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MODEL-PROTOTYPE*) CONFORMITY OF LOCAL SCOUR IN NON-COHESIVE SEDIMENTS BENEATH OVERFLOW-DAM

(Subject D.a.)

by

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Synopsis

The model-prototype conformity of local scour in experiments with non-cohesive bed material is studied for a case of an overflow-dam. A brief description of the time-scale and the relationship between the time and the scour depth established through previous systematic model investigation is given. Recently this relationship and the conformity of the scour holes were verified by means of prototype investigation. The evolution of scour in the time both in model and prototype are presented. Also some considerations are given as to the practical application of the results.

Resumé

La similitude des essais d'affouillements locaux dans les matériaux non cohésifs est étudiée pour le cas d'un déversoir. On donne une brève description de l'échelle des temps et de la relation entre le temps et la profondeur de la fosse telle qu'elle a été établie lors de recherches systématiques antérieures. Cette relation et la similitude des fosses d'affouillement ont été vérifiées récemment par un essai en grandeur nature. L'évolution de l'affouillement dans le temps, tant dans le modèle qu'en nature, est présentée. Quelques remarques sont également faites quant aux applications pratiques des résultats.

*) prototype = nature

1. Introduction

The prediction of local scour plays an important role in the design of hydraulic structures. This problem was, and still is, of great importance for the closure of the final gaps of the tidal sea-arms of the "Delta plan" in the Netherlands. The problem of the local scour is commonly solved by means of model investigations. However, for the translation of the model results to prototype, the proper knowledge of the time-scale is needed. For this reason, a systematic investigation on the time-scale for two- and three-dimensional local scour in loose sediments has been conducted in the last years by the Delft Hydraulics Laboratory and the Delta-Department, [1]. From the model experiments on different scales and various bed materials, relationships have been derived between time-scale and scales for velocity, water depth and material density. The final relationship allows the translation of the time-scour depth evolution from model into prototype. Until now, this relationship could not be properly verified in the prototype, because the prototype conditions during the previous closures were mostly not exactly the same as in the respective model investigations. The main problem was always the unsufficient knowledge of the hydraulic conditions, especially the discharge and the velocity distribution.
In the case of the closing of the Eastern Schelde in the "Delta plan", by means of a storm surge barrier, which will be kept closed only during a storm surge, the reliable prediction of the future scour depths is of great importance for the stability of the construction. Therefore it was decided to perform a special prototype test so that a more exact verification of the time-scour depth relationship was made possible. The existing sluice in one of the barrier-dams was adapted for this experiment. The same geometry was simultaneously tested in a model (scale 1 : 30).
The present paper describes the results of both investigations. Additionally some practical applications of these results, especially for the case of the prediction of the local scour beneath an overflow-dam, are discussed.

2. Time-scale

From the two- and three-dimensional systematic model investigation, it has been deduced that the maximum scour-depth h_{max} increases exponentially with time:

$$\frac{h_{max}}{h_o} = \left(\frac{t}{t_1}\right)^p \qquad (1)$$

in which: h_{max} = maximum scour depth in m, h_o = original water depth at the end of the bottom protection in m, t = time in hours, t_1 = time in hours at the moment $h_{max} = h_o$, p = exponent.
The exponent "p" is nearly constant and equal to about 0.4 for two-dimensional flow conditions; the value of "p" for three-dimensional conditions depends on the geometry of the construction (i.e. degree of turbulence) and has to be determined experimentally for each geometry.
The dependence of the characteristic scouring time t_1 on the conditions of flow etc. or in other words the relationship between the time-scale on the one side and the velocity-scale, material-scale, length-scale and geometric situation on the other side, have been investigated. It could be finally concluded that the influence of the various factors on the rate of the scouring process can be described by the same general relationship both for two- and three-dimensional local scour:

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1. MEULEN, T. van der, and VINJÉ, J.J.,
Three-dimensional local scour in non-cohesive sediments,
XVIth Congress IAHR, S. Paulo, 1975, paper B 33.

$$t_1 = \frac{K\,\Delta^{1.7}\,h_o^2}{(\alpha\bar{u} - u_{cr})^{4.3}} \quad \text{(in hours)} \tag{2}$$

in which: α = dimensionless scour factor involving the velocity distribution and the influence of the turbulence intensity due to the geometry of the structure, $\bar{u}$ = mean velocity in m/s = Q/A, Q = discharge in m^3/s, A = wet cross-section at the end of the bottom protection = $(B \cdot h_o)$ in m^2, u_{cr} = critical velocity for initiation of motion in m/s, Δ = relative density of bottom material under water = $(\rho_s - \rho_w)/\rho_w$, K = numerical coefficient.
The value of K was originally determined as equal to 250 (see [1]). A recent evaluation of the previous data concluded that a value of K of about 330 is more appropriate.
Relation (2) can also be adapted for tidal flow by taking into account a succession of an infinite number of short-lasting steady situations.
Relation (2) can be converted in a dimensionless form leading to the following time scale, in which n denotes a scale relation:

$$n_t = n_\Delta^{1.7} \cdot n_h^2 \cdot n_{(\alpha\bar{u} - u_{cr})}^{-4.3} \tag{3}$$

By combining eq. (1) and (2), the following expression of h_{max} can be obtained:

$$h_{max}(t) = \frac{(\alpha\bar{u} - u_{cr})^{1.7} \cdot h_o^{0.2}}{10 \cdot \Delta^{0.7}}\, t^{0.4} \quad \text{(in m)} \tag{4}$$

From relation (4), it is evident that the influence of the water depth on the scour depth is rather negligible. The influence of the bed material is expressed by Δ and u_{cr}. It is also clear that the factor $(\alpha\bar{u} - u_{cr})$ is the dominant one in the scouring process. This factor represents mainly the influence of the flow velocity ($\bar{u}$) and the geometry of the construction (α). It has to be mentioned that relations (2) and (4) are only applicable for situations where maximum (equilibrium) scour is still not reached.
The problem of calculation of the time needed to reach an equilibrium stage is beyond the scope of this paper.

Besides the maximum scour depth, the slope at the upstream end of the scour hole (β) is important for the stability of the bottom protection. When this slope exceeds a certain critical value in non-cohesive sediments, a slide can occur and even liquefaction of the soil under the bottom protection may be possible.
From the systematic model investigation, it can be deduced that:

$$\text{cotg}\,\beta = 5.5\,\frac{w}{d}\left(\frac{\nu}{\Delta^2 g^2}\right)^{1/3}\left(2.5 + \frac{0.75}{\alpha - 1.32}\right) \tag{5}$$

in which: β = upstream slope of scour hole in radians, w = fall velocity of bottom material in m/s, d = mean diameter bottom material in m, ν = kinematic viscosity of water in m^2/s, g = acceleration of gravity in m/s^2.
From relation (5) it appears in particular that the values of "α" and w/d are of importance for the development of the upstream slope of the scour hole.
Relation (5) can be converted in a dimensionless form:

$$n_{\text{cotg}\,\beta} = n_w \cdot n_d^{-1} \cdot n_\Delta^{-2/3} \tag{6}$$

From relation (6), it can be concluded that the upstream slope cannot be exactly reproduced in a scale model when the bottom material differs from the prototype, which is mostly the case.

3. Prototype

3.1 General

The existing discharge-sluice in the barrier-dam (Brouwersdam) between the North Sea and the Grevelingen-lake (closed sea-arm) was chosen for the prototype test. Because of environmental requirements, the use of this sluice was restricted to about 3 months (Dec., Jan., Febr. '79/'80). To obtain a sufficient scour in such a short time, it was necessary to change the outlet-construction of the sluice. The type and the geometry of the new outlet-construction was determined by means of prior model investigation. The chosen construction consisted of a sill 5.4 m hight (= a half water depth) with two side constrictions equal to 2.5 m on the left side and 1.5 m on the right side. The length of the bottom protection from the centerline of the sill was equal to 65 m (about 10 x dam height from the toe of the dam). The water depth above the bed protection was equal to about 10.8 m. The other dimensions of the outlet-construction are presented in Fig. 1. The soil characteristics were measured beforehand. The diameter of the bed material varied with the depth from $d_{50\%} = 0.2\ 10^{-3}$ m to $0.3\ 10^{-3}$ m. Some thin clay-lenses on different levels were present, especially in the upper soil-layer between 2 and 4 meters below the original bottom.
The thickest clay-layer of about 0.2 m was situated at about 3.5 m below the bottom. The other clay-lenses were mostly in the range of 0.01 to 0.02 m. It is evident that the present soil structure is not the ideal one for an optimal comparison of the prototype and model results (the model-sediment is homogeneous and non-cohesive).
The main advantage of the choice of this sluice, was that the prototype experiments could be carried out under controlled hydraulic conditions. The discharge (varying between 0 and about 430 m^3/s, for mean tidal conditions on the sea-side) was measured continuously by means of an acoustical discharge meter. The variation of the tidal sea level and the level of the Grevelingen-lake were also measured continuously. The level of the Grevelingen-lake was kept nearly constant at 0.20 m below the mean sea level. The daily variation of this level due to the use of sluice was usually no more than 0.1 m. The sea water was discharged into the lake during the flood and out during the ebb. The last had no influence on the development of the scour, because of the very low velocities above the scour hole while discharging into the sea. The suspended transport from the sea into the lake was also negligible.

During the prior model investigation, the dam height and the length of the side constrictions were varied. On the base of the results of this model investigation the definitive geometry has been chosen for the prototype test (Fig. 1).
From the prior model results, it was predicted that for the chosen outlet-construction and the present soil structure, the maximum scour depth would be about 10 m within 3 months. It was not possible to take into account the retarding effect of the existing clay-layers.
The development of the scour pattern was measured frequently by soundings. The upstream slope of the scour hole was sounded every 5 m, whereas the scour hole itself was sounded every 10 m. The necessary accuracy of the soundings of the upstream slope was difficult to obtain, because of the inaccuracy of positioning of the sounding ship.
The model tests were made at the Delft Hydraulics Laboratory using a special model which reproduced the geometry of the prototype situation on scale 1 : 30. The model test conditions were somewhat different than in prototype because:

- bottom protection in the model was fixed, while in prototype it was a flexible one whose end could settle.
- model bed material was polystyrene with $d_{50} = 0.13\ 10^{-3}$ m, $\Delta = 0.05$, $\rho_s = 1{,}050\ kg/m^3$, $u_{cr} = 0.10$ m/s, while in prototype sand with $d_{50} \approx 0.25\ 10^{-3}$ m, $u_{cr} = 0.49$ m/s,
  The velocity-scale according to Froude is equal to $n_u = n_l^{\frac{1}{2}} = 5.5$.
  Because u_{cr} of the model and prototype bed materials are reproduced nearly in the scale of flow velocity, it can be expected that the reproduction of the scouring process in the model is similar to that in prototype even in conditions approaching the equilibrium state of the scour hole.
- steady flow in the model, while tidal flow in the prototype. This difference is eliminated by integration over a tidal period in the prototype (eq. 7).

3.2 Prototype experiment and results

The experiment started on November 19th, 1979. At that moment, a small scour hole of 2.4 m below the original bottom was already present due to the use of the sluice before the changing of the outlet-structure. The experiment ended on February 29th, 1980. During the experiment 202 flood-periods were available, from which only 141 have been used effectively. During the other flood-periods, the sluice was closed for different reasons: sounding of the scour hole, rising of the lake-level above a certain limit, bad (storm) weather, etc.
A comparison of the flow velocities is given in Fig. 2. The model velocities are vertically averaged, whereas the prototype velocities are measured at 3 m below the water surface. This does not introduce a significant error.
During the first two weeks of the experiment (until 3 December), the development of the scour hole was rather slow. The reason for that was the presence of the clay in the upper soil layer. This effect is clearly shown in Fig. 3, where the time-scour depth relation is presented on a linear scale. By means of extrapolation of the experimental points, where no influence of the clay-layers was present, the fictive starting point of the test was determined i.e. the beginning of the scouring process as it would be in pure sand. This fictive starting point was used for determining the nett experiment time which has been used for comparison of the prototype and model data. When the starting point of the test is thus determined, an error of ± 10 ÷ 20 hrs. can be expected. This inaccuracy makes the comparison of the prototype-model results somewhat difficult, especially at the beginning of the experiment.
The maximum depth of the scour hole achieved in the prototype was 8.8 m. The results at the end of the test were again somewhat influenced by the presence of a very thin clay-lense.

The following time-scour relation was adopted for the described situation with tidal flow towards the lake:

$$t_1 = \frac{330\ \Delta^{1.7}\ h_o^2\ \phi}{\frac{1}{T}\int_o^T (\alpha\,\bar{u}_{(t)} - u_{cr})^{4.3}\ dt} \qquad \text{(in hours)} \qquad (7)$$

where: $\bar{u}_{(t)}$ = average velocity as a function of time, T = tidal period, ϕ = time correction factor (only flood-period was responsible for the scour). The other symbols have already been defined.
The time-scour depth relationships for the prototype and model are presented on log-log scale in Fig. 4. The model data are translated to the prototype conditions. The time-scale is related to the fictive starting point. The representative value of u_{cr} (calculated from Shields) for $d_{50} = 0.25\ 10^{-3}$ m, is 0.49 m/s.

A comparison between the scour holes in model and prototype at the end of the test is given in Fig. 5 and 6. Fig. 4, 5 and 6 show a reasonable reproduction of prototype results in the model as to the time-scour depth relation and the shape of the scour hole. A purely scientific comparison is not possible because of the earlier mentioned restrictions (mainly concerning the non-homogeneous soil structure in the prototype) but it seems that for the practical application, the developed time-scale can be used with sufficient reliability. In respect to the upstream slope, it has to be mentioned that the variation in the slope over the first few meters was rather large; the slope became steeper and steeper until the critical slope of about 1 : 1.5 was reached, then a little slide took place so that a milder slope resulted. After that, the steepening of the slope started again and the whole process was repeated. The average upstream slope at the end of the prototype test was about 1 : 2.
Because of slides, periodic settlements of the end of the (flexible) bottom protection took place in prototype. The bottom protection in the model was fixed and therefore, the slides in the model were more intensive than in prototype and undermining of the bottom protection took place. This makes the comparison of the upstream slopes in model and prototype somewhat difficult.

3.3 Practical applications

Estimation of the value of "α" without model investigation can be very usefull for a first approximation of the scouring process. It must be emphasised, however, that the values given below are coupled to the definition of the flow velocity and the other parameters given with relation (2). Fig. 7 gives the relation between "α" and the dam height D in the case of a 10 h_o long bottom protection. The two-dimensional situation is a somewhat academical case, which can be seen as a lower limit of "α".
The three-dimensional situation is another extreme case which corresponds to a situation with an abutment on one side, creating a strong vortex trail. Most common situations, as spillways and closure dams, will lead to values of "α" situated in the hatched area. Especially in a case with abutments on one or both sides of the stream, it is advisable to consider 25% of the stream on both sides as three-dimensional, while 50% in the middle may be considered as "normal" (hatched area in Fig. 7).
The influence of the length of the bottom protection is described by:

$$\alpha = 1.5 + (1.57\,\alpha_{10} - 2.35)\, e^{-0.045\, L/h_o}, \qquad \text{for } L \geq 5\, h_o \qquad (8)$$

where L = length of bottom protection in m, α_{10} = value of "α" for L = 10 h_o (Fig. 7).
It appears that $\alpha = 1.5$ may be considered as a minimum value.
The above mentioned estimations of "α" may then be used in relations (2), (4) and (5) to make a first approximation of the scouring process by means of relation (1) with p = 0.4, which appears to be a fair approximation in most common cases.

4. Conclusions

- The results of the systematic investigations and the results of the recent model-prototype experiments support the presumption that each geometry of a construction can be properly expressed by a certain value of the scour factor "α". This means that the value of "α" determined through a model investigation can be used in relation (2) for calculating the characteristic prototype scouring time t_1.
- It has been proved by prototype test that there is a reasonable similarity in scour development for model and prototype when using the time-scale relation as has been established through the earlier systematic model investigation.

- The relations (1), (2), (4) and (5) can be used for a rough estimation of the scouring process if the value of "α" is known. If not given by model investigation, the variations of "α" with the dam height and the length of the bottom protection may be estimated by Fig. 7 and relation (8), respectively.

Recently it has been decided to repeat the prototype test during the winter 1980/81 with homogeneous sand (the present scour hole will be filled with pure sand). The results of this test can be used for the scientific verification of the scour laws and eventually for the further improvement of the present method of modelling and calculating the local scour.

5. Relevant literature

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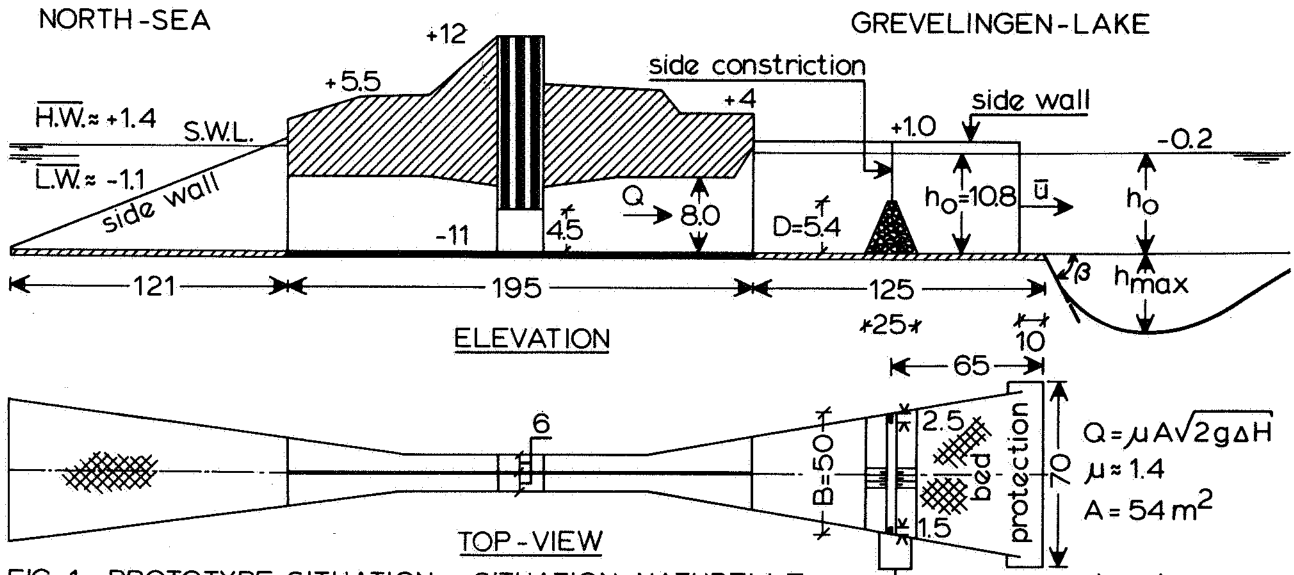

FIG. 1: PROTOTYPE SITUATION - SITUATION NATURELLE

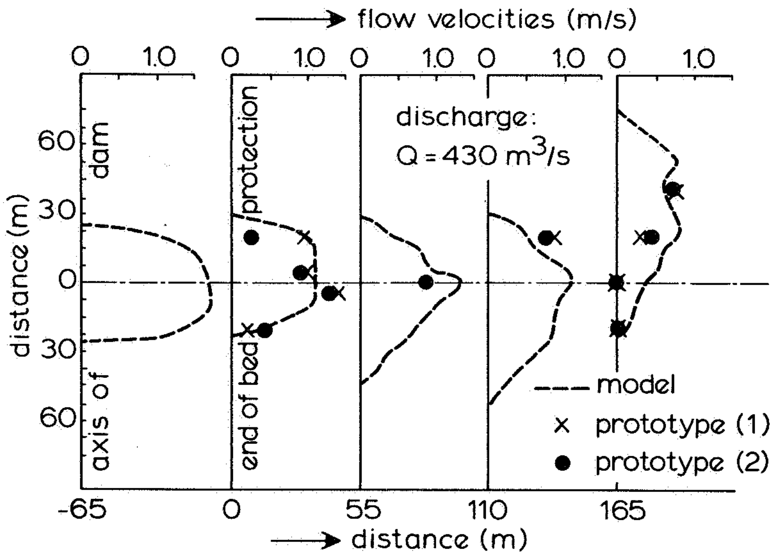

FIG. 2: FLOW VELOCITIES - VITESSES DE COURANT

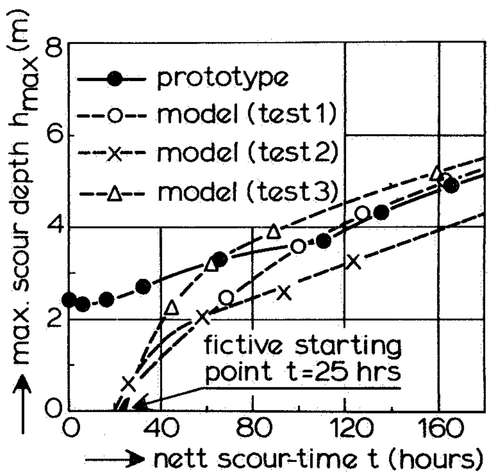

FIG. 3: FIRST PHASE OF SCOUR
PREMIERE PHASE D'AFFOUILLEMENT

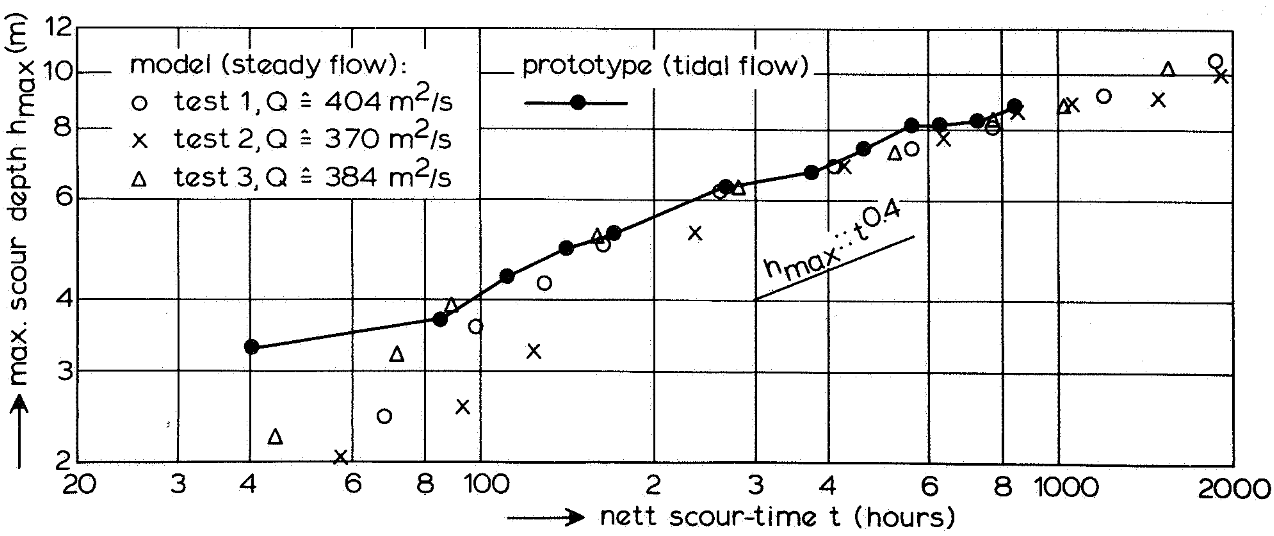

FIG. 4: TIME-SCOUR RELATION - RELATION TEMPS-AFFOUILLEMENT

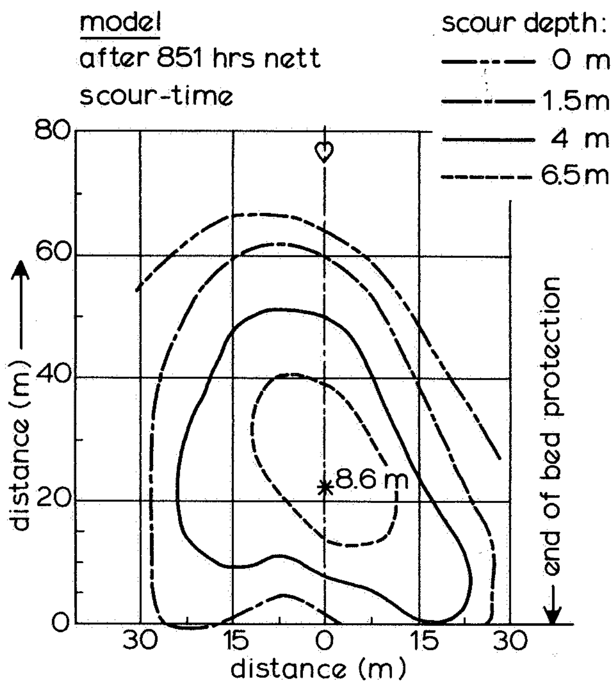

FIG. 5a: SCOUR HOLE IN MODEL
FOSSE D'AFFOUILLEMENT
EN MODELE

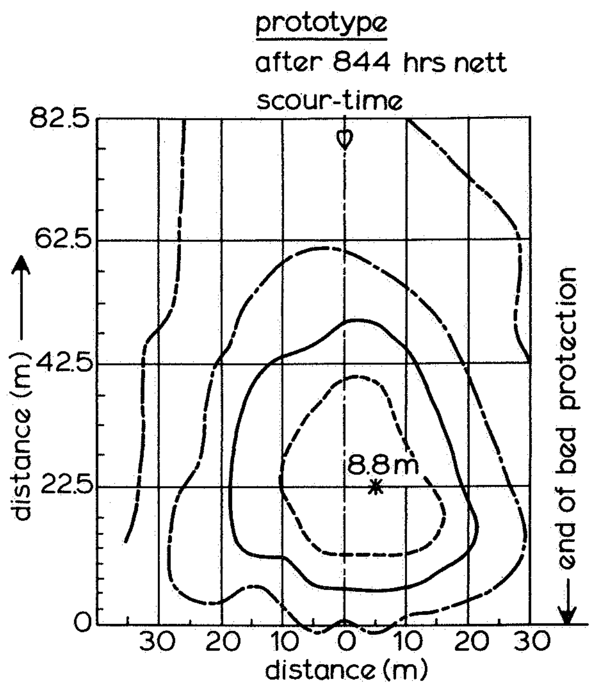

FIG. 5b: SCOUR HOLE PROTOTYPE
FOSSE D'AFFOUILLEMENT
EN NATURE

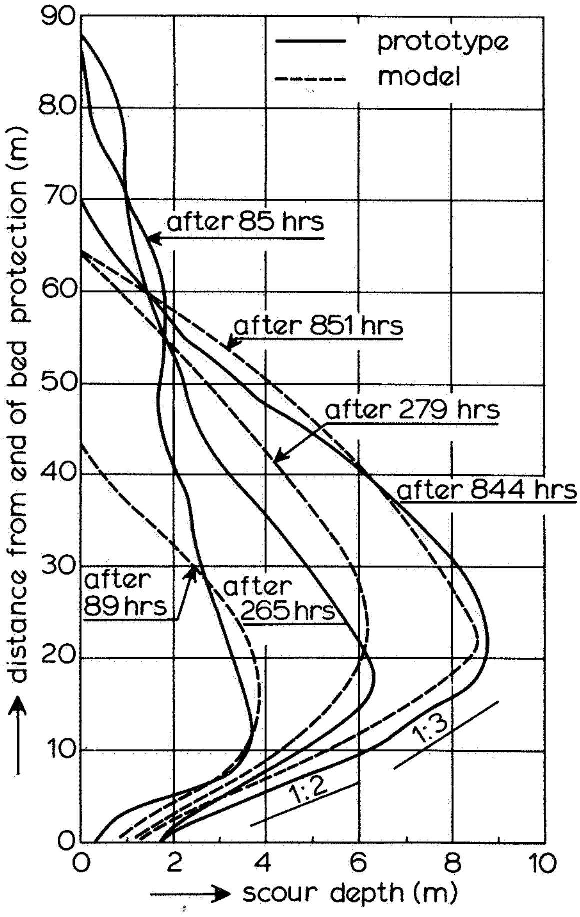

FIG. 6 : SECTIONS OF THE HOLE
SECTIONS DE LA FOSSE

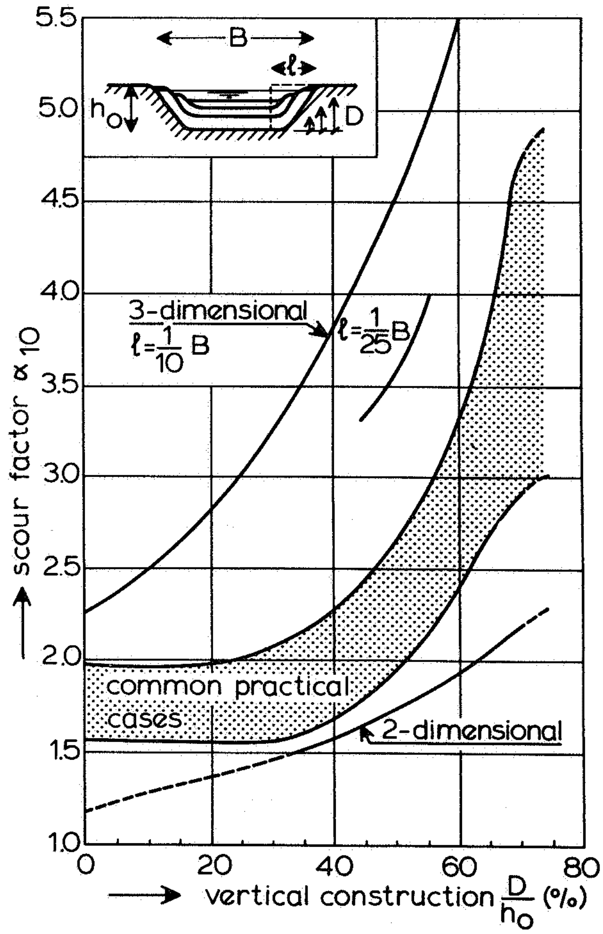

FIG. 7: α AS A FUNCTION OF VERTICAL
CONSTRICTION
α EN FONCTION DU RETRECISSE-
MENT VERTICAL