SEABED SCOUR BY CURRENTS NEAR PLATFORMS

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ABSTRACT

The gravity platforms in the North Sea, sitting directly on granular seabeds, may be undercut by scour and need scour protection. Conventional methods of protection are developed for structures 1 or 2 orders of magnitude smaller and seem unnecessarily conservative when scaled to these larger sizes. The reason is that some of the flow details that exert extra stresses on the bed, are not preserved during scale-up.

Some new ideas for scour protection are discussed. These are all built into the structure so as to reduce expensive offshore operations as much as possible. A breakthrough in protection technique is anticipated before long as a result of the present effort in several countries to come up with satisfactory designs.

INTRODUCTION

The research reported here was initiated by the appearance of a new type of structures in the North Sea: The gravity platform made of concrete. This structure had its fore-runners in the concrete lighthouses developed in Sweden during the last 35 years (Reinius *et al.*, 1971). Several lines of reasoning converge on the gravity platform as the solution for a certain range of depths and wave conditions. Low construction cost is probably the most powerful argument, but it is also claimed that maintenance costs will be low because concrete corrodes very slowly compared with steel.

An underlying assumption is that the scour problem is relatively unimportant. That is, a reasonable safety must be obtained by a reasonable investment in scour protection. If we were to apply the recommendations of the literature on scour, this is by no means a foregone conclusion.

Consider, for instances, the recent predictions for unidirectional flow (Fig. 1) by Bonasoundas (1974) and by Hjorth (1975) that an area some 35, respectively 14 times the cylinder cross section be protected, and apply that to a platform of 100 m diameter. The cost for that kind of protection is no longer a minor item in the total cost of the platform. Before recommending such a massive protection work, we felt the need for an investigation of the similarity conditions when scaling up 1000 times from typically 100 mm laboratory cylinders to 100 m full scale cylinders.

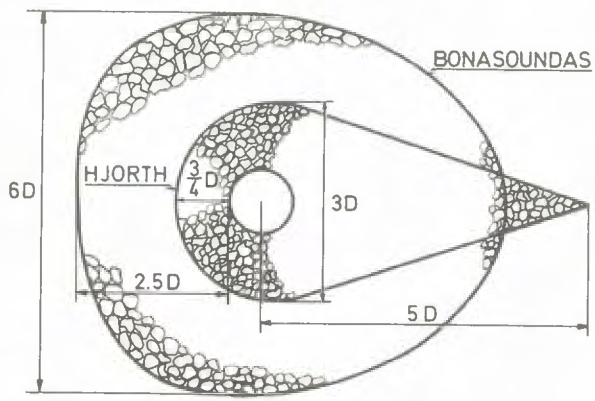

Figure 1. Recommended scour protection for piers.

Our suspicion was triggered by the prediction of scour depth, which by published formulas would fall in a range between 1.4 and 2.4 times the cylinder diameter. We found it hard to believe that a hole 100 m deep or more would open up in the seabed, no matter how wide the obstacle. If this were to happen, there ought to exist deeper natural scour holes in the vicinity of rock outcrops and other large obstacles. An interesting example of the general lack of dramatic scour holes is the echogram taken across the wreck of *Lusitania* and reproduced in Fig. 2.

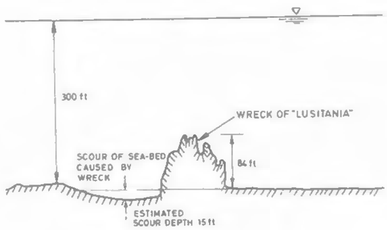

Figure 2. Echogram across the wreck of *Lusitania*.

Another clue to limiting factors in scour as the size of the obstacle increases is afforded by the erosion and deposition pattern of snow near buildings and other large obstacles. The action of the flow feature referred to in the literature on scour as the horse-shoe vortex is readily seen: It is the characteristic trench near exposed walls of a house surrounded by snow drifts. The width of this trench is at most a weak function of the length of the house, while it is a stronger function of the height of the house.

THE FLOW FIELD

The Potential Mean Flow

The wellknown two-dimensional potential flow around a cylinder

$$U_r = U_\infty\left(1 - \frac{a^2}{r^2}\right)\cos\theta$$
$$U_t = U\left(1 + \frac{a^2}{r^2}\right)\sin\theta \qquad (1)$$

where

U_∞ = undisturbed flow velocity

a = radius of cylinder

r, θ = polar coordinates

is shown in Figure 3. The velocity is slowed down by the buildup of pressure in an upstream sector which is 30° (i.e. half the central angle) wide at the wall, increasing asymptotically to 45° with increasing radius. For $\theta = \pm 90°$ the velocity at the wall has a maximum of twice the free stream velocity U_∞. A doubling of the velocity means a quadrupling of the bed shear stress τ_o which is proportional to the velocity squared, $\tau_o \sim u^2$. Substantial velocity increases prevail on the sides one radius out from the wall.

The primary flow pattern U/U_∞ versus r/a (Fig. 3) is nondimensional and can be scaled to any velocity and any diameter.

It is well to remember that outside of the bottom boundary layer the real flow pattern cannot be much different from potential flow. A wall boundary layer will necessarily envelope the cylinder, but its displacement thickness will be small (of order $10^{-2}r$).

This means that under no circumstance will it be possible to avoid stresses on the bed near the cylinder that are several times the free stream bed shear stress. Unless this latter stress is down to 25 % or so of the limiting shear stress for movement of the particular bed material in question, scour protection of some kind will be required.

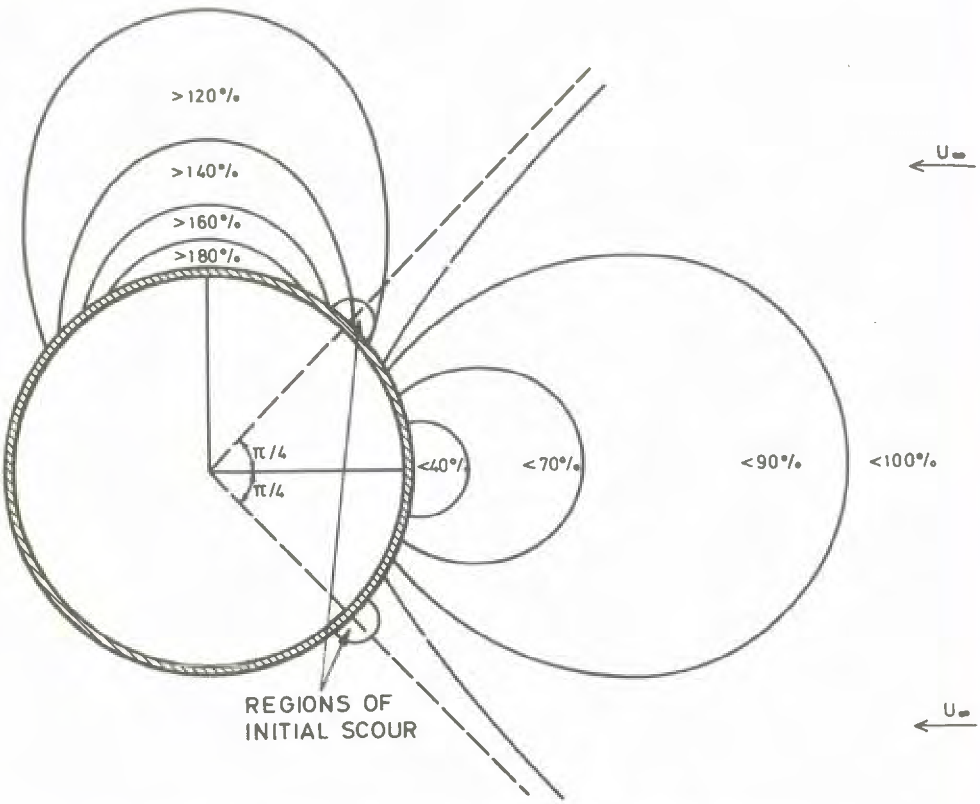

Figure 3. The two-dimensional potential velocity field.

The Secondary Flow

The no-slip condition at the bed causes a vertical velocity gradient which is felt within a boundary layer of, say, 10 m thickness. The actual thickness depends on the eddy viscosity which in turn depends on the roughness of the seabed. In any case a stagnation pressure is set up at the upstream face of an obstacle. The initial pressure distribution might look something like $P_{st} = 1/2\rho u^2$ in Figure 4, but such a pressure gradient has never been observed. The observed pressure is almost uniform, but has a slight dip in the middle part of the boundary layer (P_{obs} in Figure 4).

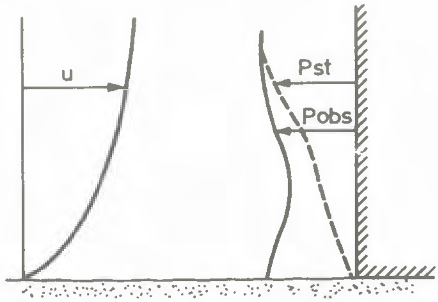

Figure 4. Stagnation pressure distribution.

The primary stagnation pressure gradient P_{st} causes a vertical flow which is referred to as secondary flow in the literature. This secondary flow (Fig. 5) in turn causes a secondary stagnation pressure when deflected by the bottom. Since the strength of the secondary flow about equals that of the primary flow, P_{obs} at the bottom approximately equals P_{st} above the boundary layer.

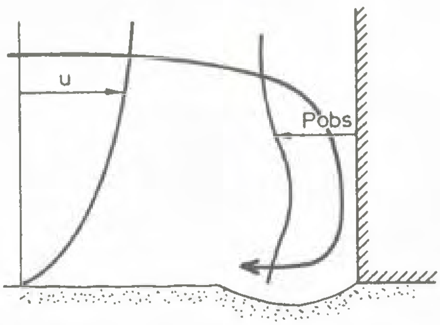

Figure 5. Secondary flow.

Unlike the two-dimensional potential flow which is scalable with the simple parameter r/a, the three-dimensional secondary flow depends not only on r/a, but also on a/δ, where δ is the thickness of the bottom boundary layer, and on h/δ, where h is the water depth.

BED SHEAR

Because of the secondary flow bed shear stresses will be magnified many times in the vicinity of the upstream wall of a cylinder. Hjorth (1975) has made an extensive investigation of scour near cylinders, and Figures 6 and 7 are taken from this report. Figure 6 shows the flow pattern obtained by studying details on a plaster of Paris model. Figure 7 shows the relative bed shear stress obtained by hot film technique.

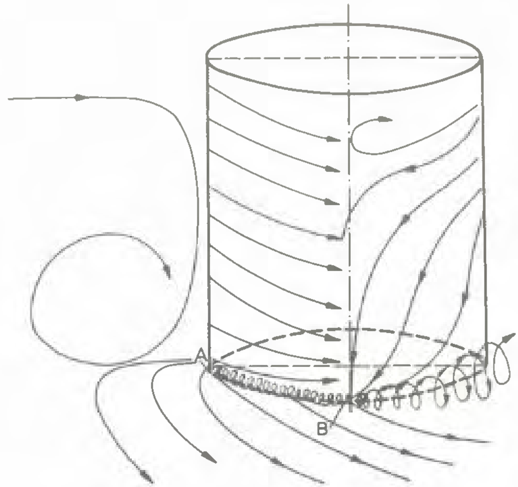

Figure 6. Flow around a cylinder. After Hjorth (1975).

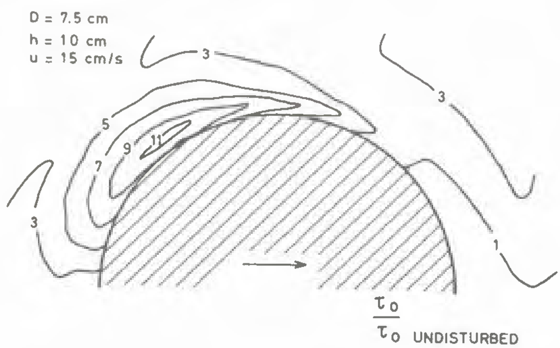

Figure 7. Relative bed shear stress. After Hjorth (1975).

An area of intense shear stress with a maximum $\tau = 12\ \tau_o$ was found around $\theta = 45^o$ a short distance from the wall.

Several model studies of scour have corroborated this result (Carstens and Sharma, 1975). The scour hole contours are similar to the shear stress isolines of Figure 7.

The area of the bed covered by the secondary flow shows up readily in tests where the bed is covered by a thin layer of sand (Fig. 8). The bed is wiped clean by the flow away from the cylinder upstream. Downstream the sand is picked up primarily by vertical eddies rolling up along the separation surfaces and acting somewhat like vacuum-cleaners.

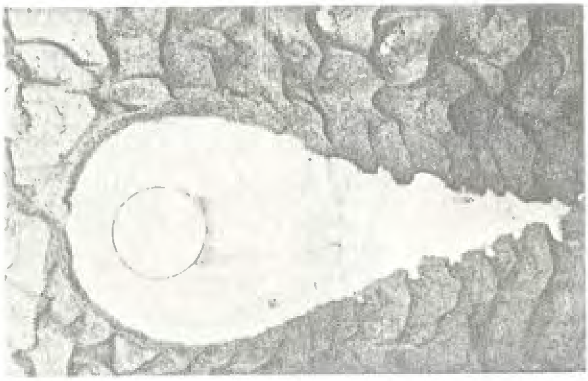

Figure 8. Scour induced by cylinder. After Hjorth (1975).

It is unlikely that the secondary flow observed on these small scale models is preserved for large upscaling. A mathematical description of the flow seen in Figure 6 is not readily forthcoming, however, and we shall have to learn by watching large scale experiments.

SCOUR PATTERN

Our experience with snow drifts again has influenced our thoughts on the scaling of scour processes. A characteristic feature of the drift pattern around obstacles of many sizes from tree trunks to buildings is that the horse-shoe vortex has downstream extensions. Between the trailing eddies on either side there is an area of deposition, which does not show up near small diameter cylinders in movable sand models.

We hypothesized that by increasing the diameter of the test cylinder, keeping everything else the same, the scour pattern ought to change. The inverted frustum reported by so many researchers would eventually have to yield to a horse-shoe pattern, with scour around less than entire periphery.

Figure 9 shows the result of such a simple test series. The upper figure shows a nearly symmetric scour hole obtained with a 0.12 m cylinder. The pattern in the middle, with a 45° arch downstream where deposition rather than scour occurred was obtained for a 0.50 m cylinder. The lower figure shows accretion along 110° of the periphery, for a 0.75 m cylinder. As the scour near the cylinder decreases, downstream trails appear. In this case the transport happens to generate dunes, which explains the succession of scour holes instead of clean trenches downwards.

All three tests were run with approximately the same water depths, the same undisturbed mean flow velocity $V/V_{cr} = 0.8$ and the same bed material, polyethylene shavings with a limiting velocity for incipient motion of 0.10 m/s.

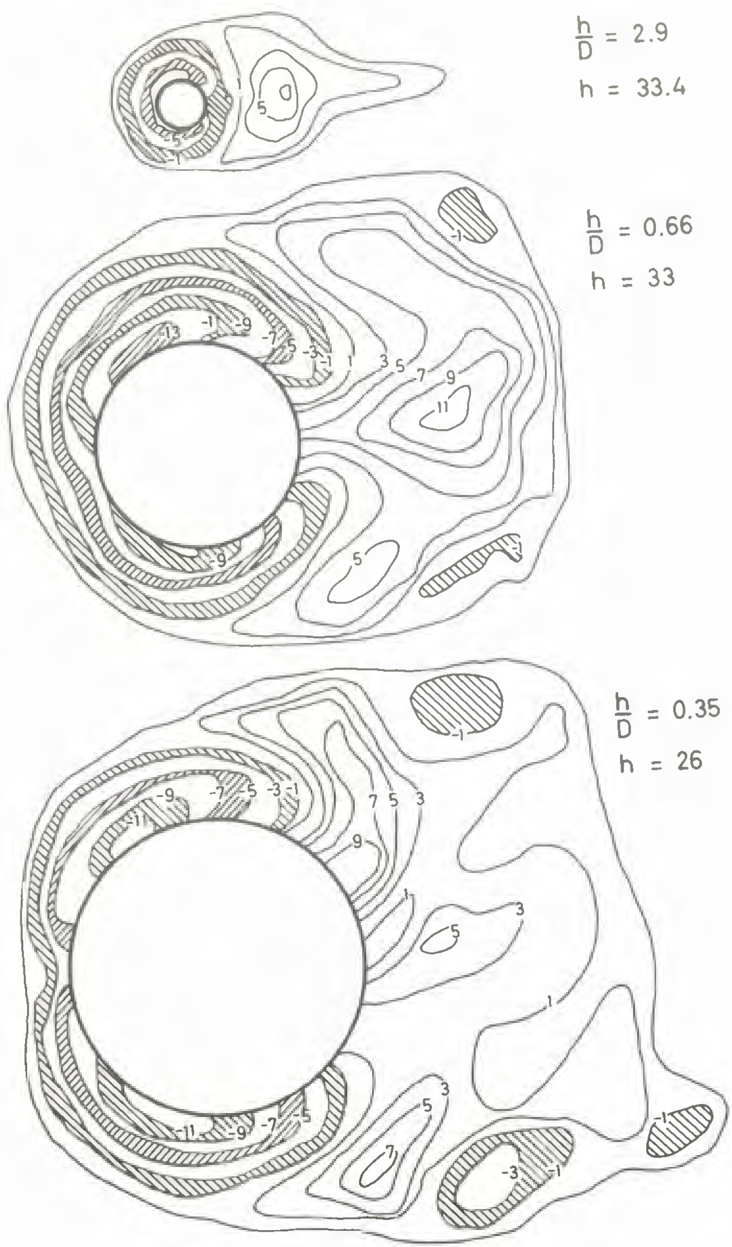

Figure 9. Change in scour pattern with diameter of cylinder.

SCOUR DEPTH

Our simple test series also yielded interesting results on scour depth. Looked at separately, the observed scour depth could be considered independent of the diameter, with but little scatter. In fact, Torsethaugen (1975) proposed $S/D = 1.8\ (V/V_{cr} - 0.54)\ h/D$.

When the range of diameters was extended downwards with results from other sources, a strong dependence of scour depth on diameter appeared. The curve in Figure 10 has the expected shape, but we had not anticipated that S/D should fall off quite so quickly with D.

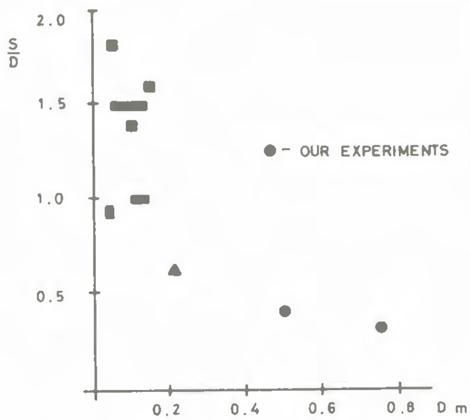

Figure 10. Change in scour depth with diameter of cylinder.

While we are willing to accept a trend such as revealed in Figure 10, we do not recommend that particular curve for prediction purposes. There is probably a lower limit to the relative scour depth S/D which is approached asymptotically. This asymptote depends on a number of factors, among which both vertical (depth of flow, boundary layer thickness) and horizontal dimensions (diameter) are important.

SCOUR PROTECTION

Once we had gained an understanding of the fluid mechanics of the scour process, several ideas for scour protection suggested themselves.

First of all, it should be clear from the discussion above that one cannot get away from a substantial increase of the bed shear stress $\tau_o \sim \rho u$ near the 90^o points. In fact, the best one can hope for is purely horizontal flow, which would give essentielly a potential flow pattern around the structure. As we have seen, the maximum velocity is then $2\ U_\infty$ for a cylinder and the maximum shear stress is $4\ \tau_\infty$.

To obtain the reduction of τ_{max} from $12\ \tau_\infty$ to $4\ \tau_\infty$ it is necessary to modify the structure so as to reduce, eliminate or reverse the secondary flow.

Deflector

In hydraulic design a common trick to prevent scour at outlet works, spillways and other threatened areas is to deflect the high-velocity flow away from the bottom. The deflected jet will entrain water from underneath. This process reverses the flow along the bottom, feeding in sufficient material to maintain the bed level and frequently even building it up with deposits.

In the present case a similar mechanism is conceivable where the secondary current has a substantial component away from the wall at the bed. The deflector might be a suitably designed bottom plate, with or without a sill as suggested in Figure 11.

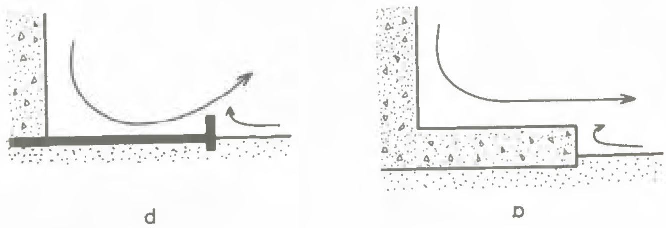

Figure 11. Deflector.

The deflected secondary outflow will cause a tertiary inflow which is more or less efficient in transporting bottom material.

We hypothesized that there ought to be an optimum height of the deflector. If it is too low, the eddy underneath will be too small, and the jet will reattach too close to the structure and cause scour (Fig. 12a). On the other hand, if the deflector is too high, it will induce a new secondary flow down its own face, below the entrained backflow (Fig. 12c).

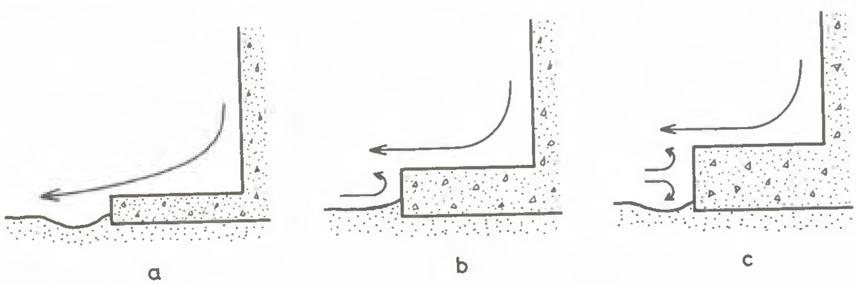

Figure 12. Effect of height of deflector.

A set of tests confirmed this reasoning. Whether the bottom plate had a sill or not seemed to make little difference provided the combined height of plate plus sill was used. Figure 13 shows the experimental scour depth versus deflector height.

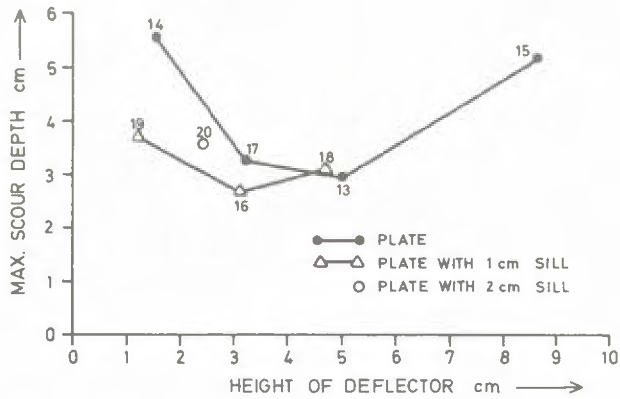

Figure 13. Optimum height of deflector.

A deflector should minimize the area requiring protection, and the results obtained are encouraging.

Shape of Caisson

A commonly used base for a vertical cylinder is to flare it out in a cone. Structurally this gives a strong and stiff tower, while from a construction point of view it is somewhat complicated. The conical base is best suited for structures subjected to heavy loadings such as platforms in deep water or in ice.

For less severe loadings a simpler solution is a cantilevered horizontal foundation plate. Potential flow gives a velocity u(x,y,o) at the base of a cone which is higher than it would be if the cone were not there. This implies a higher shear stress for such an imagniary flow with the cone than without.

However, secondary currents, driven by gradients in stagnation pressure as described above, will subject the bed to additional stresses that may outstrip the primary flow differences.

The amplification of bed shear due to secondary currents near a cone should be less than for a cylinder. The potential flow itself has a vertical component away from the bed on the upstream half of the cone. This will counteract the vertical secondary current which is towards the bed. For a certain angle between the cone surface and the horizontal the opposing vertical flow components will cancel, resulting in a horizontal flow sideways and around the cone.

However, for a given slope of the cone this reasoning is only valid in the plane of symmetry. We cannot eliminate the vertical flow simultaneously around the entire cone. In principle this is feasible if the slope is varied around the periphery, perhaps with a cone tilting downstream. That solution is ruled out for marine structures, because the current is rotary and oscillatory. On the other hand, in unidirectional flow in rivers and canals it is common practice to give bridge piers and similar structures asymmetric shapes.

"Tent"

Realizing the difficulties involved in completely eliminating secondary currents by manipulating the shape of the base, we tried out various ways of living with a limited scour. One such idea was to arrange a cone of hinged plates that were free to fall into the scour hole at their lower ends (Fig. 14).

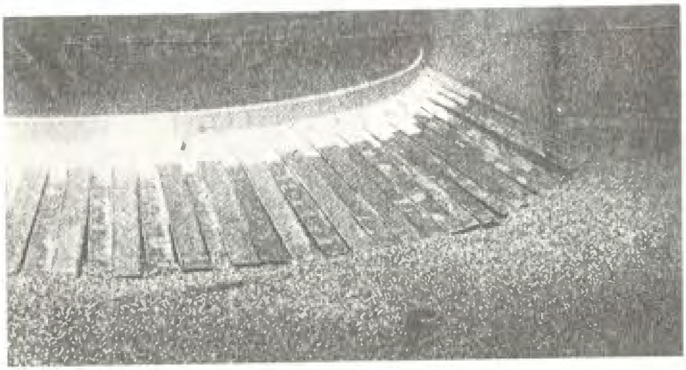

Figure 14. "Tent" of hinged plates.

Together the plates formed a leaky tent, as it were, around the cylinder, enclosing an area protected against direct flow.

The test setup in a 1 m wide flume left much to be desired, and a number of scale effects must have influenced the results. Nevertheless, the basic flow mechanisms described above were dominating, and the results were reasonable.

For comparison the cantilivered plate was also tested. The results indicate that there was little to be gained from a tent compared with a slab that covered the same area. The scour depth was not reduced by the hinged plates, although they did act as intended, falling into the scour hole and thus shielding the inner slope.

EXISTING SCOUR PROTECTION

The protection used so far is interesting in that it illustrates the two basic strategies available. These strategies are i) to accept the flow pattern and provide protection against the prevailing forces and ii) to modify the flow so as to ease the stresses on the bed near the structure.

Ekofisk

The perforated wall structures of Doris/Jarlan design are of the second category. Both The Ekofisk and the Frigg structure (Fig. 15) have a perforated wall outside the actual platform. Model studies, Marion (1974) demonstrated that this wall had the desired effect of reversing the flow along the bottom as suggested in Figure 15.

The Ekofisk structure included a permeable nylon cloth that was attached to the structure and unrolled on the seabed. This screen was then weighted down with a stone blanket of 8 - 10 m^3 per m of tank periphery with rocks of maximum diameter 10 cm.

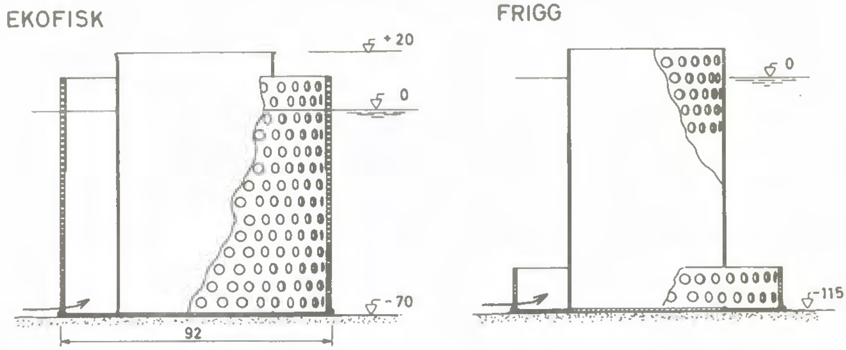

Figure 15. The perforated wall design (schematic).

In view of the inflow along the bed this latter protection may seem redundant. However, on the sides where the wall is parallel to the flow, such inflow is not assured while we know the potential flow to have its maximum here. Since the flow must be assumed to take on any direction, it is necessary to provide protection against the primary flow. Thus we have to fall back on a basic scour protection against prevailing forces. In this case, however, the amplification of forces due to secondary currents is eliminated or reduced.

So far no scour has been observed. Current measurements and tracer studies with labeled sand indicate only weak currents without any preferred direction (Bratteland, 1975).

Condeep

The second gravity platform to be placed on the seabed was the Condeep structure on the Beryl and Frigg fields in the British sector of the North Sea. The base of this structure consists of 19 cylinders, and the periphery is a set of 12 arches of radius 10 m. The circumscribed radius is 50 m (Fig. 16).

Observations near a model to scale 1:200 revealed that the amplification factor for the flow velocity at $\theta_1 = 90^\circ$ was not 2 as for a single cylinder of radius r_1, but higher. The explanation appears to be that a superposition takes place at A in Figure 16 of the flow caused by the bundle of cylinders, with the local flow field around the individual cylinder to produce a strong amplification of the flow velocity in a thin layer near the wall.

Protection is in this case by a stone blanket, which has proved difficult to dump in place due to rough weather.

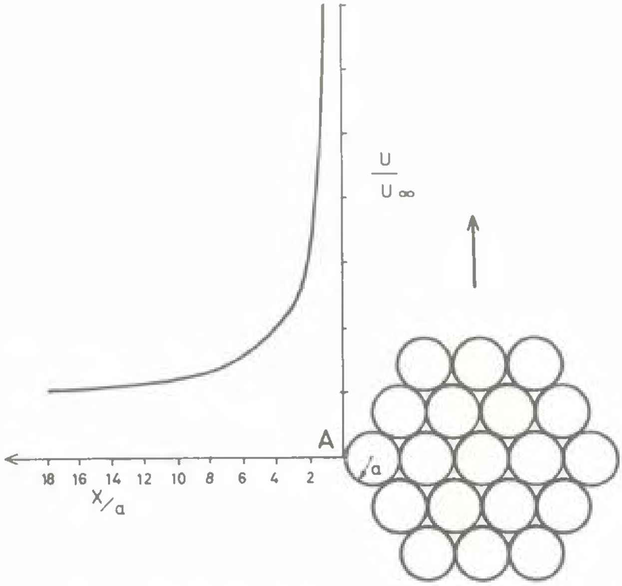

Figure 16. High velocity jet near bundle of cylinders (Condeep).

Other proposed protections

The Norwegian Subtank, which is yet to be built, is proposed with an interesting design. The basic idea is that the scour protection should be operational from the moment the platform is sunk in position. The soundness of this philosophy has been proved lately by the difficulties experienced in placing rocks at the first Condeep.

Figure 17. Hinged plates (Subtank).

Figure 17 illustrates the idea, which features a set of hinged plates around the lower circumference. In the space between the cylinder wall and the plates in their "up" position, stones can be stored during towing. As soon as the platform is placed on the seabed at its permanent location, the plates are lowered and the stones spread out.

The British company ICI has proposed an artificial seaweed type solution in which numerous bundles of polyester filaments are suspended under a frame cantilevered from the wall of the platform (Fig.18). The field of porous and resilient material has accumulated sand in full scale tests and is a very promising idea. The fluid mechanics of this type of protection has not been studied, however.

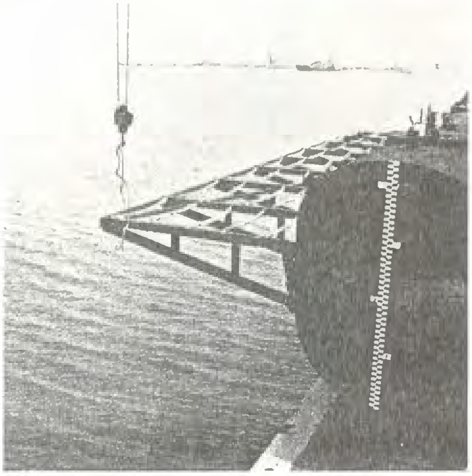

Figure 18. Polyester filaments to be suspended near platform base (ICI).

CONCLUSIONS

We have shown that the existing prediction formulas for scour depth at bridge piers are likely to be misleading when applied to large gravity platforms. With increasing diameter the scour at the cylinder wall becomes less extensive both in relative area and relative depth.

Scour will nevertheless occur, and ideas for built-in scour protection are discussed. These ideas have been tested to some extent in small scale hydraulic models, with results ranging from full protection to reduced scour. Full scale performance data are still missing or at best uncertain. Several promising methods are at present in the development phase and need large scale testing before they can be finally evaluated. There is every reason to be optimistic in the sense that one or the other of these methods will provide a technically and economically sound solution to the scour problem.

ACKNOWLEDGEMENT

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