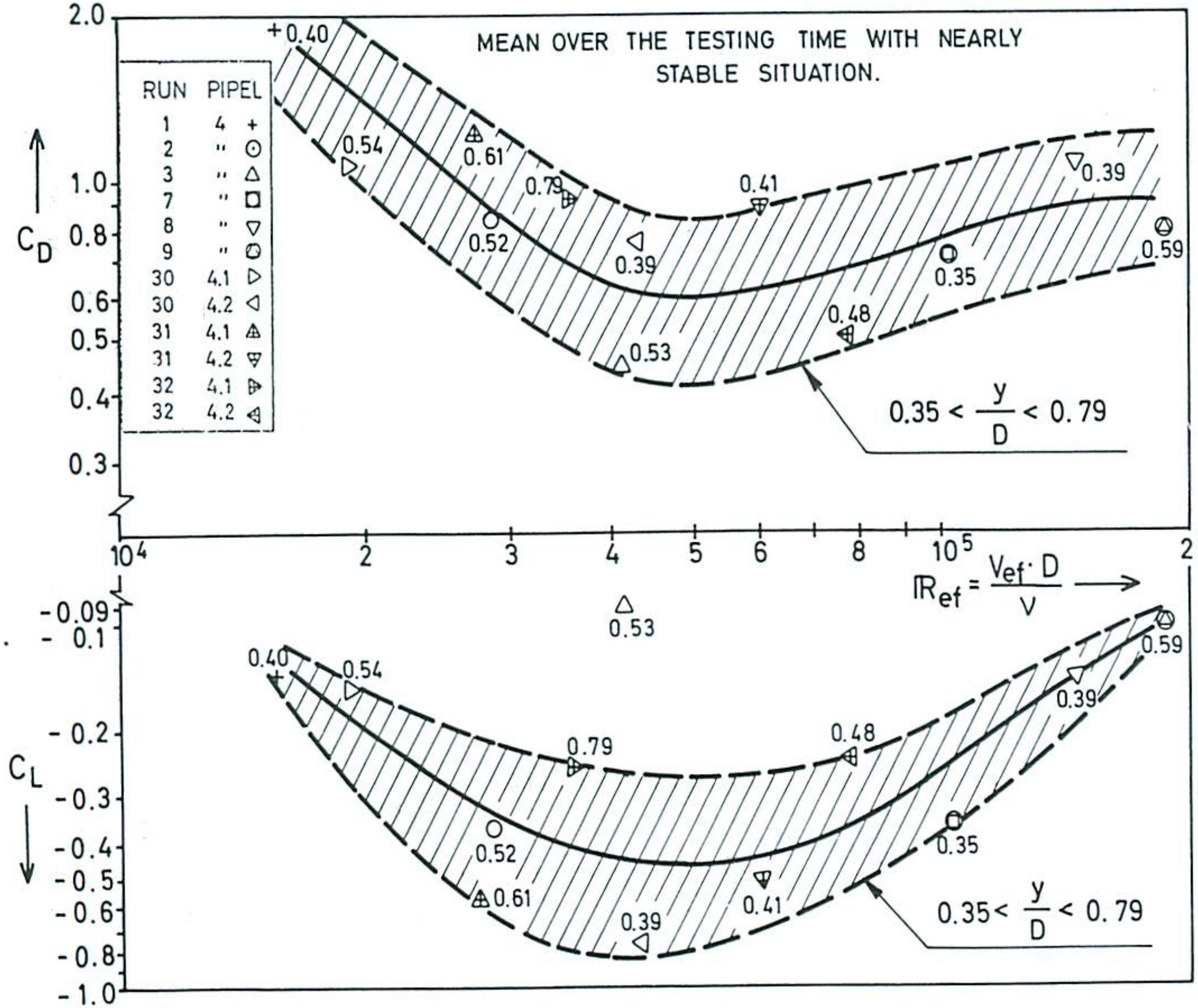

FIG. 11. LIFT AND DRAG COEFFICIENTS AS FUNCTIONS OF REYNOLD'S NUMBER BASED ON EFFECTIVE VELOCITY.

following variables:

$$y = f(V, D, h, d_{50}, \rho, g, \mu) \tag{2}$$

Here
- y - scour depth measured from bottom of pipeline
- V - mean flow velocity
- D - diameter of pipe
- h - water depth
- d_{50} - mean grain diameter obtained in sieve analysis
- ρ - density of water
- g - gravity acceleration
- μ - fluid viscosity

Here, instead of a dimensionless number describing the ratio between a scour depth and a characteristic length, an Euler number is used, describing the head loss around an immersed body. Using Bernoulli the head loss can be described by a scour overpressure $\Delta p = 2\ \rho g y$.

If Δp is taken on the left side in equation (2) the Buckingham π-theorem can be used, and this gives that all relations between the eight variables in eq. (2) in 3-dimensions can be described as relations between the 5 following dimensionless numbers:

$$\mathbb{E} = g(\mathbb{R}, \mathbb{F}, H_1, \beta) \tag{3}$$

Here

$\mathbb{E} = \dfrac{V}{\sqrt{2gy}}$ is the scour Euler number

$\mathbb{R} = \dfrac{\rho V D}{\mu}$ is the Reynolds number for the pipeline

$\mathbb{F} = \dfrac{V}{\sqrt{gD}}$ is the Froude number for the pipeline

$H_1 = \dfrac{h}{D}$ is the dimensionless approach depth

$\beta = \dfrac{d_{50}}{D}$ is the dimensionless material size

If $\mathbb{E}$ is plotted as a function of one of the variables in equation

(3), a set of curves is expected for the variation of each of the other variables.

Fig. 12 gives an example of this, where the Euler number is plotted as a function of the Reynolds number for the pipelines. In the plot 15 tests are included with scour depth for a pipeline initially resting on bottom. Here it is seen that for each value of β a curve is obtained. A regression analysis indicates a line for each set of data points, more points are needed to fix the curves.

Fig. 13 gives a presentation of the scour Euler number plotted as a function of the Froude number for the pipeline.

Here it is seen that all points from the 15 tests in the two flumes correlate with a correlation coefficient 0.97.

This relation can be expressed as:

$$\mathbb{E} = 0.767 \cdot \mathbb{F}^{0.80} \qquad (4)$$

Solving equation (4) with y as the dependent variable gives

$$y = 0.972 \left(\frac{V^2}{2g}\right)^{0.20} \cdot D^{0.80} \qquad (5)$$

The main result of the performed tests is that equilibrium scour depths for pipelines initially resting on the bottom can be expressed by equation (5).

The scour depth depends mainly on the pipe geometry, but a weak influence of flow velocity can be seen. No influence from the parameters H_1 and β is observed on fig. 13.

5. CONCLUSION

The scour development and the equilibrium scour depth is dependent first on geometry and to a certain extent on velocity.

The geometry causes turbulence to be generated in local zones, and

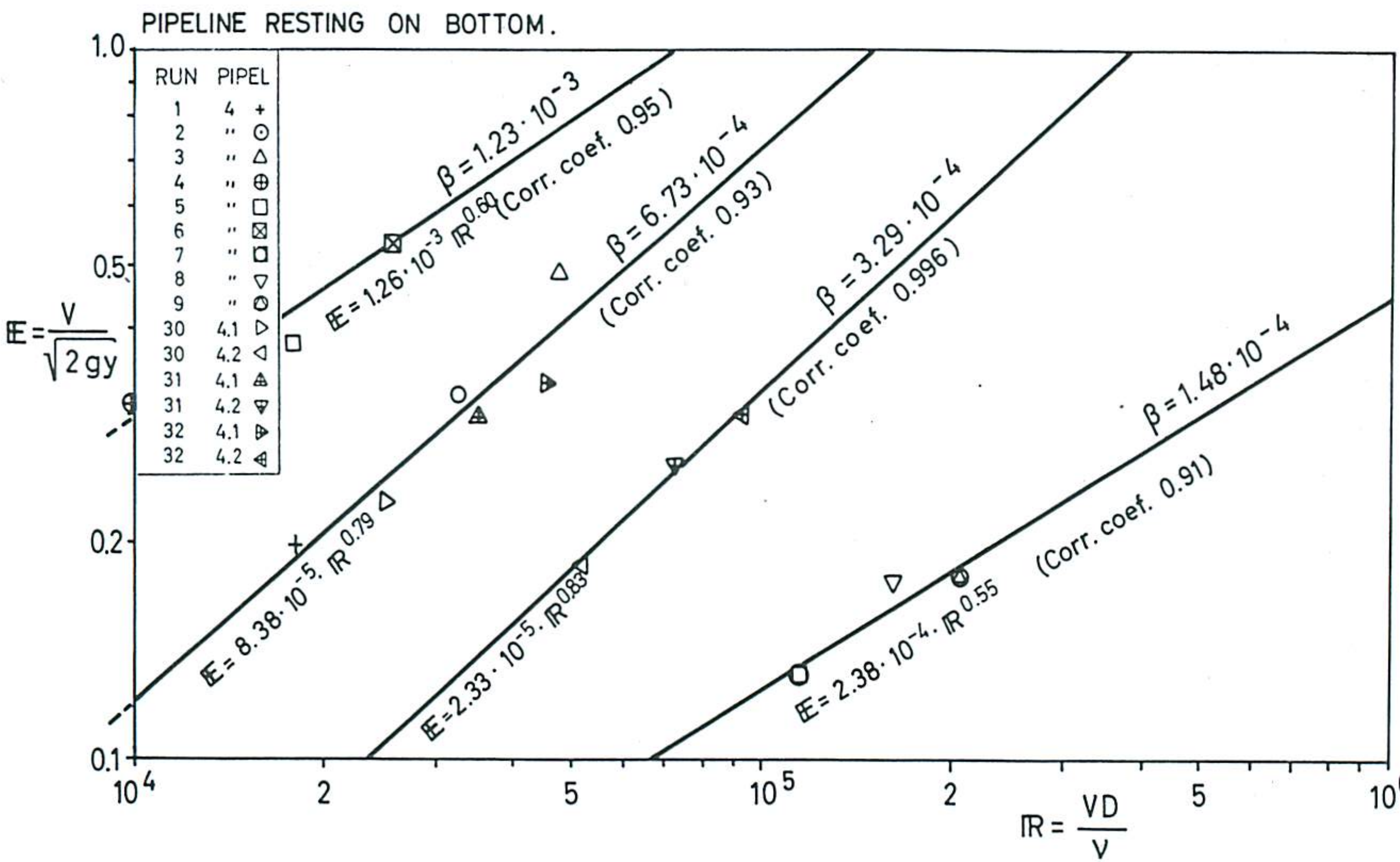

FIG. 12. EULER - REYNOLD RELATIONS.

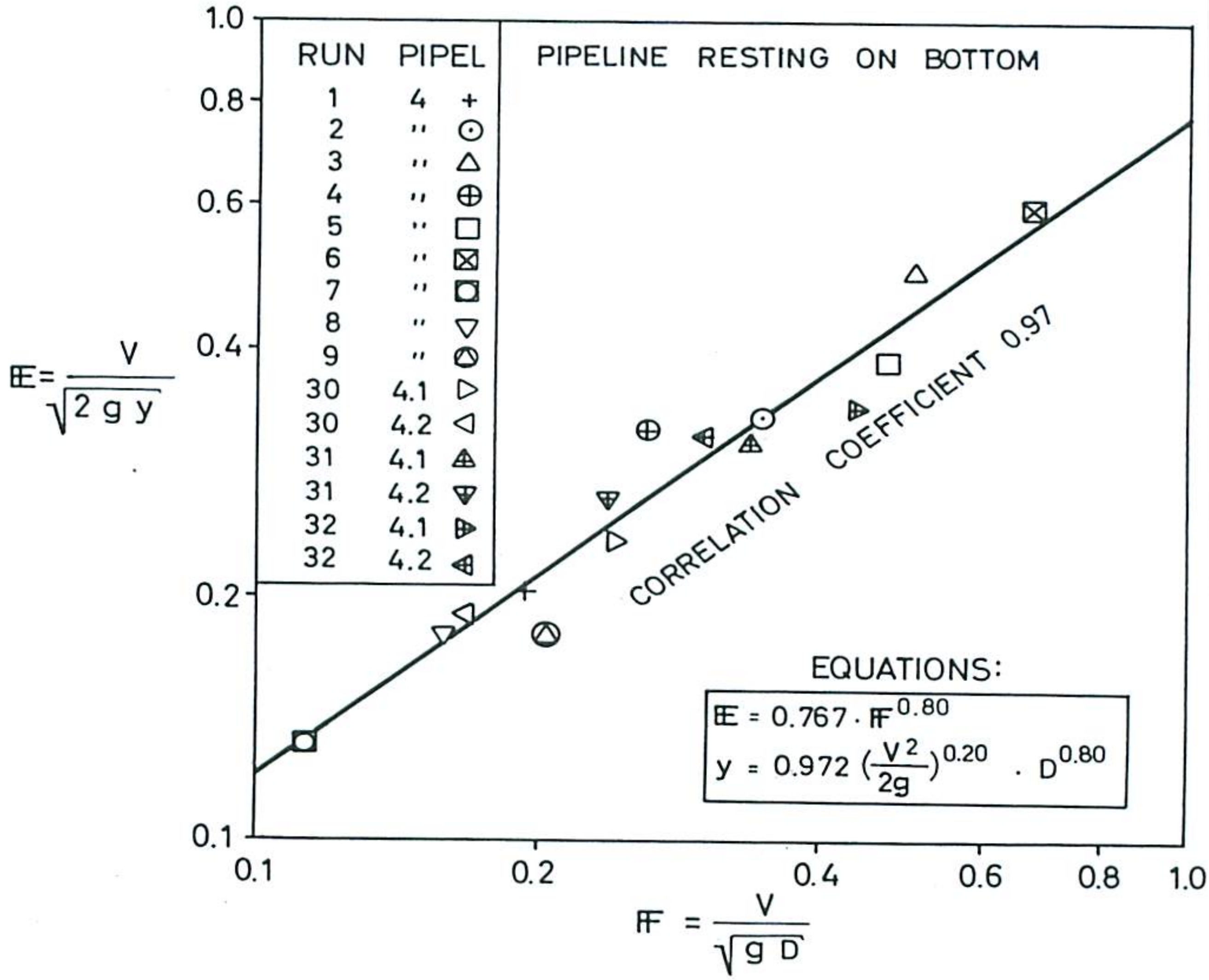

FIG. 13. EULER – FROUDE RELATION

this is responsible for the scour.

The tests were carried out with a mean grain diameter d_{50} = 74 μ typical for some North Sea Materials. Other investigations performed with different types of fine sand have concluded that the grain diameter and the relative water depth are of less importance for the equlibrium scour depth if the relative water depth exceeds a certain critical value.

For practical purposes equation (5) therefore gives a good approximation for equilibrium scour depths under pipelines initially resting on the bottom in a uniform flow.

Further tests will be carried out to study the effect of waves and the combined effect of waves and currents.

6. ACKNOWLEDGEMENT

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