Model Tests on Anchoring Capacity of Vertical and Inclined Plates

Essais sur Modèles pour Déterminer la Capacité d'Ancrage de Dalles Verticales ou Inclinées

by S. HUECKEL, Professor, Technical University of Gdansk, Waterworks Institute of the Polish Academy of Sciences, Poland

Summary

The paper deals with model tests carried out for the determination of anchoring capacity of vertical and inclined plates embedded in beach sand.

The form of sliding wedge, the influence of inclination of plates and of distance between the plates is discussed.

Sommaire

L'étude offre une description de plusieurs essais sur modèles arrangés pour déterminer la capacité d'ancrage des dalles verticales ou inclinées, posées dans le sable de dunes.

La forme du prisme d'éboulement, l'influence de l'inclinaison des dalles, ainsi que des distances réciproques sont discutées.

Introduction

Square plates, vertical or inclined, are often used for anchoring sheet-pile bulkheads, the anchoring capacity of which depends on the value of the passive earth pressure developed in front of them. The ultimate passive earth pressure is usually computed by using Coulomb's theory, taking into account friction of the theoretical sliding wedge against the vertical wall. Such computations however lead to uneconomical results. Moreover, this classical theory does not explain adequately the mutual influence of neighbouring plates on their anchoring capacity.

The model tests of BUCHHOLZ (1930) have furnished much information on this problem, but there are, nevertheless, many points unexplained by them. The author initiated model tests to explain some of the problems not dealt with by Buchholz, and these were carried out in the Maritime Construction Laboratory of the Waterworks Institute of the Polish Academy of Sciences in Gdansk.

This paper describes tests carried out during 1955–56 and discusses the results obtained. The tests are being continued with the aim of explaining additional problems.

Aim of Tests

The tests described have been carried out to investigate:

(1) The influence of surface roughness on the anchoring capacity of plates.

(2) The influence of inclination on the anchoring capacity of inclined plates.

(3) How the anchoring capacity of sets of plates is influenced by their mutual positions.

Arrangement of Tests

The ratio of the depth H of the lower edge of the plate to its height h was 2:1 in all tests.

A cross-section of the general arrangement is shown in Fig. 1. Sand was poured to a depth of 1 m in a box 2·0 × 1·4 m by 4 m long. Above this level the sand was formed 0·2 to 0·4 m thick, the left side supported by a vertical wall with a slope on the right side.

The uppermost sand was poured afresh in layers 10 cm thick before each test, and in order to obtain uniformly compacted soil a light roller (63 kg) was passed 100 times over each layer which was covered with a wooden mat. The model anchoring plates were set in while the sand was being put in place.

Sets of plates were loaded by a 'yoke' composed of two small beams screwed together and attached to the ropes in the horizontal position.

The outline of the sliding wedge on the top ground surface was measured from a grid of squares with 10 cm sides impressed on the surface.

Soil Materials used for Tests

All tests were performed using beach sand taken from the seashore of the gulf of Gdansk (Sopot or Brzezno); its grain-size

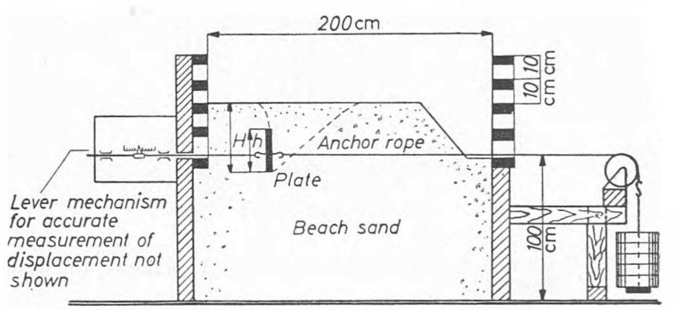

Fig. 1 Cross-section of the arrangement
Coupe du dispositif d'essai

characteristics are given in Fig. 2. Measurements of the bulk density of the sand and of its moisture content were performed before each test, taking for this purpose samples of compacted sand. For each group of tests the mechanical properties of the sand (angle of internal friction and cohesion) were measured on several samples. The mean values obtained are given in Table 1.

Table 1

	Sopot	*Brzezno*
Bulk density (γ)	1·46 ton/m³ (± 1·1%)	1·55 ton/m³ (± 2·1%)
Moisture content (w)	0·79 to 1·55	0·74 to 3·34
Angle of internal friction (ϕ)	34°	36°
Apparent cohesion (c)	0·14 ton/m²	0·18 ton/m²

The apparent cohesion was checked by measuring the vertical height, h_c, to which the soil would stand, applying the following formula:

$$c = \frac{\gamma h_c \sqrt{\lambda_p}}{2}$$

The properties of coloured sand differed slightly from the natural sand ($\phi = 37$ degrees), but otherwise remained within the above divergence limits.

Description of Tests

Four main groups of tests were performed—each containing several series of 5 tests, followed by two groups of supplementary tests: in all about 130 were carried out. The results, after compensations, were considered as sufficiently accurate.

The test results were compensated by computing the average divergence in each series and rejecting those which revealed a divergence greater than twice the average. The number of disqualified tests was insignificant, and the divergence from the mean arithmetical figures in each series of tests did not commonly exceed 5 per cent. The variation limits did not depend

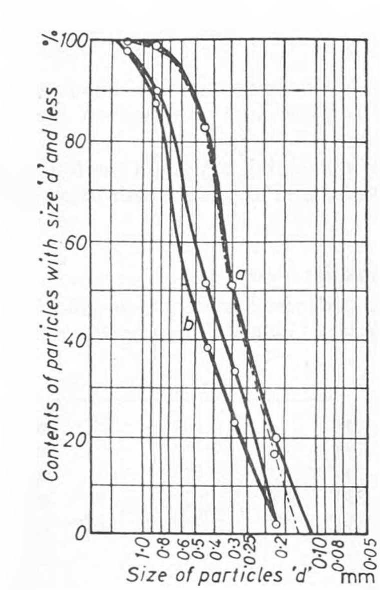

Fig. 2 Grain size characteristics of sand: (a) from Sopot; (b) from Brzezno

Granulométrie du sable: (a) de Sopot; (b) de Brzezno

on whether the sands came from Sopot or Brzezno or on their moisture content. It can therefore be assumed that the tests were all made with the same soil, the properties being the average of the two types.

Group I

Single square steel plates were used, 7·5 × 7·5 cm; 10 × 10 cm, 15 × 15 cm and 20 × 20 cm, set vertically in the sand. Each plate was submitted to a gradually increasing force until a sliding wedge was thrust out in front.

Five tests under the same conditions were performed for each plate, and the following measurements were taken:

(1) The displacement of the plate as the horizontal force increased.

(2) The critical load (assumed equal to the force causing first cracks on the top ground surface).

(3) The ultimate load thrusting out the sliding wedge.

(4) Dimensions of the outlines of the sliding wedge appearing on the top surface of the ground.

In many cases the ultimate load was the same as the critical load, i.e. cracks on the top surface of the ground appeared simultaneously with the rising of the sliding wedge.

The sand used here was from Sopot.

The numeral results are given in Tables 2 and 3; Table 2 containing the average values of the critical and ultimate loads, and Table 3 the average outline dimensions of the sliding wedge measured on the top surface of the ground for each size of plate.

Table 2

Series No.	Dimensions of plates $h \times b$ cm	Average passive earth pressure kg				Remarks
		Critical		Ultimate		
		Q'_{kr}	$Q_{kr} = Q'_{kr} - Q_c$	Q'_{gr}	$Q_{gr} = Q'_{gr} - Q_c$	
1	7·5 × 7·5	24·46	14·76	26·12	16·42	$\gamma = 1{\cdot}46 t/m^3$
2	10 × 10	50·00	38·80	51·90	39·70	$w_{av.} = 1{\cdot}00\%$
3	15 × 15	127·60	110·70	139·50	122·60	$\phi = 34°$
4	20 × 20	234·89	213·19	278·00	256·30	

Designations: Q'_{kr}, Q'_{gr} average critical or ultimate total horizontal force
Q_{kr}, Q_{gr} average critical or ultimate passive earth pressure
Q_c average resistance of the rope

Table 3

Series No.	Dimensions of plates $h \times b$ cm	Average axial lengths of the sliding wedge outline on top ground surface cm		Remarks
		2*A*	2*B*	
1	7·5 × 7·5	23·4	23·2	$\gamma = 1{\cdot}46 t/m^3$
2	10 × 10	29·6	33·8	$w_{av.} = 1{\cdot}00\%$
3	15 × 15	47·2	46·0	$\phi = 34°$
4	20 × 20	61·0	60·0	$H:h = 2:1$

Designations: 2*A* axial length of sliding wedge outline on top ground surface taken along horizontal force
2*B* as above, but in the cross direction

Fig. 3 presents the average curves showing relation between passive earth pressure and displacements. Fig. 4 shows an outline of sliding wedge on the top surface of ground, obtained in one test.

Group II

This group of tests was aimed at examining the influence of the roughness of the plate surface on its anchoring capacity. Six series, each consisting of five tests, were performed with single vertical plates measuring 10 × 10 cm, made of various materials. The following plates were used: wooden plate with horizontal grooves; wooden one with crosswise grooves; wooden smooth plate; glass plate; concrete plate; steel plate.

The test results are shown in Table 4.

Group III

This group concerned inclined plates. The tests were performed on a square steel plate 15 × 15 cm and the depth of the pulling rope under the ground surface was kept constant.

Four series each containing 5 tests were performed. In each series the plate was inclined at different angles to the vertical

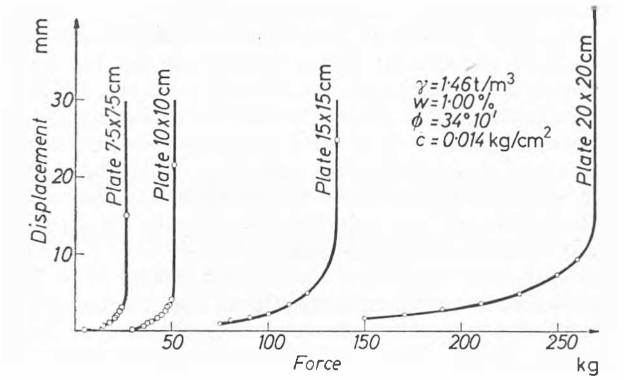

Fig. 3 Curves showing relation between the horizontal force and displacement of plate

Courbes montrant le rapport entre la force horizontale et le déplacement de la dalle

Table 4

Series No.	Type of plate 10 × 10 cm	Average passive earth pressure kg				Remarks
		Critical		Ultimate		
		Q'_{kr}	Q_{kr}	Q'_{gr}	Q_{gr}	
1	Steel plate	50·00	38·80	51·90	39·70	$\gamma = 1{\cdot}55$ t/m³
2	Wooden, smooth	*	—	54·20	42·00	$w_{av.} = 1{\cdot}52\%$
3	Wooden, horizontal grooves	53·00	40·80	54·20	42·00	$\phi = 36$; $H:h = 2:1$
4	Wooden, cross-wise grooves	51·00	38·80	54·20	42·00	* Cracks on the top ground surface appeared by Q_{gr}
5	Concrete plate	*	—	47·30	35·10	
6	Glass plate	*	—	49·30	37·10	

Designations as in Table 2

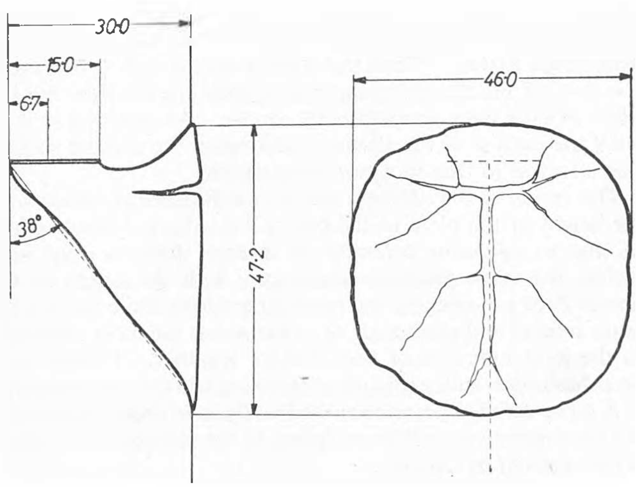

Fig. 4 Outlines of sliding wedge for single vertical plate

Profil du prisme d'éboulement pour une dalle verticale

direction (± 30 and ± 45 degrees). Sand from Sopot was used.

The results are shown in Table 5 and Fig. 5.

Group IV

These tests concerned the anchoring capacity of sets of plates. The sets were made with 3 vertical steel plates each

Table 5

Series No.	Angle of inclination from the vertical* plate 15 × 15 cm	Average passive earth pressure kg				Remarks
		Critical		Ultimate		
		Q'_{kr}	Q_{kr}	Q'_{gr}	Q_{gr}	
1	− 45°	92·50	75·60	95·90	79·00	$\gamma = 1{\cdot}46$ t/m³
2	− 30°	92·30	75·40	95·00	78·10	$w_{av.} = 1{\cdot}00\%$
3	+ 30°	79·80	62·90	83·60	66·70	$\phi = 34°$
4	+ 45°	64·00	47·10	70·00	53·10	* + inclination in direction of horizontal force; − inclination in opposite direction

Designations as in Table 2

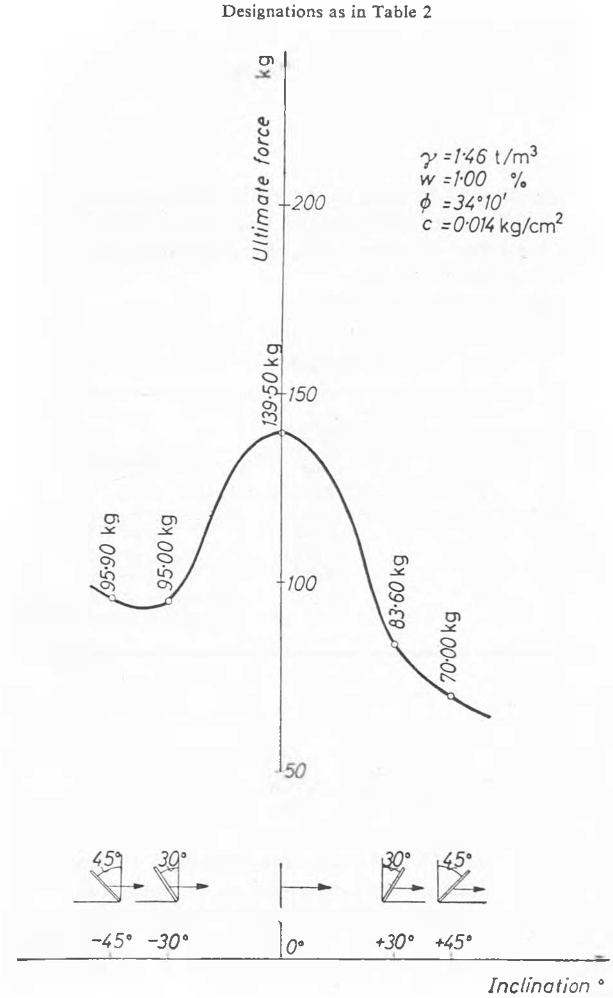

Fig. 5 Comparison of ultimate loads upon inclined plates

Comparaison des charges de rupture pour des dalles inclinées

10 × 10 cm, and the following tests were carried out: (1) set of 3 plates at 14 cm (= $b + 0{\cdot}2H$) centres; (2) the same set at 25 cm (= $b + 0{\cdot}75H$) centres; (3) the same set at 31 cm (= $b + H$) centres; (4) the same set at 36 cm (= $1{\cdot}2(b + H)$) centres; (5) single plate, 10 cm high and 72 cm wide (72 cm = $2(b + H) + b$), where b = width of plate.

Each of the series contains 5 single tests, and sand from Brzezno was used.

The results are shown in Table 6.

Table 6

Series No.	Axial distance between plates 10 × 10 cm	Average passive earth pressure kg		Remarks
		Q'_{gr}	Q_{gr}	
1	14	110	72·2	$\gamma = 1{\cdot}55$ t/m³
2	25	145	107·2	$w_{av.} = 1{\cdot}52\%$
3	31	149	111·2	$\phi = 36°$
4	36	150·5	112·7	Cracks of ground surface appeared at Q_{gr}
5	—	187	149·2	A 'continuous' plate measuring 10 × 72 cm

Designations as in Table 2

Supplementary Groups

In addition to the four groups of main tests, two groups of supplementary tests were carried out.

Group V

These investigations were to determine the resistance of the steel rope. The tests consisted of four series using different depths of sand over the rope, with the rope length equal to the length used in the main tests.

The results are given in Table 7.

Table 7

Series No.	Depth of upper layer cm	Average resistance of pulling rope kg	Remarks
1	10	8·04	$\gamma = 1{\cdot}55$ t/m³
2	15·6	12·60	$w_{av.} = 1{\cdot}52\%$
3	20	15·34	$\phi = 36°$
4	30	20·54	Diameter of rope 1·9 mm Length of rope 1100 mm

Group VI

The tests of this group were aimed to measure, under test conditions, the shape of the sliding wedge along a vertical section parallel to the direction of the horizontal force.

Seven tests were carried out behind a glass on soil with intermittent coloured layers, 1 cm thick and 4 cm apart, when a vertical steel plate 15 × 15 cm was subjected to horizontal forces. The coloured sand extended to a depth of 10 cm. Further tests were made with the plate inclined to the vertical at an angle of ± 30 degrees. Finally, the shape of the sliding wedge produced by a low vertical plate 2·5 × 15 cm was measured.

Conclusions

The results of the above tests may be summarized as follows:

The surface roughness of plate had no essential influence on the value of the ultimate passive earth pressure. Divergences from the average value of passive earth pressure amounted to 10 per cent.

The ultimate passive earth pressure in front of inclined plates is smaller than in front of vertical ones, independently of the direction of inclination; plates inclined at the top in the direction of acting force show the smallest resistance, decreasing at an inclination of 45 degrees to half the anchoring capacity of a vertical plate. It is of some importance that the vertical projection of an inclined plate presents a smaller height than in the vertical position; however, previous tests showed that this inclination did not influence the value of the anchoring capacity by more than 10 per cent.

The anchoring capacity of three plates located at $(b + H)$, centres is the same as the capacity of three single, isolated plates. If placed closer together, the anchoring capacity of the set decreases. Hence, the distance between centres $a = b + H$ may be considered as the limiting distance. A set of plates disposed in this manner shows an anchoring capacity of about 33 per cent less than anchoring capacity of a continuous plate having a width equal to the distance between extreme edges of outside plates. It was impossible to prove a 'critical space' at which the anchoring capacity of a set of plates was equal to the anchoring capacity of a continuous plate. Even at an axial distance $a = (b + 0{\cdot}2H)$, the anchoring capacity of the set was smaller than that of a corresponding continuous plate.

The shape of the sliding wedge in front of single isolated plates resembled a calyx with a wavy outline, having an average inclination to the level of 65 degrees at the sides, and 40 degrees in the direction of the horizontal force. This latter inclination was the same when caused by vertical or inclined plates, except where plates sloped back at 45 degrees, when the inclination of the wedge reached 52 degrees. On the top surface of the ground the sliding wedge presented a figure similar to an ellipse with average axis lengths:

$2A = 1{\cdot}5H$, in the direction of horizontal force
$2B = b + H$, in the cross direction

When a low plate was used $(H/h > 5{\cdot}5)$ the sliding wedge was narrow and funnel-shaped, but its outline upon the top surface was like an ellipse with the above-mentioned dimensions. The sets of plates at centres not less than $a = (b + H)$ developed in front of each plate separate, quite independent, sliding wedges having outline top dimensions identical to those from single plates. When the centres were $a = b + 0{\cdot}2H$ and $a = b + H$, the sliding wedges overlapped one another, but the effect of each plate was distinctly visible. At centres $a = b + 0{\cdot}2H$ the outline of the sliding wedge upon the ground surface was identical to that of a continuous plate.

The values of the ultimate passive earth pressure varied with the height of the plate to the power 2·8. Such a result might be due to apparent cohesion (if internal friction only were acting, the earth pressure would vary with the height to the power 2) or to changing the plate dimensions while leaving the grain sizes of soil unaltered; or, what seems the most probable, to the joint influence of both factors together. Further tests on cohesionless soils are in progress to explain this phenomenon.

A more detailed description and analysis of these results with critical suggestions will be published in the periodical *Archiwum Hydrotechniki* in Gdansk.

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