CHAPTER 218

SOIL MECHANICS OF SHIP BEACHING

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Abstract

When a ship hits a soil or gravel slope it will create a large transient pore pressure in the soil which will force the ship bow upwards. At the same time the pore water will cause ruptures in the soil which influences the lifting forces on the ship bow. Methods of analysis are presented for the pore water build up, the soils rupture and the resulting reactions on the ship bow for frictional soils. Soil slopes with low permeability (sand in connection with a scour protection) generates large reactions on an impacting ship with the result that the ship will ride up on the surface of the slope and be brought to a stop by friction . Soil slopes with high permeabilities as pebbles or quarry run generate smaller reactions, and the ship will plow itself into the slope. It will then be stopped by a combination of friction and passive soils pressure. The analytical results are compared with test results made in a hydraulic laboratory and by full scale testing in nature of a ship sailed into a beach. Good agreement was found between the theoretical findings and the test results.

Introduction

In many places structures are placed adjacent to heavily trafficked navigation channels. The ship traffic is supposed to stay in the main navigation channel. Some ships, however, do loose their way or their steering and may ram the structure. One method to protect against the impact is to surround the structures with works built in fill materials. An example of this is the protective works for the side span

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piers of the Great Belt suspension bridge in Denmark. They are designed to stop all ships with a displacement greater than 4000 tonnes before they reach the bridge foundations, figure 1. The impact of smaller ships can be sustained by the bridge piers themselves.

Such protective works will have the effect that they either force the ship to ride up the slope and absorb the energy of the ship by friction or they will absorb the ship impact inside the soil skeleton as passive soil pressure. An accurate calculation of the stopping length of the ship will therefore be important. Typical marine structures to protect are bridge foundations or immersed tunnel elements.

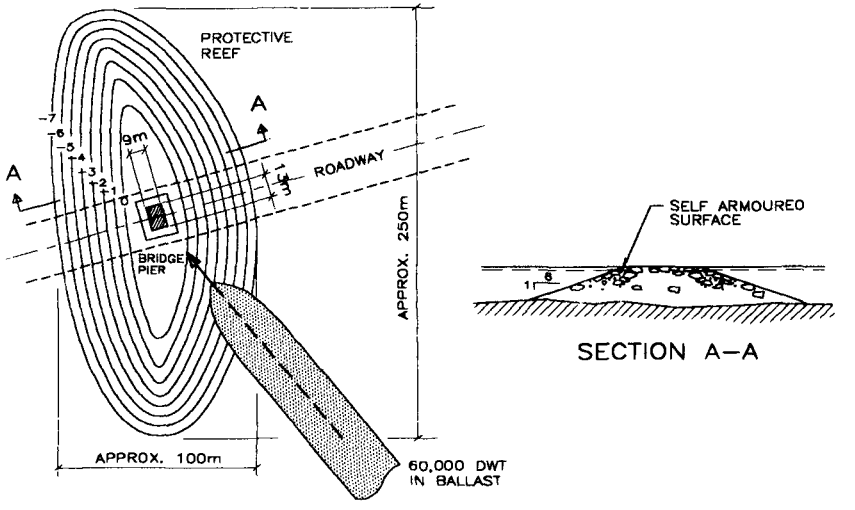

Figure 1. Protective work for one side span foundation of the Great Belt suspension bridge, Denmark.

Mechanics of Ship Grounding

The stopping force acting on a beaching ship is the result of ruptures in the soil at the areas of contact between bow and soil. The mechanics of this rupture is complicated. This is illustrated by an example where a ship with cylinder bow with vertical sides is rammed horizontally into a submerged slope of sand of 1:6, Figure 2. The bow has a semi-circular shape with a radius of r = 378 mm. The bottom is flat. The sand is very uniform in gradation with a mean diameter of 0.125 mm, permeability coefficient $9 \cdot 10^{-5}$ m/s and frictional angle of 39^0. The ship is rammed with constant velocity and it is locked in the horizontal position such that it cannot heave or pitch.

In figure 2 the horizontal forces and vertical forces for different impact velocities are presented as a function of horizontal position for a ship with cylindrical bow rammed into a slope of 1:6. The soil reaction is shown for tests in both dry sand and submerged slopes of different impact velocities.

The horizontal resisting force and the lifting force as the bow depends on the velocity. The force is 10-20 times larger than the resisting force for the identical tests peformed out of water where the bow is rammed into the same slope of dry sand, figure 2.

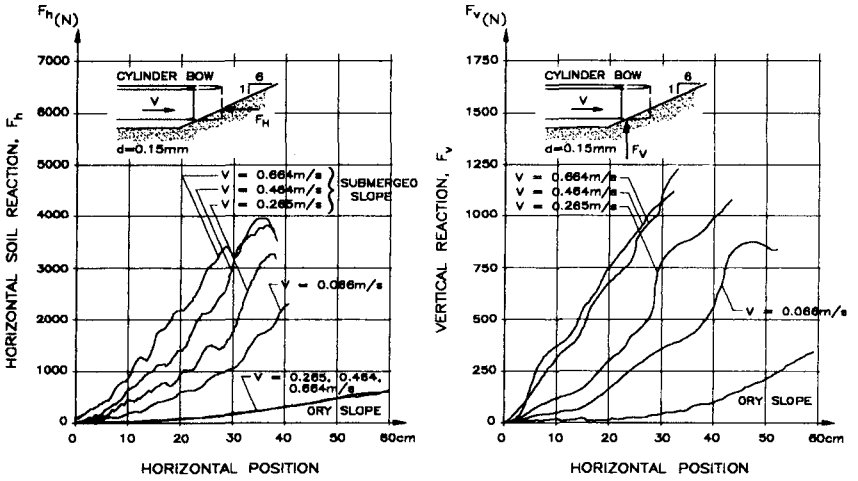

Figure 2. Force on ship bow.

Therefore the porewater flow generated by the bow during the impact must have great influence on the behaviour of the ship. The porewater flow creates strong effective stresses in the soil which act on the hull both as normal stresses and as tangential stresses. It is then the question of how these effective stresses are generated. There seem to be two possible mechanisms to choose:

1. At the rupture the sand will dilatate and thereby create a large suction in the pore water in the rupture zones. This suction will result in a just as large effective stresses in the grain skeleton.

2. At the impact the sand will be compressed and pore water will be squeezed out in the compression zone creating an additional pore water flow. This pore water flow will build up large effective stresses in areas of the grain skeleton.

In other areas liquified zones will be formed.

Which of the two mechanisms are correct can be decided by investigating the vertical lift on the ship bow. This lift must partly be caused by friction on the front and partly of the pore water pressure at the bottom of the model ship. From figure 2 it can be seen that there is a relatively large lift on the bow. Consequently there must be an excess pore pressure underneath the bow. This indicates that the impact follows the mechanism, 2, where the sand skeleton is compressed and the pore water squeezed out.

The pressure generated by the porewater has further been demonstrated by establishing a vertical downwards directed pore water flow through the sand (originally made to compact the laboratory sand), figure 3. This drainage will reduce the initial pore pressure with depth. Figure 3 shows the difference between the lift on the ship bow with and without the additional vertical pore water flow. The important finding is that even though the initial pressure underneath the bottom of the model ship is reduced, still a lift is generated. This proves that excess pore pressures are generated by the impact.

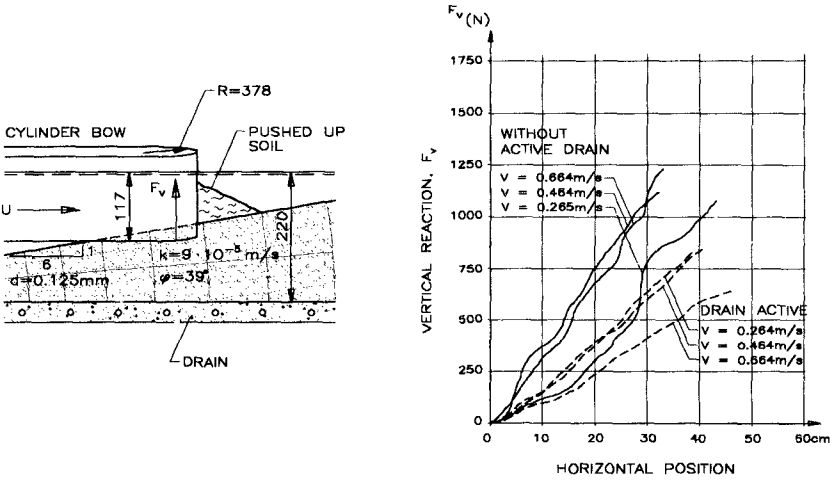

Figure 3. Variation in lifting force
for various drainage conditions in the soil.

Method of Analysis

The analysis of the soils forces acting on an impacting ship must be made with some simplifications in order to obtain a result.

Ships with bulb- and V bows have a narrow keel such that the foot print into the slope becomes oblong, figure 4. Hence the soils resistance can locally be calculated by two-dimensional methods.

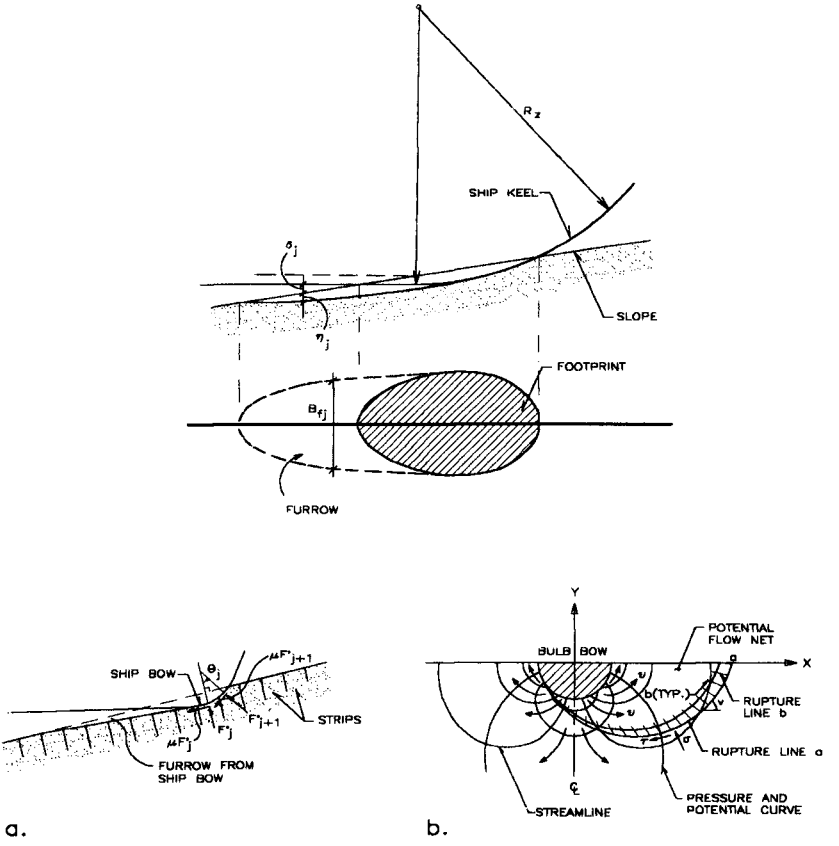

Figure 4. Principle of strip calculation model.
a) The division of the slope into elements.
b) Soils movement and porewater flow lateral to ship movement in a strip.

The slope is divided into a series of strips. Within these strips the soil deformation and porewater movement are calculated using a two-dimensional solution, figure 4. Using this reference frame the deformation of the slope can be described in detail and it is possible to determine which strips are in contact with the bow, furrow geometry etc.

The total soil reaction is found by summing up the soil reaction force from

each of the soil strips in contact with the bow. This provides a normal force perpendicular to the slope and a frictional force parallel with the slope. They can be used for the equations of motion of a beaching ship. The ratio between the frictional force and the normal force is defined as the effective frictional coefficient.

Thus the system is reduced to a two-dimensional system which is easier to analyse.

The cylinder bow mentioned as an example in the preceding paragraphs can be approximated with strips along the perifery of the bow in the vertical plane.

Basic Assumptions

In order to explore the impact on the soil the basic one-dimensional case of the cylinder bow is considered

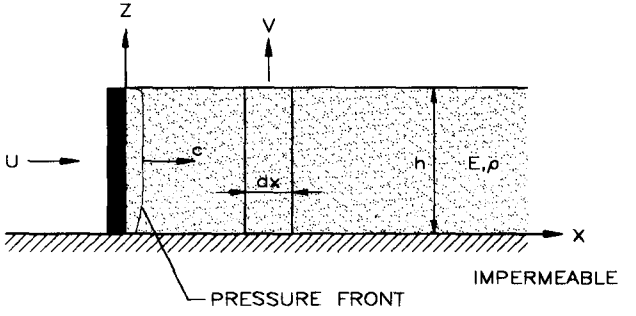

Figure 5. Basic case of impact of cylinder bow.

For an impulsively started motion at t = 0 to U, a pressure wave with celerity, c, is sent out. Joukowski's law then gives for the horizontal force, F_H

$$F_H \sim \rho c U h \quad , \quad c \sim \sqrt{\frac{E}{\rho}}$$

ρ is the density of saturated soil and E the Young's modulus of dry sand. The ratio between effective stresses from pore water flow and inertia force are decided by the soil permeability, k and given by

$$\frac{\rho_w g h U}{\rho k c^2}$$

This means that the forces from the pore water for normal sand dominates over the inertial forces.

From the expression for F_H it can be seen that the stresses at the impact in this example will be very high ($\sim$ 100 kN/m^2 - 500 kN/m^2). This is extremely high. So high that a soil rupture must occur. The rupture force will depend on how large vertical stresses can be generated by friction against the ship hull.

Hence in the following the inertia forces can be neglected, and calculations can be treated as a quasi steady soil rupture problem even though it is an impact problem.

Equilibrium Equations for an Element of saturated Soil in Rupture

In order to analyse the rupture problem, the approximation of using a series of circles as rupture lines is used. The rupture figure are then kinematically allowable and will produce stresses which are slightly higher then the correct stresses. The method is an adaption of the equilibrium method of Brinch Hansen, 1953.

The stress conditions for soil elements in a circular rupture line are shown in figure 6. There is a flow of pore flow through the element which generates tangential and radial pressure gradients

The shear stress, τ_{rv}, along the circular rupture line in frictional soil is given by the Kötter equation, Brinch Hansen, 1953:

$$\frac{\partial \tau_{rv}}{\partial v} + 2\tan\varphi\,\tau_{rv} + \gamma' r \sin(v+\varphi)\sin(\varphi) - \sin^2(\varphi) r \frac{\partial p_p}{\partial r} + \sin(\varphi)\cos(\varphi)\frac{\partial p_p}{\partial v} = 0$$

r,v are the polar coordinates and γ' is the submerged weight of the soil. φ is the frictional angle of sand. P_p is the pore water pressure.

The normal stress, σ_r, is found from the Coulomb relationship

$$\tau_{rv} = \tan\varphi\, \sigma_r$$

With the known boundary conditions and pore water pressure field, p_p, this equation can be integrated to give the effective shear stress, τ_{rv}, along the considered rupture line.

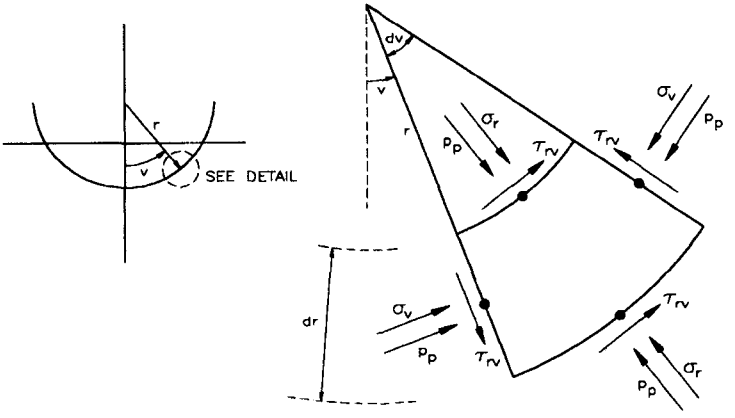

Figure 6. Effective stresses and pore water pressures on a soil element in a circular rupture line.

Soil Reaction on a Strip of the Bow

To demonstrate how the soil reaction is calculated, one strip on the slope (see figure 4) is considered. Normal velocity and acceleration of the bow at the considered strip is u_b and $\dot{u}_b$ respectively, figure 7a.

The first simplification of the problem shown in figure 7a is achieved by assuming that the penetrating bow can be modelled by a plate of width B corresponding to the immediate width of the bow in the plane of the slope, figure 7a,b.

Initially the grain skeleton is compressed elastically and a pore water flow is generated. When the force reaches a certain level soil rupture will develope. During beaching of a ship the deformations of the soil are sufficiently large to develope complete rupture.

The geometry of the rupture body can be approximated by a circular arc with its center placed off the surface of the soil in (x,y) = (a,b), figure 7. This is the most simple approximation. A better approximation would be to use a number of

consequtive circles. For an impact problem this additional accuracy is not warranted. The procedure is now to choose a,b, and the unknown force on the bow, F, such that the rupture body is in both horizontal, vertical and moment equilibrium.

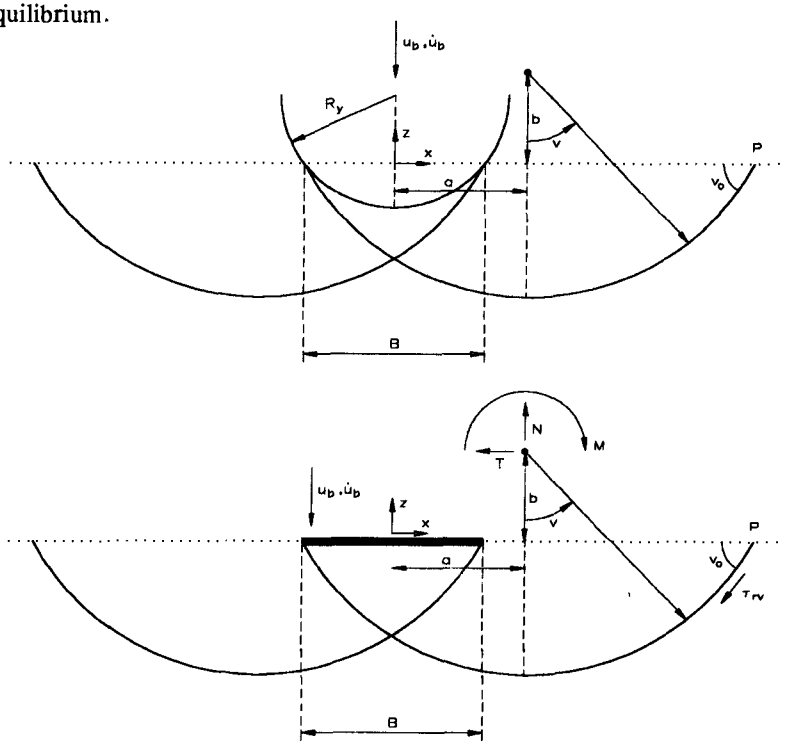

Figure 7. Assumed circular rupture below a bow penetrating saturated soil. Equivalence between bow and flat plate.

The total loads, T, N and M, on a given rupture body are the resultants of the effective stresses, τ_{rv}, σ_r in the rupture line, the pore water pressure, p_p, along the edge of the rupture body, the submerged weight of the soil in the rupture body and the load from the bow, F

The effective stresses, τ_{rv}, σ_v and σ_r in the rupture line can be calculated from the Kötter equation, if the pore water pressure, p_p, and the boundary conditions for τ_{rv} are known.

In the general case the pore water pressure cannot be found without considering the kinematics of the grains. However, in this case of modest penetration of a bow it can be assumed that the displacements of the grains are small compared with that of the pore water. The pressure field, p_p, can then be

found by use of Darcy's law and the of continuity equation for water.

The solution can be written, Lamb, 1932

$$\frac{p_p(x,z)}{\gamma''\frac{B}{z}} = z'\sqrt{z'^2+\frac{1}{2}(1-x'^2-z'^2)+\sqrt{z'^2+\frac{1}{4}(1-x'^2-z'^2)^2}}$$

$$\gamma'' = \frac{\rho g u_b}{k}+\frac{(1+e)}{e}\dot{u}_b$$

$$x' = \frac{x}{B/2} = \frac{a}{B/2}+\frac{r}{B/2}\sin\nu \quad , \quad z' = \frac{z}{B/2} = \frac{b}{B/2}+\frac{r}{B/2}\cos\nu$$

in which ρ_w is the density of the pore water, g the gravity acceleration, e the void ratio, and k the permeability coefficient.

Inserting these equations into the Kötter equation the variation of τ_{rv} along the rupture line is expressed in terms of the non-dimensional parameters.

$$\frac{\gamma'}{\gamma''} \; , \; \frac{r}{B/2} \; , \; \frac{a}{B/2} \; , \; \frac{b}{B/2} \; , \; \nu, \; \varphi$$

The boundary conditions for τ_{rv} and the angle, v_0, of the rupture line at point P are, figure 7

$$\tau_{rv}(P) = 0$$

$$v_0 = \pi/2 - \varphi/2$$

Using the approximation of a circular rupture there will not be sufficient degrees of freedom to satisfy all boundary conditions. However, the second condition can be neglected without loosing too much accuracy, Brinch Hansen, 1966.

If boundary condition for the shear stress is used in the solution of the Kötter equation negative effective stresses will occur in an area around P. They cannot exist. Therefore there is liquefaction in this area and no contribution to the resistance. Therefore the boundary condition is $\tau_{rv} = 0$ from P to the point in the

rupture line where the shear stress can grow towards positive values, see for instance figure 9. This point is characterized by

$$\frac{\partial \tau_{rv}}{\partial v} = 0$$

The effective stresses and the porewater pressure acting on a given rupture body at a given value of γ'/γ'' can be calculated. The resulting values of γ'/γ'', a,b,F are the ones which result in equilibrium for both horizontal and vertical forces and for the moment. The results of the analysis are presented in figure 8 in which the force F on the plate is expressed as a function of γ'/γ'' for soils with a frictional angle of $\phi = 32^0$.

Typical values for the parameters in γ'/γ'' are $\rho_w = 10^3$ kg/m^3, $\gamma' = 10^4$ N/m^3, $u_b = 1$ m/s, $k = 10^{-4}$ m/s, $\dot{u}_b = 0$ m/s^2 giving a typical value of γ'/γ''

$$\gamma'/\gamma'' \approx \frac{k}{u_b} = 10^{-4}$$

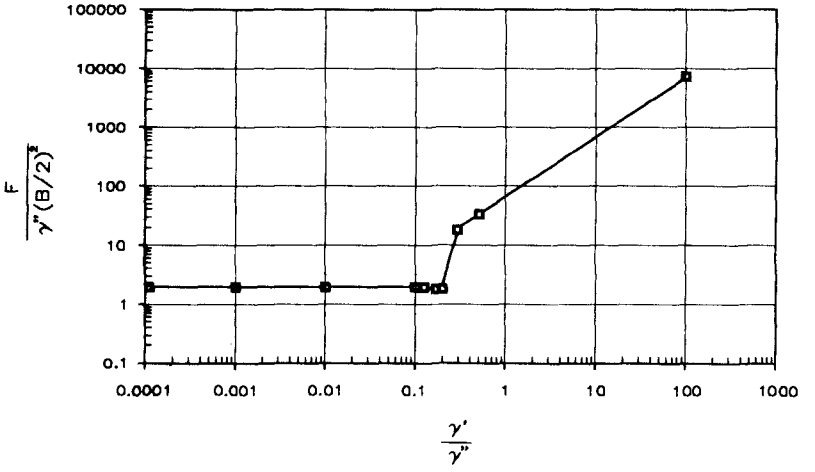

Figure 8. Non-dimensional rupture load for different values of γ'/γ'' for $\phi = 32^0$.

For values of γ'/γ'' below 0.1 the nondimensional total force, F, is seen to be approximately constant

$$\frac{F}{\gamma''(B/2)^2} \approx 2$$

Thus for $\gamma'/\gamma'' < 0.1$ the model does not predict an upper level for the soil reaction - it is simply proportional to

$$\gamma'' \left(\frac{B}{2}\right)^2$$

The pore water pressure gives a vertical reaction which is included in the above total force. The pore water contribution, F_{pw}, is

$$\frac{F_{pw}}{\gamma''(B/2)^2} = \frac{\pi}{2} \simeq 1.57$$

Therefore in this example of $\phi = 32^0$, the effective stresses between plate and soil only account for approximately 20% of the total load for small values of γ'/γ''.

Figure 9 shows the rupture body and the effective stresses on the rupture body for $\gamma'/\gamma'' < 0.01$.

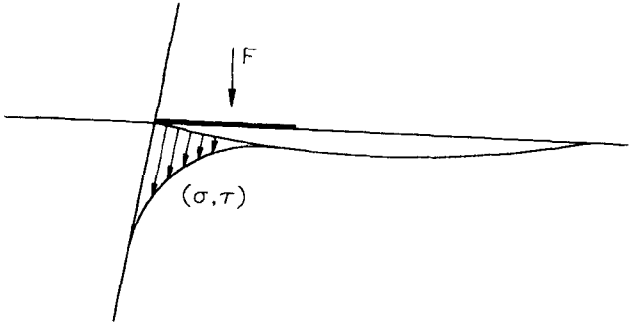

Figure 9. Rupture body and effective stresses
in the rupture line for small values of γ'/γ'' ($\gamma'/\gamma'' < 0.01$).

For such small values of γ'/γ'' the rupture load is carried by very large effective stresses directly below the bow, figure 9.

Knowing the effective soils normal force, F, on the bow at the considered strip, the tangential force, T, is simply taken as

$T = \mu \cdot (F\text{-}F_{pw})$

μ is usually set to 0.38.

Knowing the soil reaction in each strip in contact with the bow, the total soil reaction is found by summing up forces vectorially. Inserting this expression into the equation of motion for the ship, the beaching course can be calculated.

For V-bows similar expressions can be developed. Instead of using a flat plate-approximation, a wedge approximation is used.

COMPARISON WITH TESTS

The results of the soil reactions have been compared with both laboratory tests and with full scale tests. Parameters such as apparant coefficient of friction and calculated and measured stopping lengths were compared.

The laboratory tests were performed with a ship model corresponding to a 20,000 DWT ship in scale 1:60. The ship was forced into a sand slope inclined 1:6. Both fine and coarse sand were considered. Various bow types were considered.

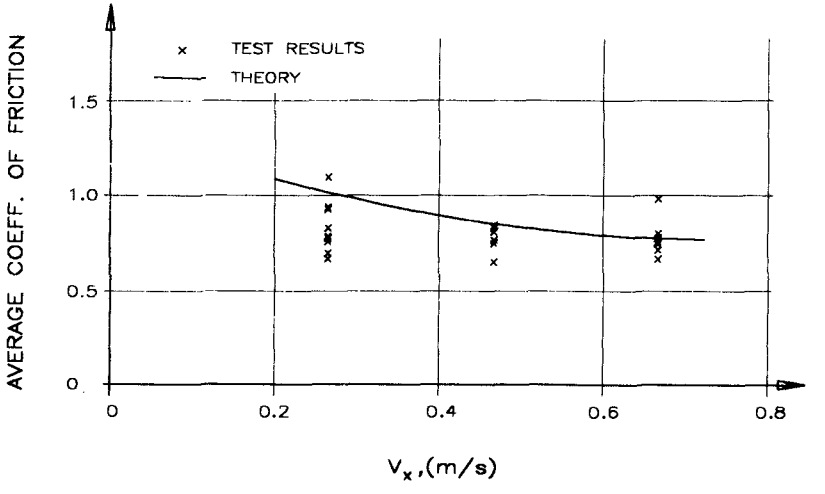

Figure 10. Comparison between theory and test results for effective coefficient of friction.

The measured effective coefficients of friction were compared with the corresponding calculated values, figure 10. This effective coefficient of firction is the ratio between the tangential and normal components of the soil and pore water reaction.

It is interesting to note that the effective coefficient of friction is in the order of 0.6 - 1.0 whereas the coefficient of friction between fill and ship plating is 0.38 (for the effective soils stresses).

The full scale tests were performed with a condemned 300 DWT fishing vessel which was rammed into an island built of the same materials as will be used for the protective works of the Great Belt suspension bridge. The vessel had a V-bow. The tests were made with velocities up to 10 knots. The stopping length and ship motions were recorded. Further, the foot prints in the slope were surveyed. The tests were repeated for various impact energies and various slopes.

Figure 11 shows a comparison between the calculated and the measured stopping length.

It is seen that the agreement is satisfactory. The measured furrow depths on the in-situ tests further show good agreement with the calculated furrow depth.

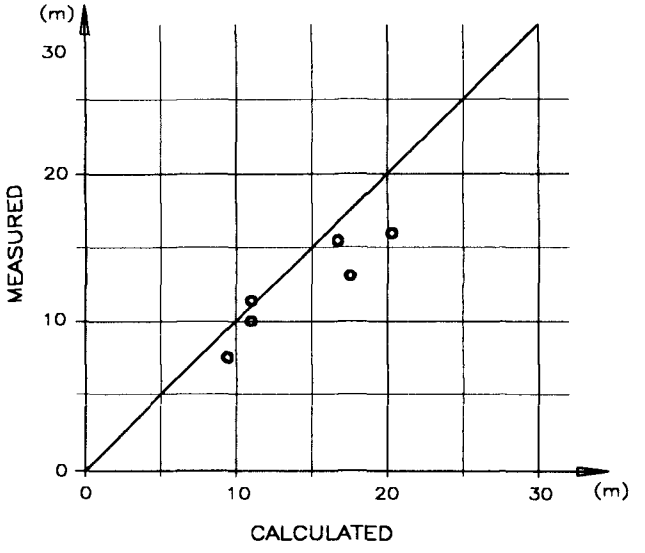

Figure 11. Measured stopping length depicted as function of calculated stopping length for a 300 DWT fishing vessel rammed into sand

slopes varying between 1:6 and 1:11.

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