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Horizontal Loading Tests on Large Diameter Piles

Essais de Chargement Horizontal sur Pieux de Grand Diamètre

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SYNOPSIS

Two steel tubular piles of the Easterscheldt cableway with diameters of 3.1 m and 4.1 m were testloaded by horizontal forces up to 600 kN resp. 700 kN. The embedded lengths of the piles were 18 m resp. 20 m and the forces were applied on a level of 33 m resp. 50 m above the sea floor. The subsoil consisted of sand. The horizontal displacements of the piles were registrated optically at three reflector points above the surface of the water. Furthermore a distance measuring device on the seabottom recorded the movements at that level. The angular rotations were measured by means of an electrical inclinometer which slid along a fixed rail. In the embedded part of one of the piles electrical strain gauges were installed. For practical reasons a quick, static and simple test was required. Nevertheless interesting information was obtained about the horizontal deformations and the seize of irreversibility of these informations, especially at sea-floor level. The deflection curves deduced from the integration inclinometer measurements and from the measured strains were in accordance with the deformation measurements.

INTRODUCTION

In 1973, in connection with the damming of the Easterscheldt estuary, a start was made with driving the piles for the supporting structures of a cableway to be used for dumping blocks of concrete for the final closure of the remaining openings in the dam.
For this purpose, with the aid of the mobile offshore platform (spud-leg pontoon) "Stevin 73", 12 steel tubular piles ranging in diameter from 3.1 m to 4.8 m were driven into the bottom of the estuary. These piles were subsequently provided with a superstructure on top of which the cableway would be guided.

In order to ensure that the cable would not become dislodged from its bearings in consequence of an unfavourable combination of loads, two requirements had to be fulfilled by the movements of the pile head: the horizontal displacement δ_H in the direction perpendicular to the centre-line of the dam must not exceed 0.25 m, and the angular rotation ϕ in the vertical plane through the centre-line must not exceed 1^o.

Since the predictions as to the maximum magnitudes that δ_H and ϕ could be expected to attain for the proposed pile dimensions and pile penetration depths varied rather considerably and were indeed for the most part above the specified limits, it was decided to carry out horizontal tensile tests on two of the first batch of these piles to be driven.

The object of the tests was:
- to check whether the test piles fulfilled the requirements laid down for them;
- to obtain insight into the mechanisms and orders of magnitude of the soil parameters which determine the deformation process of large-diameter tubular piles under the influence of horizontal loads;
- to obtain insight into the nature and extent of the measures that would be necessary if the test piles were found <u>not</u> to conform to the requirements;
- to obtain more accurate prognoses as to the deformations that could be expected in piles subsequently to be driven.

LOCATION

For practical reasons it was decided to perform a horizontal tensile test in which a static force would be applied to the pile head by means of a cable. Piles 9 and 10 located in the northern final gap for closure were selected for testing. The cable was pulled by winches installed on the adjacent Roggenplaat artificial service island (see Fig. 1).

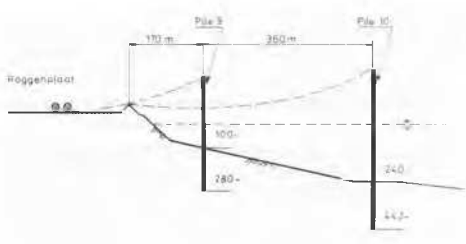

Fig. 1 Situation

Although the significant load would have had to act in a direction perpendicular to the centre-line of the dam, the force actually applied by means of the cable had a different direction on account of these winching arrangements.

The condition of the soil at the piles was determined by means of static penetrometer tests which were performed in combination with pressiometer tests before the piles were driven; the results of both sets of tests are presented in the same diagram (see Fig. 2).

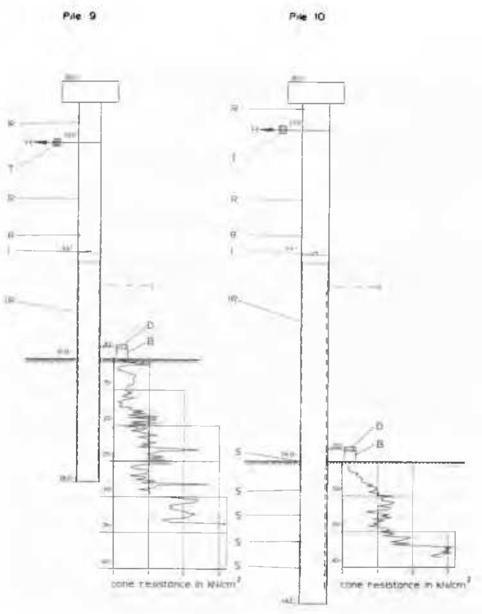

Fig. 2 Subsoil and instrumentation

T = tensile load cell	IR = inclinometer rail
H = horizontal force	D = distance measuring device
R = reflector	
I = optical inclinometer	B = concrete block
	S = strain gauges

The subsoil in the final gaps of the dam consists mainly of sand intersected by thin layers of clay and/or silt. The upper strata are formed by fairly loosely packed young marine sand (Holocene), while at greater depths, below 30 to 40 m - N.A.P. (= Standard Amsterdam Datum), the more densely packed older Pleistocene formation is encountered.

Information of thickness and penetration depth of the test piles is also given in the two diagrams.
The water level varies between approximately 2 m + N.A.P. and 2 m - N.A.P.

In order to prevent scour between the piles, the bottom (bed of the estuary) was locally covered with gravel and steelworks slag.

INSTRUMENTATION (see Fig. 2)

- The requisite horizontal force applied by means of the cable was continuously recorded with the aid of a tensile load cell installed close to the pile. The horizontal component of the recorded force constituted the relevant horizontal load which had to develop the desired bending moment at the level of the bottom: for pile 9 the maximum magnitude of the moment was about 16,000 Nm and for pile 10 about 31,000 Nm.

- The horizontal displacements of the piles at three reflector points above the surface of the water were optically observed with the aid of Distomat distance measuring devices installed on the dike of the service island. Furthermore, divers placed a concrete block on the bottom of the water at some distance from the pile to be tested. A distance measuring device in the form of a rod pressing against the pile was mounted on the block and continuously recorded any changes in the distance between the block and the pile.

- The angular rotation associated with each increment of the pile test load was observed with the aid of a levelling instrument (inclinometer) mounted on a sheet of glass and installed on the measuring plateau at a level of 4.4 m + N.A.P.

- Furthermore, the angular rotations from 3.25 m + N.A.P. down to the tip (i.e., the toe) of the pile were measured for each value of the test load by means of an electromagnetic inclinometer which slid along a fixed rail extending down into the pile. Before the pile was driven, this guide rail was bolted to the inside of a protective tube which had been welded to the inner surface of the wall of the tubular pile.

- Before pile 10 was driven, studs were welded to the inner surface of its wall on the tensile and on the compressive side of the pile at five different levels. Electric strain gauges were installed between the respective sets of studs. The studs and also the electric cables of the gauges were accomodated in channels extending longitudinally and attached to the inner surface of the wall of the pile. The channels were filled with synthetic resin which subsequently hardened, so that all these components behaved in the manner of a monolithic structure under the influence of the pile-driving accelerations.

RESTRICTIONS

- On the one hand, permanent deformations of the pile and soil were undesirable and, on the other hand, the test results were required quickly for utilization for the sake of further progress of the job. For these reasons the tensile test was performed as simply and quickly as possible, with the minimum of obstruction to navigation on the estuary.

- The maximum permissible force to be applied was determined at 600 kN and 700 kN respectively; at bottom (sea bed) level these forces developed the maximum anticipated bending moments of about 16,000 Nm and 31,000 Nm respectively. The structure had originally been designed to resist moments of these magnitudes, which in reality would be due to static as well as to dynamic forces.

- The test load was to be applied in three incremental stages up to its maximum value, subject to the condition that the displacements occurring after each load stage were not allowed to exceed certain specified values; if they did, the test would have to be stopped (see Fig. 3).

- Furthermore, after each stage, the pile was to be unloaded as completely as possible, with the condition that no significant permanent displacements were allowed to occur.

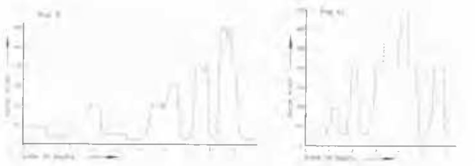

Fig. 3 Time-loading diagrams

- The time-consuming inclinometer measurements, taking 15 - 20 minutes, were allowed to be performed only at the end of each stage and for zeroing in the initial and the final position.

- In the testing of pile 9 a limited amount of unloading (by 30 - 50 kN) and reloading was interposed at the end of each load stage. For practical reasons this extension of the testing program was omitted in the case of pile 10.

- During the measurements, disturbances were found to occur in the readings in consequence of radio transmitters, oscillations of the tensile testing cable in the wind, vibrations generated in the pile itself by wind, waves and/or current, impact effects caused by ships, etc.

- The results of the measurements were also affected by random loads of varying duration which occurred during the installing of the cable, incidental loads of long duration due to trouble with the measuring equipment, and partial slip of the cable at pile 10.

TEST LOADING OF PILE 9

Pile 9 was tested on 2 November 1973. The displacements above water as observed at the top reflector (23.20 m + N.A.P.) are presented in Figure 4a.

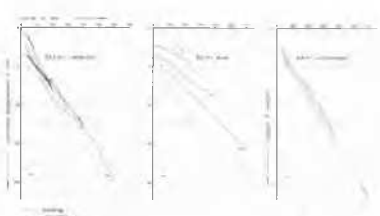

Fig. 4 Pile 9: measured displacements and rotations

Furthermore, the displacements just above bottom level have been plotted in Figure 4b, while the angular rotations at a height of 4.4 m + N.A.P. are given in Figure 4c.

Since the pile had, before the actual start of the test, already been subjected to all sorts of horizontal loads due to a variety of causes and circumstances, corrected zero readings were introduced for the reflector displacements and angular rotations. The zero of the load-bottom displacement graph was not corrected, because the zero reading for this had been obtained already many days before any incidental initial loads had acted on the pile. The measurements performed with the rail-guided inclinometer showed that while every deviation from evenness of the rail was faithfully reproduced, irregularities nevertheless occurred as a result of faults in the recording apparatus and of disturbances from outside.

TEST LOADING OF PILE 10

Pile 10 was tested on 10 January 1974. The experience gained in the testing of pile 9 was useful in the execution of this test, which was in principle identical with the previous one.

During the test a discontinuity occurred in relation to the planned loading scheme: while the load was being increased to 700 kN, the cable slipped through the cable clamp for a short distance when a load of 550 kN had been reached; as a result of this incident the load suddenly decreased to about 400 kN.

A considerable amount of difficulty was encountered in installing the concrete block on the bottom of the water.

No acceptable values were recorded up to the instant when the cable slipped.

The three load-displacement graphs and the angular rotation measurement at 4.4 m + N.A.P. are presented in Figures 5a to 5d.

Fig. 5 Pile 10: measured displacements and rotations

The measurements performed with the rail-guided clinometer yielded better results than they did in the test on pile 9, though there were still a few disturbances.

Some of the integrated inclinometer results at various load values are indicated in Figure 6.
A notable feature of these was that the primary load gave deflection curves that were in reasonably good agreement with the other measured results. However, when the loads were removed and subsequently reapplied, the integrations of the slope measurements in most cases gave S-shaped deflection curves which must probably be attributed to creep of the subsoil (see also Fig. 3). During the application of loads in excess of 200 kN there were likewise indications

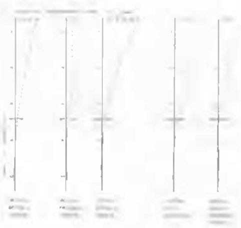

Fig. 6 Integrated inclinometer results

of creep phenomena; the continuously recorded cable force was found to decrease in course of time although the cable was not slackened.

On evaluating the strain gauge results it emerged that all the gauges yielded improbable values up to the maximum load of 700 kN. Thereafter, and furthermore in the "sway test" performed on 29 January 1974, the readings obtained at 200 kN, 400 kN and 700 kN, were found to have quite reasonable values.

The bending moment diagrams obtained at various loads, and the bending moment diagram for a load of 700 kN obtained from them by extrapolation, are indicated in Figure 7.

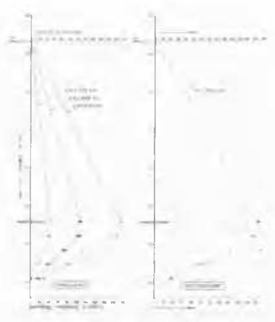

Fig. 7 Bending moments from strain gauges results

SUMMARY AND CONCLUSIONS

The results of the tests on the two piles lead to the following conclusions:

- The structures in question fulfilled the specified requirements in so far as horizontal displacement and angular rotation were concerned.

- For the measuring points located above water the relation between load and displacement was practically linear. It should be borne in mind, however, that the displacement is actually composed of the so-called "proper deflection" of the steel pile and the deflection due to the behaviour of the ground in which the pile is installed.

- Clear indications were obtained with regard to the occurrence of irreversible soil behaviour. Because of the relatively short distance between the concrete block and the pile the displacements measured close to the bottom of the water probably did not represent correct absolute values, but they did provide an indication of irreversibility in the behaviour of the system.

- Some idea of the displacements of an infinitely rigid pile were obtained by subtracting from the measured displacements (at the level of the reflectors) and angular rotations at 4.4 m + N.A.P. the displacements and angular rotations due to the "proper deflection" of the pile for the above-ground part thereof. In Figure 8 the deformations of an infinitely rigid pile have been plotted for all the primary loads.

- These results, as also the deflection curves deduced from the integrated inclinometer measurements (see Fig. 6) and from the measured bending moment diagram according to Figure 7, show that no major errors were introduced by the assumption that the pile is infinitely rigid below bottom (sea bed) level.

- On the basis of this last-mentioned assumption the displacements and angular rotations at the pile head for the maximum loads of 600 kN and 700 kN respectively, and also for the inclined position of the pile after completion of testing, are listed in the table below.

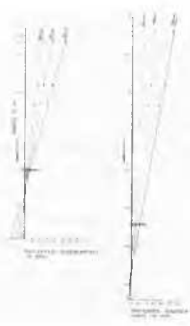

Fig. 8 Deformation of infinitive rigid piles

displacements δ_{Htop} angular rotations φ_{top} at pile head	PILE 9		PILE 10	
	27 m + N.A.P.		30 m + N.A.P.	
on loading	600 kN	0 kN	700 kN	0 kN
δ_{Htop} due to "proper deflection"	10.45	0	13.75	0
δ_{Htop} due to $\varphi_{0bottom}$	9.95	3.15	9.4	2.15
δ_{Htop} due to $\delta_{0bottom}$	1.5	1	2.0	1.5
δ_{Htop} total [mm]	22	4	25	3.5
φ_{top} due to "proper deflection"	4.05	[illegible]	3.88	0
φ_{top} due to $\varphi_{0bottom}$	2.69	0.85	1.4	0.40
φ_{top} total [mm/m]	6.74	0.85	5.62	0.40

ACKNOWLEDGEMENTS

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