CONFORMITY AND TIME SCALE IN TWO-DIMENSIONAL LOCAL SCOUR

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The conformity of local scour in experiments with non-cohesive bed material is studied for two-dimensional problems. A description of the flow pattern in the scour hole and development of the scouring process with time is given. The importance of the time scale in the design of structures where a temporary exposure of the bed to scouring effects occurs is stressed and some experimental data on this time scale and the conformity between various experiments are given.

1. Introduction

The problem of local scour due to structures has got much attention in the past mostly as a consequence of the occurrence of severe damage. Some obvious examples are given in [1]. The growth of the dimensions and cost of engineering works make it necessary to carry out thorough studies on the extent of scour. For example the total area of the bottom protections necessary for the stability of the works of the Dutch Deltaplan will amount to one thousand acres which stresses the importance of careful investigations.

In many cases an investigation on the equilibrium scour hole is sufficient, especially when the bottom material in nature is coarse. In these cases model investigations are successful if the critical shear stress of the model material is chosen in accordance with the ratio of shear stresses in prototype and model.

When the bottom material is fine however and the time to reach the equilibrium scour depth is very long, knowledge of the time-history of the scouring process is necessary. For such problems model investigations offer possibilities, but do require at the same time an appropriate interpretation of the results based on a correct physical understanding. The existing knowledge of sediment transport in uniform flow might be of value; however this subject in itself has already a complicated character.

The present paper describes the applications of such model investigations and the prediction of prototype scour in cases where a limited scouring time occurs.

2. The Two-Dimensional Scouring Problem

The large amount of empirical knowledge on sediment transport of non-cohesive material in uniform flow justifies a study on the value of the parameters involved in this type of flow. Their relationships may be reduced to a relation between the rate of transport, the sediment characteristics and the bottom shear stress.

This simplification is due to the fact that the bottom shear-stress determines the structure of the turbulent flow for a greater part.

In a scour hole the definition of shear stress is difficult due to the fluctuating character of the flow and *when* an average shear stress is obtained, this value does not govern the average rate of sediment transport. It is necessary therefore to use other quantities which determine the sediment transport. Once a relationship between these quantities and the transport has been obtained a second step is necessary : the determination of these characteristic quantities from the given flow geometry. Some details of the flow pattern in a scour hole are given in para. 3. Generally the flow geometry is so complicated that a theoretical solution is impossible. Only the model experiment can provide the required information with all the difficulties of scale effects and limitations in instrumentation.

To overcome these difficulties it is necessary to predict the scouring directly from the movable-bed model. The action of the turbulent flow on the bed may be studied in a model with a geometrically similar structure in which a movable-bed material replaces the bed material of the prototype. If the material in the prototype is coarse sand or gravel, the choice of the model material is not so difficult. If it is fine sand ($d = 100 - 200\,\mu$), materials with a lower specific weight are required.

For problems in which the development of the scouring process with time is important, as in the case of the enclosure of a tidal channel, the determination of the time scale for scour is essential. It is clear that for a definition of a time scale, which is constant during the process, conformity of the scour hole in model and prototype is necessary :

$$\frac{h(x,t)}{h_0} = f\left(\frac{t}{t_1}, \frac{x}{h_0}\right) \qquad (1)$$

in which h = scouring depth,

h_0 = waterdepth at the end of the bottom protection,

x = distance from the end of the bottom protection,

t = time,

t_1 = a characteristic time of the scouring process.

If the function f is the same for model and prototype the time scale may be defined as the ratio of the values of t_1 in the prototype and in the model. As there are hardly any prototype test cases which may be used for comparative tests, it is necessary to study the validity of (1) by means of scale tests. Subsequently the influence on the time scale by the length scale, the velocity scale and the material characteristics in the model must be derived from these tests. Experimental evidence on the time history of the scouring process and the time scale will be given in para. 4.

3. Flow Patterns

The flow downstream of dams and sluices is nearly always decelerating. From measurements on diffusers [2, 3] it is known that the turbulence intensities are high in the regions with retarding flow due to the formation of layers with large velocity gradients. Also in abrupt expansions regions with large velocity gradients and high turbulence intensities are found. This is shown in fig. 1 where profiles of axial mean velocities and turbulence intensities, measured with a propeller current meter, are given.

After reattachment of the flow an equalisation of mean velocity and turbulence intensity takes place and the final distribution is gradually approached. From this type of measurement an optimal length of a bottom protection may be deduced.

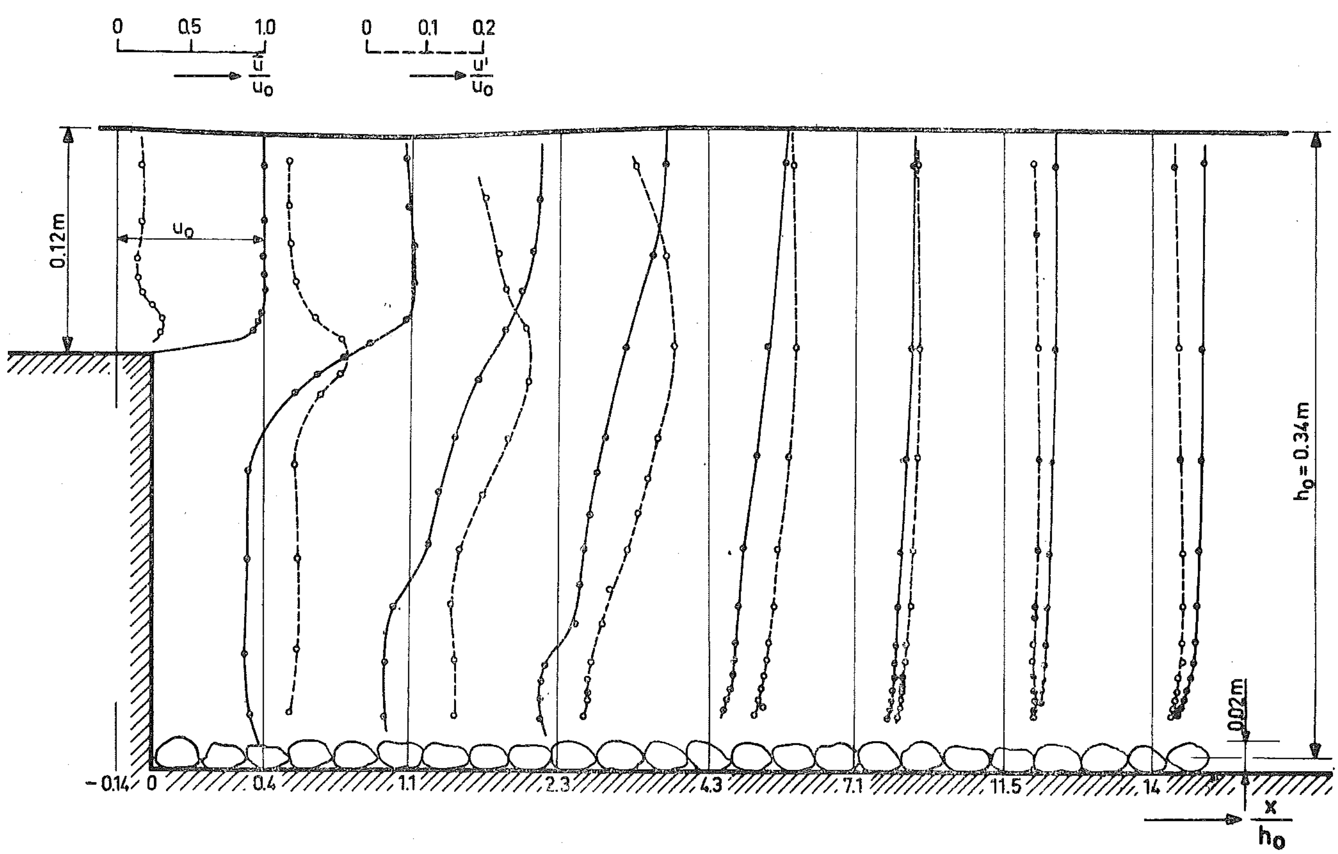

FIG. 1 DISTRIBUTION OF $\bar{U}$ AND U' DOWNSTREAM OF A STEP $U_0 = 0{\cdot}8$ m/sec.

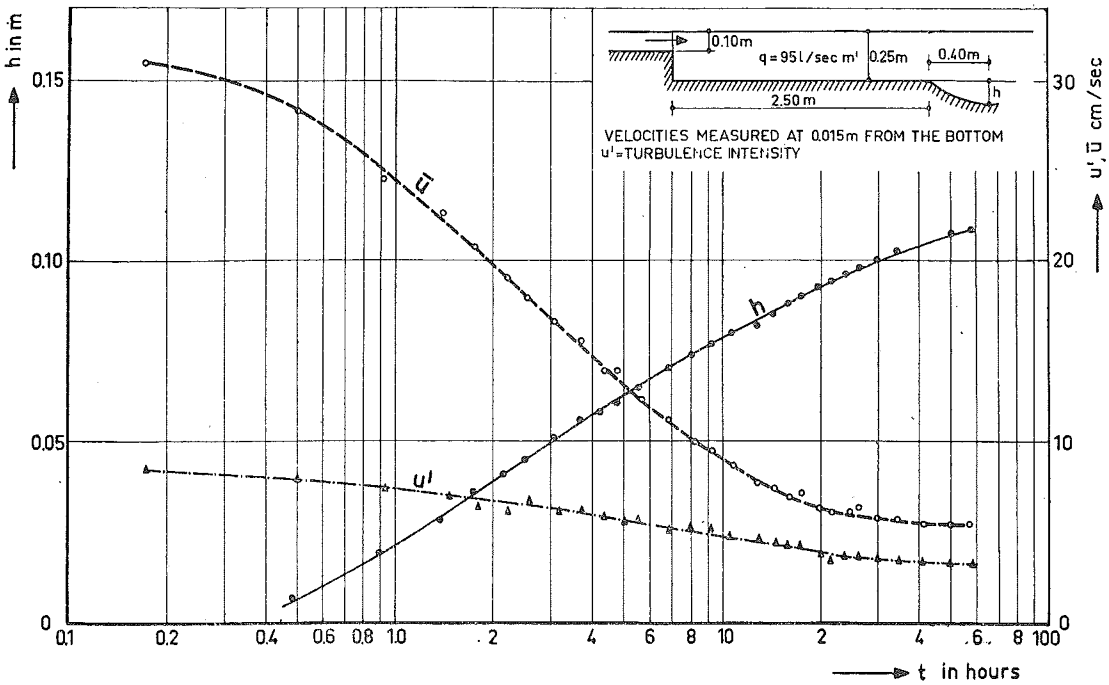

FIG. 2 SCOURING DEPTH AND BOTTOM VELOCITY AS A FUNCTION OF TIME

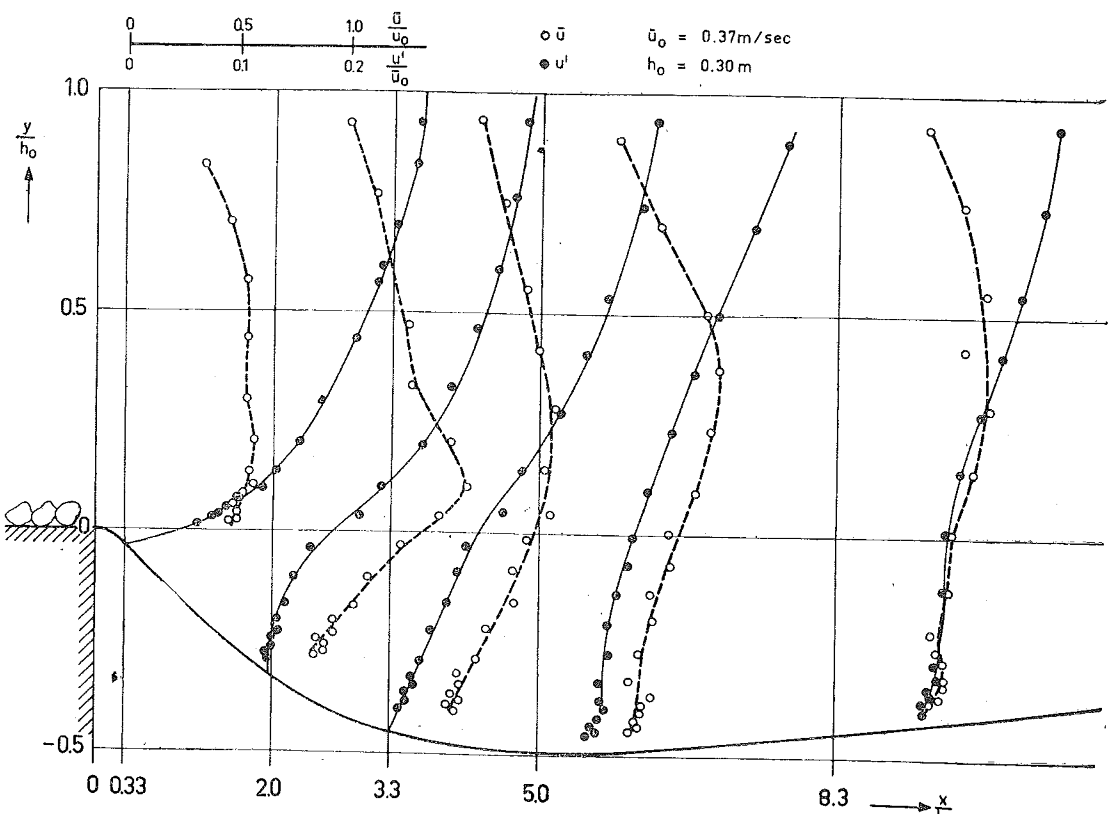

FIG. 3 VELOCITY AND TURBULENCE INTENSITY PROFILES IN THE SCOURING HOLE

Behind the bottom protection a second region with decelerating flow is formed in the scour hole. The mean velocity near the bottom decreases rapidly as the scour depth increases, whereas the turbulence intensity remains more constant (fig. 2). The velocity profiles in the first part of the scour hole (fig. 3) have a form similar to that found in a free mixing layer [4, 5]

The spreading of the flow is a function of the velocity profile at the end of the bottom protection. A more flat velocity profile gives a larger spreading angle and consequently a steeper slope at the upstream side of the scouring hole.

From observations on the scouring process it is clear that especially eddies with large dimensions and low frequencies are important. Because viscosity has nearly no influence on these eddies a reasonable similarity between the important parts of the turbulence structure in model and prototype may be expected.

4. Description of the Scouring Process

Observations on the scouring process must be obtained from model experiments, due to the inaccuracy and scarcity of prototype measurements. For a detailed description many laboratory experiments have been performed with variation of velocity, water depth, material and flow geometry. An example is given in fig. 4 where the scouring downstream of a rough bottom at a waterdepth h_0 is given. Generally the scouring depth h, at a point a distance x from the end of the bottom protection, increases as

$$h/h_0 = A(x) \ln (t/t_0(x)) . \qquad (2)$$

At small values of x/h_0 an equilibrium scour depth is reached after certain time. From the observations it appeared that both $A(x)$ and $t_0(x)$ increased exponentially with x [6]. From this fact and (2) it may be deduced that the *maximum* scour depth h_{max} also increases exponentially with time.

$$h_{max} / h_0 = (t / t_1)^{\alpha} . \qquad (3)$$

This relationship is in accordance with the experiments for a wide range of velocities, water depth and materials as appears from fig. 5. If similarity in the geometry of the scour hole is obtained, the time t_1 may be considered as determinative of the whole process. In general this is true for every fixed ratio of t/t_1 (fig. 6). From these experimental results it is clear that deviation from the condition, that the ratio τ/τ_{crit} be equal for model and prototype, is possible. If similarity in the form of the scour hole is accepted as being sufficient, the value of t_1 may be used to compare different tests with different conditions. The ratio of the t_1-values

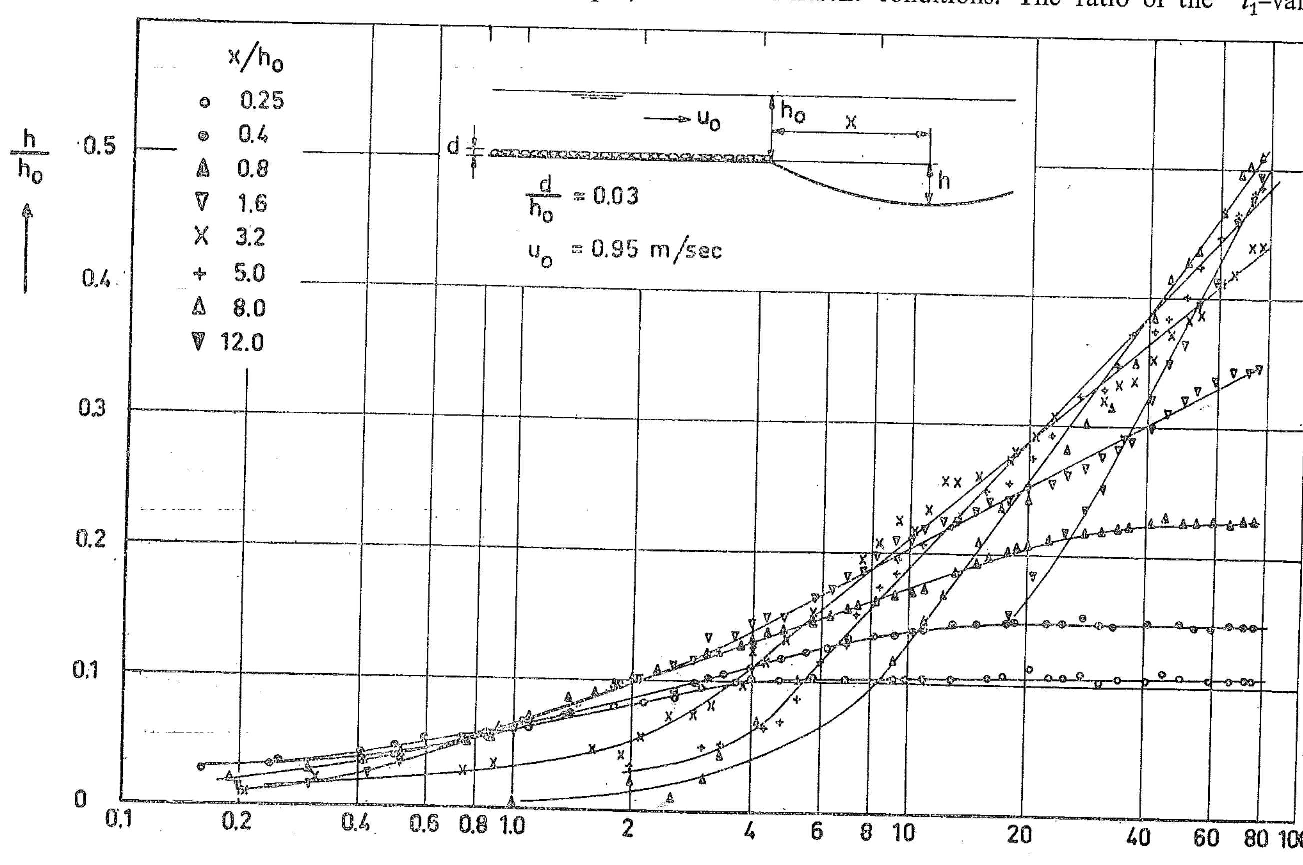

FIG. 4. LOCAL SCOURING DEPTH AS A FUNCTION OF TIME

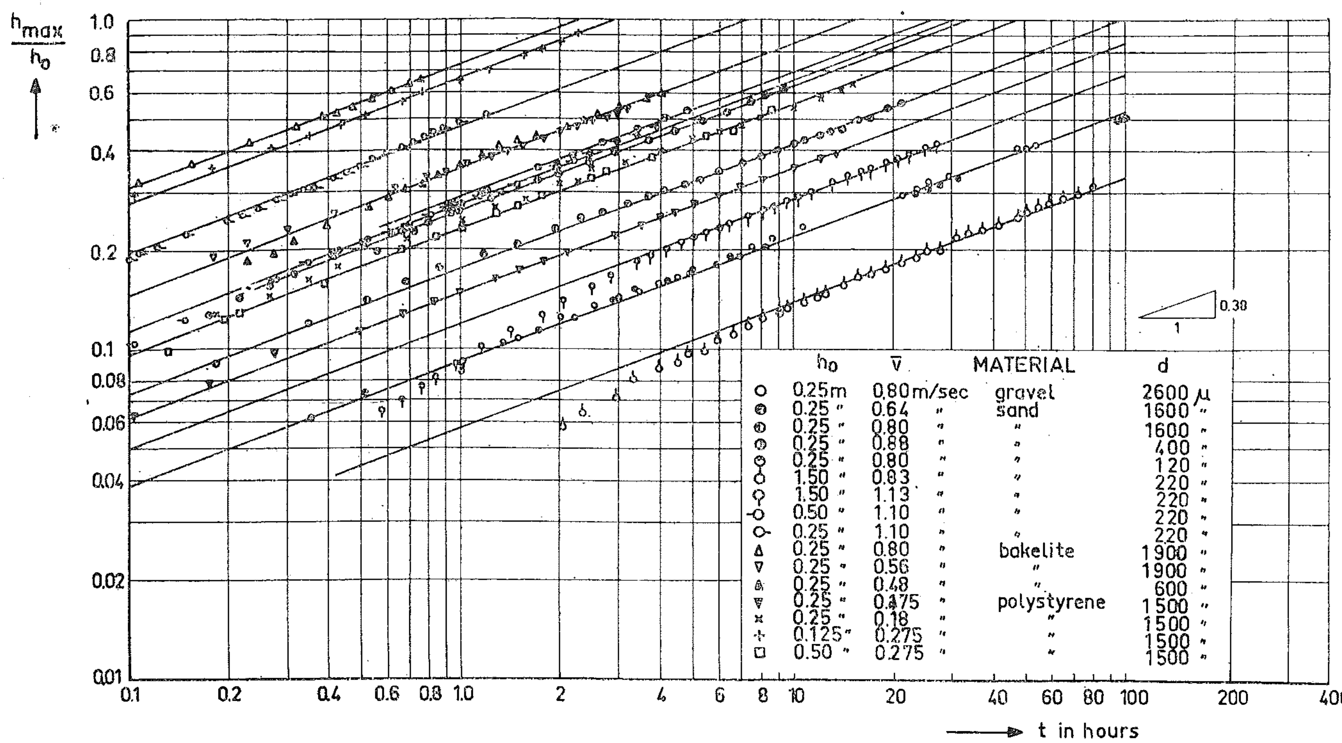

FIG. 5 h_{max} AS A FUNCTION OF TIME SCOURING DOWNSTREAM OF A ROUGH BOTTOM

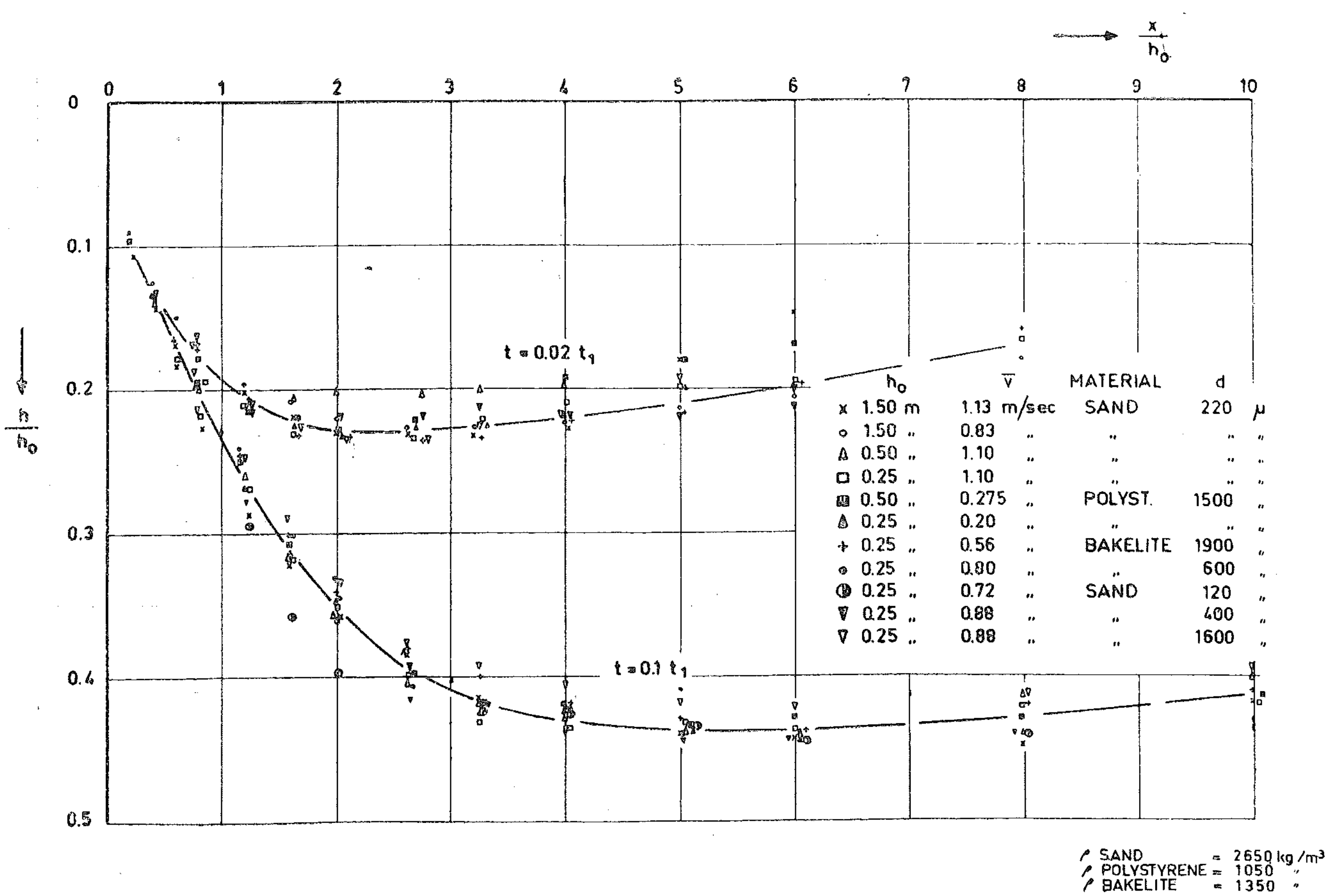

FIG.6. COMPARISON OF SCOUR PROFILES

of two tests may be taken as the time scale of the tests. The influence of the various parameters on the time scale will be discussed in the next para.

Besides the maximum scour depth, the slope at the upstream end of the scouring hole is important for the stability of the structure and the bottom protection. Observations show that the equlibrium of this slope is a dynamic one, achieved by equalization of the material transport governed by the back-flow currents and the rate of suspension of the bed material.

The fall velocity of the material is important as shown in fig. 7 where the equilibrium upstream slope is given as a function of the ratio of mean upstream velocity and fall velocity of the material. If this ratio is taken equal, similarity in model and prototype may be expected. With more turbulent upstream conditions, much steeper slopes were found.

The variations in the slope at the downstream end of the scour hole are rather large because the increase in transport capacity with velocity is different for the first part of the scouring hole and the part downstream of the point with the maximum depth (fig. 6).

5. The Time Scale

The possibility of a description of the time scale n_t over a wide range of conditions was demonstrated in para. 4. The influence of the various parameters on the time scale might be derived from theoretical considerations but depends on the accepted physical relationships. The influence of the lengthscale n_h on the time scale n_t, obtained by assuming that the transport consists of bottom transport only, will be

$$n_t \therefore n_h^2 \qquad (4)$$

which follows from the equation of continuity

$$\frac{\partial h}{\partial t} = \frac{\partial T}{\partial X} \quad \text{and} \quad n_x = n_h.$$

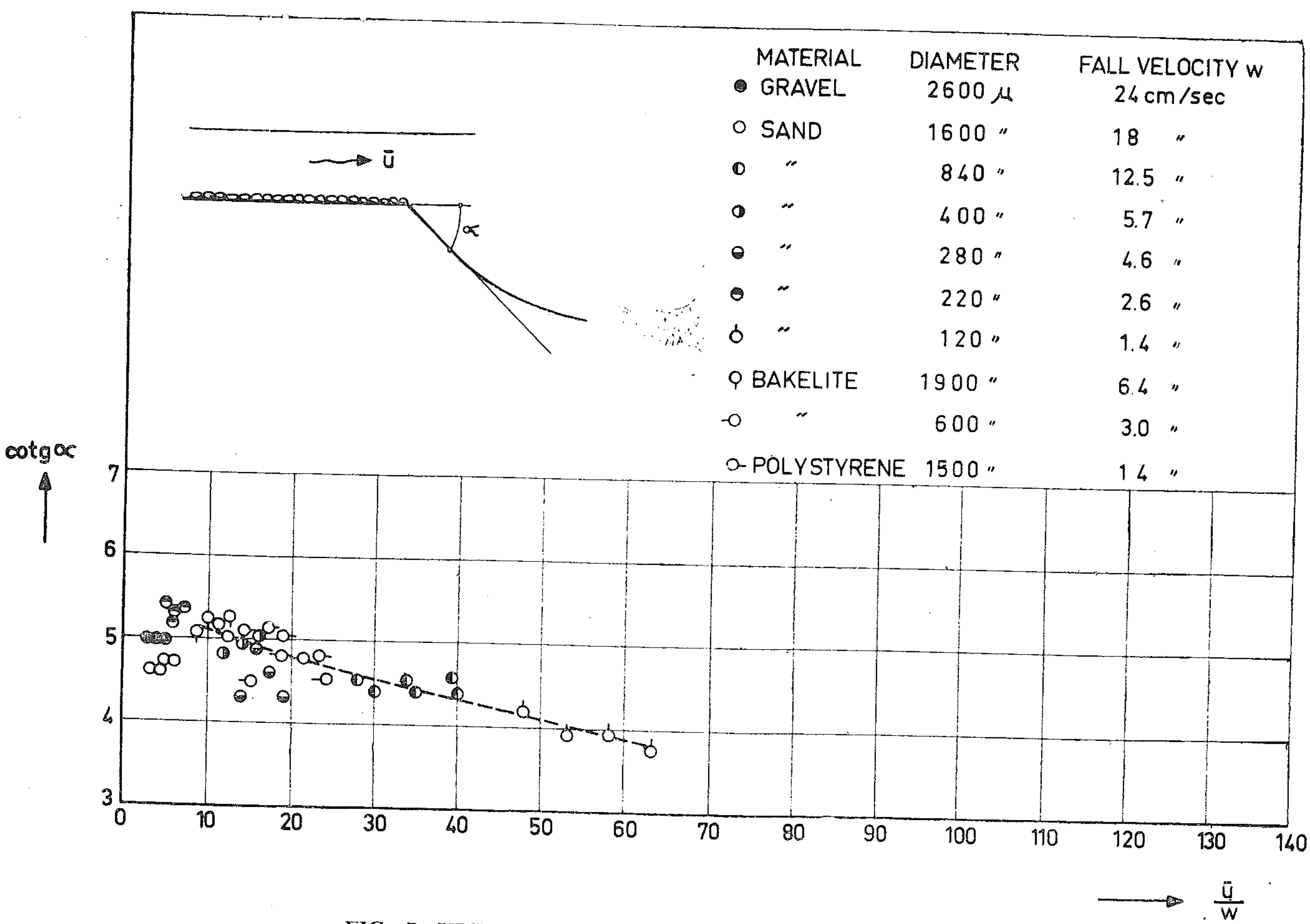

FIG. 7 UPSTREAM SLOPE OF THE SCOURING HOLE

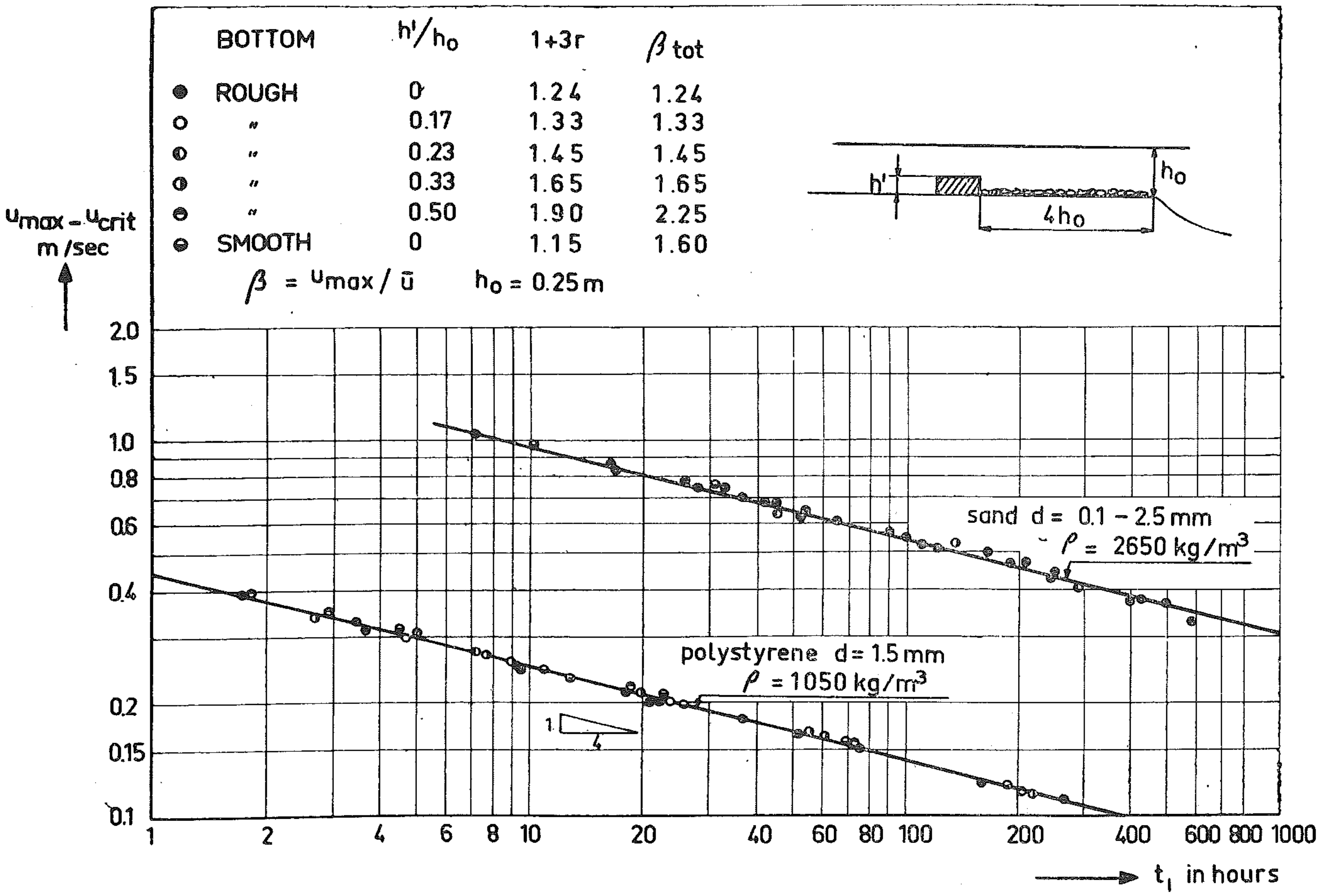

FIG. 8 RELATIONSHIP $t_1 - (U_{max} - U_{crit})$

If on the other hand it is assumed that all material goes directly into suspension it follows that

$$\frac{\partial h}{\partial t} = f\,(T_{local}) \quad \text{and} \quad n_t \;\therefore\; n_h. \qquad (5)$$

The influence of the velocity and material characteristics may be derived from experiments on sediment transport. The divergence between different formulas however makes it necessary to rely fully on comparative experiments. From these experiments it was found that the influence of the length scale was very near to the relation (4). The influence of the mean velocity and the material diameter could be represented by the relation

$$t_1 \;\therefore\; (U_{max} - U_{crit})^{-4} \qquad (6)$$

in which $U_{max} = (1 + 3r).\bar{U}$ and U_{crit} is the critical mean velocity computed from the critical shear-velocity as given by Shields. r is the mean relative turbulence intensity at the end of the bottom protection. The relationship (6) is shown in fig. 8 for some tests. The factor $(1 + 3r)$ was determined from the experiments.

The influence of the material diameter on the critical velocity was sufficient to take into account the influence of the grain diameter on the time scale. The material density is very important (fig. 8) and makes the use of materials with a low specific weight advantageous because a large time scale may be achieved.

The relation $U_{max} = (1 + 3r)$ is only valid for fully developed velocity profiles over a rough horizontal bottom. For a smooth bottom and distorted velocity profiles, the influence of this profile must be represented by a separate factor in the computation of U_{max}. This factor may be as high as 1·5. Further experiments are necessary to obtain the influence of all parameters, but a solution seems to be possible.

6. Conclusions

From the considerations given, the following conclusions may be drawn :

1. The flow pattern and the material transport in the scour hole are too complicated to give a prediction of the scouring process based on a mere theoretical consideration.

2. From model experiments it was derived that conformity of the scouring hole is possible even if the ratio τ/τ_{crit} is not the same in the experiments.

3. The use of comparative scale tests and the determination of the time scale of the scouring may provide a solution especially if the time factor is important in the practical problem.

4. The time scale depends on the length scale, the velocity scale, the material density and the flow geometry. The grain diameter of the material is not very important except for conditions near the beginning of movement.

Symbols

h = scouring depth

h_{max} = maximum scouring depth

h_o = water depth at the end of the bottom protection

n_t = time scale of the scouring

n_h = length and height scale of the model

r = average relative turbulence intensity at $x = 0$

t = time

t_1 = characteristic time as defined by (3)

T = rate of bottom transport

$\overline{U}$ = mean velocity at $x = 0$

U_{crit} = critical mean velocity of the bottom material

x = distance from the downstream end of the bottom protection

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