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Geotechnical Model Tests for the Design of Protective Islands

Iles de protection et essais sur géotechniques modèle

Bemessung von Schutzinseln und geotechnische Modellversuche

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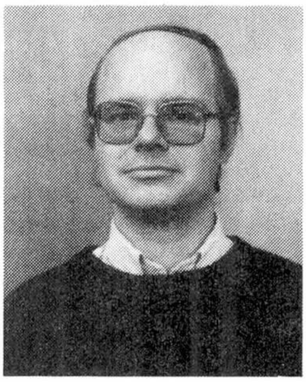

Hans Denver, born 1943, holds M.Sc. and Ph.D. degrees from the Technical University of Denmark. After short employment in a private consulting engineering firm he joined the Research Department at the Danish Geotechnical Institute in 1968. He has been responsible for numerous geotechnical test series both in situ and in the laboratory.

SUMMARY
In connection with the design of the Great Belt Bridge (Denmark) the Danish Geotechnical Institute performed quasi-static model tests with models of ship stems in order to determine the dimensions of artificial islands placed around the piers to protect the bridge against damage from a possible ship collision. The paper describes the test programme performed and offers a review of the main results. Furthermore, some of the results are explained in geotechnical terms by means of a simple earth pressure theory.

RÉSUMÉ
L'Institut Danois de Géotechnique a exécuté des essais quasi-statiques sur modèle d'une coque de navire afin de déterminer les dimensions nécessaires d'une île artificielle autour des piles pour les protéger contre les effets d'une collision. L'article décrit le programme des essais et donne les résultats les plus importants. De plus, une explication partielle est offerte en termes géotechniques avec une théorie de butée simple.

ZUSAMMENFASSUNG
Das Geotechnische Institut Dänemark hat für die Großen Belt-Brücke quasi-statische Modellversuche mit einem Schiffskörper ausgeführt. Dies war, um die notwendigen Abmessungen einer künstlichen Insel zu bestimmen, die als Schutz gegen Schiffskollisionen dienen sollte. Das Versuchsprogramm wird beschrieben und die wichtigsten Ergebnisse aufgerechnet. Gewisse Ergebnisse können mit bodenmechanischer Terminologie und einer einfachen Theorie von passivem Erddruck erläutert werden.

1. INTRODUCTION

The general problem of the risk of a ship collision into a bridge was investigated in detail during the design of the now abandoned Great Belt Bridge (Denmark), and a general reference is made to a report describing this problem and the research work carried out in this connection [1]. The presentation in this paper is confined to the description and interpretation of a test series where a model of a ship stem is forced in horizontal direction against a model of a section of a protective island built of a cohesionless material. The tests are carried out in the Danish Geotechnical Institute's laboratory under quasi-static conditions in a dry test pit. The six components of the passive earth pressure on the ship are measured during the penetration into the island, and the advantage of such tests over conventional hydraulic model tests is the possibility to create and calibrate a generally applicable earth pressure theory covering the problem.

2. TEST PROGRAMME

2.1 Model Sand

In most of the tests, the Institute's model sand (Lund-1) is used to model the island. This sand is a pure quartz sand and the unit weight of the grains is $\gamma_s = 26.5$ kN/m³. The void ratios in the loosest and densest states are $e_{max} = 0.88$ and $e_{min} = 0.59$. The mean grain diameter is $d_{50} = 0.60$ mm and the uniformity coefficient $U (= d_{60}/d_{10}) = 2.00$.

Unfortunately, the Lund-1 sand was not suited to the hydraulic tests, so in order to compare the results from the two test types, a few tests were carried out with a more coarse grained material. This gravel (called "Material 2") has the following specifications: $\gamma_s = 27.3$ kN/m³; $e_{max} = 1.02$; $e_{min} = 0.69$; $d_{50} = 6.00$ mm; $U = 1.33$.

Four dry triaxial tests with cylindrical samples (diameter $d = 200$ mm; height $h = 200$ mm) are carried out to reveal the strength of the material. The confining pressure is obtained by maintaining a constant vacuum ($\sigma_3 = 20$ kPa) inside the specimen during the test. The density for the samples is approximately equivalent to the density used in the model tests.

The results of the tests are described as the secant angle of internal friction φ_s defined as $\varphi_s = \sin^{-1}(\sigma_1 - \sigma_3)/(\sigma_1 + \sigma_3)$ as usual. For the Lund-1 sand the mean value of the friction angle is $m(\varphi_s) = 48.7^\circ$ for a void ratio $e = 0.565$.

2.2 Model Ship Stem

Two wooden models of ship bows have been applied in this test series. Model No.1 is shown in Figure 1 and is a simplified model of the bow of a tanker. Figure 2 shows model No.2 which is the bow of a container ship with bulb-stem.

2.3 Test Set-up

The shape of the proposed protective island is shown in Figure 3. A model of a section of this island is established in the laboratory pit, consisting of one or two slopes (1:1.5) and a horizontal chest.

To get reproducible test results it is of course necessary to use sand deposits of homogeneous and reproducible densities. This was obtained for the Lund-1 sand by means of a special sand-laying machinery which can provide controllable densities in a wide range by varying the intensity and the height of fall of the sand stream. Unfortunately, this method could not be used for the gravel (Material 2) - this was placed by carefully shovelling. Extensive control of the density and homogeneity verified that a usable bed could be provided in this manner.

The exact form of the desired section of the island is obtained by means of re-

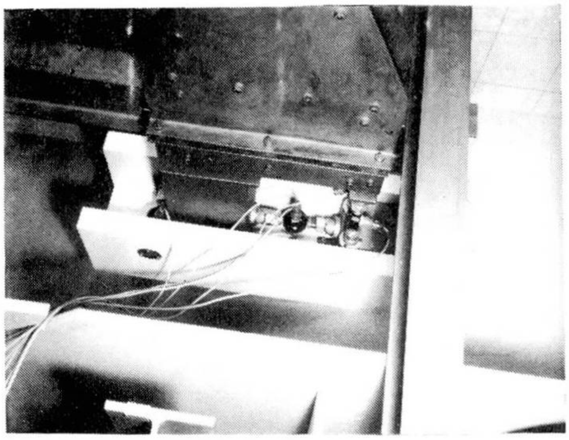

Fig.1 Model of a tanker

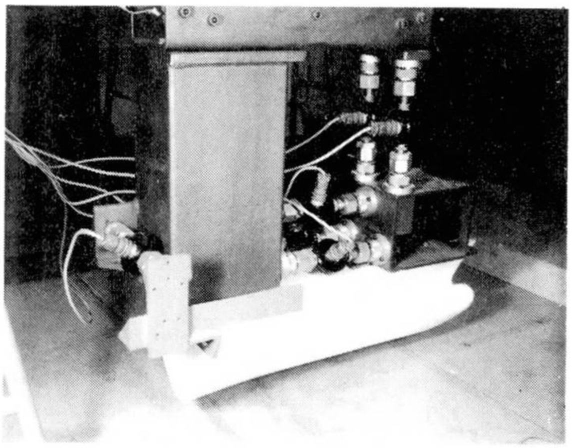

Fig.2 Model of the bow of a container ship

moving excessive material by means of a scraper resting on guiding rails fastened to the pit walls before the material was laid. The guiding rails can be seen in Figure 5.

The ship model is pressed against the island in a horizontal movement with a constant velocity of app.5 mm/min, ref. Figure 4, and the reactions of the material against the ship model are measured by six force transducers (seen in Figure 2).

The forces are logged by a data acquisition system and plotted by a computer programme.

Sand barriers created around the stem are registered by photos and motion pictures taken at regular intervals during the test.

In some of the tests a model of a pier is embedded in the island (see Figure 5). This model is provided with three force transducers to measure the horizontal component of the force on the pier caused by the penetration of the ship stem.

After a test was finished, the island was rebuilt completely (a new sand bed is established etc) to ensure a perfectly homogeneous island.

2.4 Model Tests

The total number of tests is 35. The test material was mainly Lund-1 sand - only in seven tests Material-2 has been used.

The distance between the bottom of the ship model and horizontal berm of the island has been varied from 66 to 120 mm in the tests, but is of course constant for the single test.

The vessel's angle of approach (θ-defined as $\theta = 0$ for an approach perpendicular to the edge of the berm) has been varied from 0 - 60° in the test series.

Different geometries of the section have been used:

(i) One slope and a horizontal berm

(ii) Two slopes and a horizontal berm - where the angle between the edges is 80° measured on the berm. Two slopes illustrate the point of the island (ref. Figure 3), and approach at different distances from the points have been tested.

Ship model No.1 has been used for all but six tests where ship model No.2 was applied.

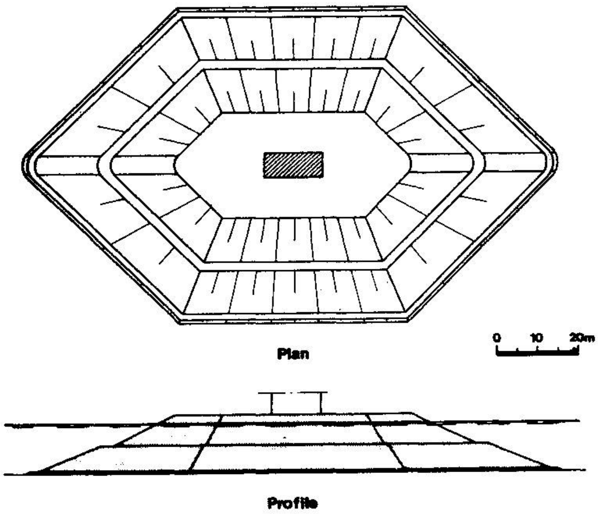

Fig.3 Proposed design of a protective island

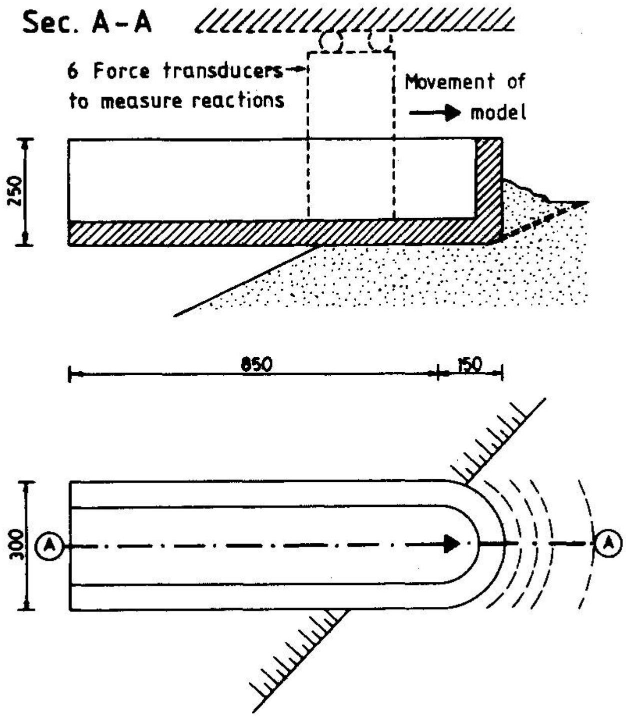

Fig.4 Principle for a test with the tanker model (dimensions in mm)

3. TEST RESULTS

3.1 Numerical Results

The numerical results from all the tests are presented in the original reports in tables where the three components of forces and three components of moments in a coordinate system fixed with respect to the vessel are logged together with the observed penetration of the model.

Furthermore, the results are plotted - both the calculated components of forces (as shown in Figure 6) and the components of moments.

3.2 Qualitative Observations

The forces measured during the translation of the model are plotted in Figure 6 for a test with the tanker bow. Traces of rupture lines appear on the sand surface as shown in Figure 4. These traces are observed on the photographs, and the positions where new rupture lines are identified around the stem of the model during the test are also marked in Figure 6. The fluctuations in the measured force correspond very well to these marked positions. It is understood that a rupture plane consists of a weak zone compared to the surrounding soil. And just when an existing rupture plane is nearly "impossible", a new plane is created.

This effect is only observed for the Lund-1 sand. The corresponding plots for the Material-2 consisted of completely smooth curves. The reason is probably that (1) the smaller relative density used for this material yielded less dilatancy when the gravel is sheared and (2) the coarser material cannot establish the rupture plane (or narrow rupture zone) observed for the Lund-1 sand.

4. EARTH PRESSURE CALCULATION FOR A TANKER

4.1 Empirical Model

An empirical model to calculate the earth pressure on the vertical surfaces of a tanker bow is derived by the Author on the bases of the performed tests.

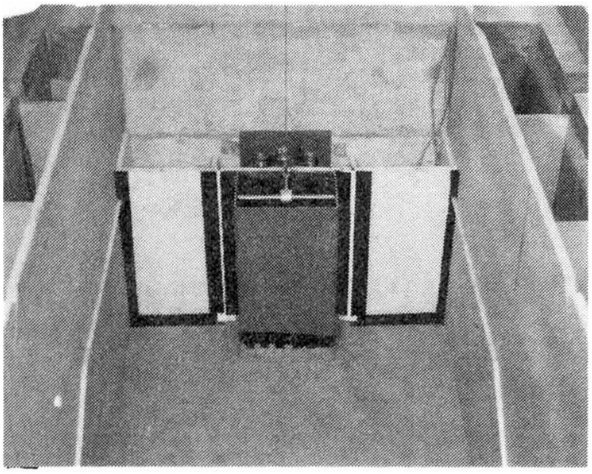

Fig.5 Pier model in the empty test pit

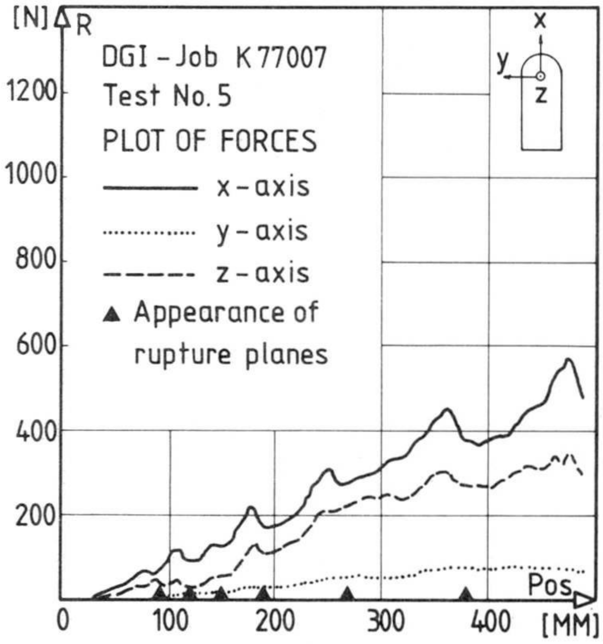

Fig.6 Components of forces plotted against the observed position (penetration) of the model

This model was controlled by the Danish Hydraulic Institute by comparing computed penetrations for a model tanker with results from hydraulic model tests performed by DHI.

Good agreement was found and an example is shown in Figure 7.

The model is presented in [2] and it includes all the parameters varied in the tests (ref. sec.2.3).

4.2 Geotechnical Model

To illustrate the assumptions in the empirical model a tentative expression is presented based on the experience from the test work.

Using the notation in Figure 8 the resultant earth pressure is calculated as

$$F_x = \int_{s_1}^{s_3}(\cos v + \mu \sin^2 v)\, dE^f - \int_{s_0}^{s_1} dF^s + \int_{s_3}^{s_4} dF^s \qquad (1a)$$

$$F_y = \int_{s_1}^{s_3}(\sin v - \mu \cos v \sin v)\, dE^f - \int_{s_0}^{s_1} dE^s + \int_{s_3}^{s_4} dE^s \qquad (1b)$$

$$F_z = -\int_{s_1}^{s_3} dF_v = -\int_{s_1}^{s_3} \mu \cos v \, dE^f \qquad (1c)$$

The coefficient of friction between the soil and the ship is denoted $\mu = \tan\delta$. In Eqs.(1) we have applied the following assumption:

$$dF = \mu \cos v \, dE^f$$

$$dF_t = \mu \sin v \, dE^f$$

where $dF^f = \sqrt{dF_v^2 + dF_t^2} = \mu\, dE^f$ for the front and $dF^s = \mu\, dE^s$ for the sides.

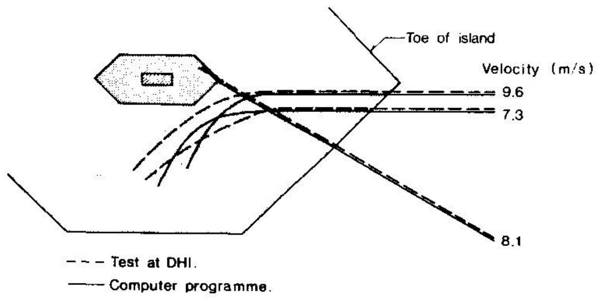

Fig.7 Examples of measured and calculated traces of a model tanker (from [1])

The total weight dG of sections ① plus ② is:

$$dG = \frac{1}{2r}\,[l_1 h_1 (r + l_1/3)\gamma_1 + l_2 h_2 (r + l_2/3)\gamma_3]\; db = c_1\; db$$

(γ_1 and γ_2 are the unit weights of the soil in section ① and ② respectively).
The earth pressure dE^f on a vertical strip on the front db is found by projecting dE^f and dG on the line a which is perpendicular to the resulting force dT on the rupture line:

$$dE^f = \frac{\sin(\varphi + w)\,\cos\delta}{\cos(\varphi + w + \delta)}\; dG = c_2\; dG$$

where $w = \tan^{-1}(h_2/l_2)$.

A reasonable calculation of E^s along the sides is based on the earth pressure at rest K_0 which for a sloping surface can be estimated to (ref.[3]):

$$K_0 = (1 - \sin\varphi)(1 + \lambda \sin\beta)$$

where $\lambda = -0.5$ for $\beta (= \tan^{-1} h_1/l_1) > 0$

The earth pressure is then calculated as:

$$dE^s = \frac{1}{2}\,\gamma (h_1 + h_2)^2\, K_0\; ds = c_3\; ds$$

- ds is the width of an incremental vertical strip and γ can be approximated to $\gamma = (\gamma_1 h_1 + \gamma_2 h_2)/(h_1 + h_2)$.

For a situation where the vessel penetrates the island with $\theta = 0$ the resultant earth pressure is calculated as:

$$F_x = 2r(1 + \mu\,\pi/4)\; c_1 c_2 + 2a\,\mu\, c_3 \qquad (2a)$$

$$F_y = 0 \qquad (2b)$$

$$F_z = -2r\,\mu\, c_1 c_2 \qquad (2c)$$

- a is the horizontal distance between s_1 and the edge of the berm. The values of c_1, c_2 and c_3 are assumed to be constant in the calculation of Eqs.(2).

The rupture plane along the bow is actually supposed to be a narrow rupture zone where the sand after a primary shearing is in a state with a critical void ratio e_k and where the direction of the rupture zone actually coincides with the direction of the strain characteristics.

The angle of internal friction measured in the triaxial tests φ_s should therefore be corrected twofold:

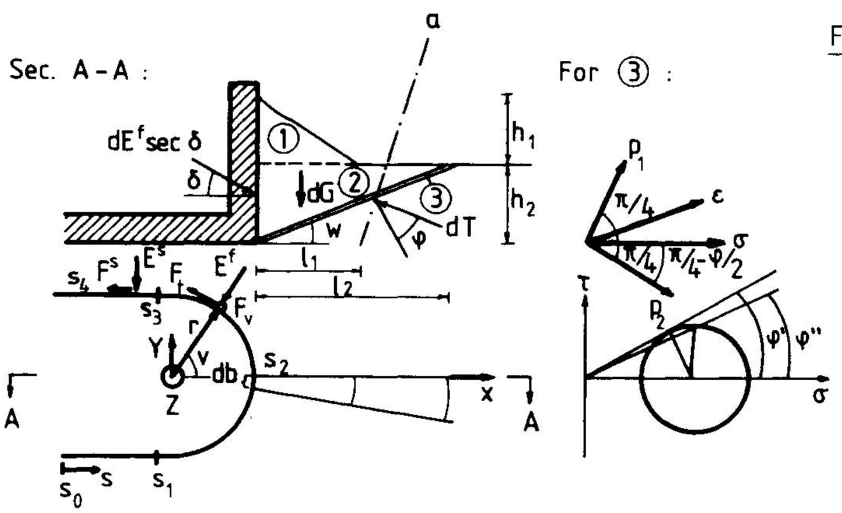

Fig.8 Notation for the earth pressure calculation

(i) The variation of φ with e follows closely the relation $e \tan\varphi = k$, and the critical void ratio is known to be approximately equal to e_{max} for the Lund-1 sand - yielding:

$$\begin{aligned}\varphi' &= \tan^{-1}(k/e_{max})\\ &= \tan^{-1}(0.643/0.88)\\ &= 36^\circ.2\end{aligned}$$

(ii) The sand dilates of course no further when e_k is reached, i.e. the angles between the strain characteristics (ε) (lines with no elongation) and the principal directions (p_1, p_2) which coincide for stresses and strains are $\pi/4$. In Figure 8 it is shown that the angle of internal friction should be reduced to φ'':

$$\varphi'' = \tan^{-1}(\sin\varphi') = \tan^{-1}(\sin 36^\circ.2) = 30^\circ.6$$

It is emphazised that this correction, which is explained more thoroughly in [4], has proved useful in many cases.

Table 1 shows a comparison between calculated and measured values of F where the following values have been used: $\gamma_1 = 14.7$ kN/m^3, $\gamma_2 = 17.1$ kN/m^3, $r = 0.15$ m, $\mu = 0.44$.

Test No.	l_1 (m)	l_2 (m)	h_1 (m)	h_2 (m)	a (m)	F_x cal. (N)	F_x mea. (N)	F_y cal. (N)	F_y mea. (N)	F_z cal. (N)	F_z mea. (N)
3	0.20	0.40	0.10	0.095	0.20	583	458	0	-7	-184	-149
20	0.20	0.30	0.10	0.065	0.25	330	297	0	-15	-102	-79

Table 1 Calculated and measured values of F

5. CONCLUSIONS

A model test series is described and there is referred to an empirical mathematical model to calculate the earth pressure for a vessel when it penetrates an island.

Furthermore, the main results are derived in geotechnical terms in this paper, taking relevant soil parameters into account. With an overestimation of 10 - 30 % the calculation method agrees fairly well with the observed values.

6. ACKNOWLEDGEMENTS

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