Pile Foundation Problems in White Chalk

Problèmes de Fondation sur Pieux dans la Craie

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SYNOPSIS The unfinished motorway from Copenhagen to Germany is crossing the approx.5 km wide stretch of water called Storstrømmen separating the islands of Zealand and Falster. Geotechnical investigations for the foundation of this link via the islet of Farø - the Farø-bridges - for the Danish Road Directorate have shown different problems concerning the 75 million years old white chalk consisting of microscopic crystals with an eroded surface. Through an extensive amount of laboratory and in situ tests an important material for the geotechnical design has been established for this rather special soil.

INTRODUCTION

In many respects, foundations on weathered chalk represent a rather special area within soil mechanics. The chalk covers the entire interval between rocks and soft soils. Moreover, the geotechnical behaviour is seldom explainable by means of conventional soil mechanics and generally, this is reflected in the literature describing case stories and load tests.

PROJECT AND FOUNDATION

The two bridges - 1.6 km and 1.7 km long respectively - for the motorway crossing the Storstrømmen, will be constructed as girder bridges founded on piles in weathered white chalk respectively direct in the glacial deposits. The suspended spans are designed as a cable-stayed structure.

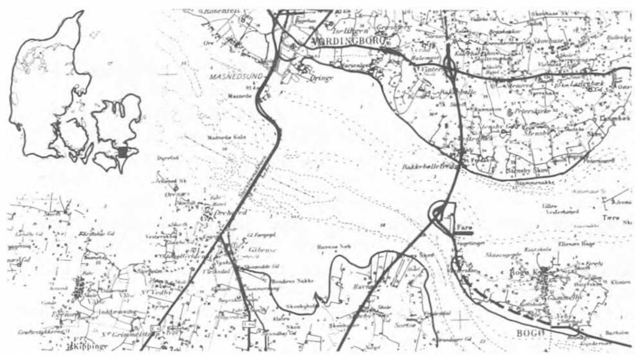

Fig.1: Location of the Farø-bridges to the east of the existent "Storstrømsbro".

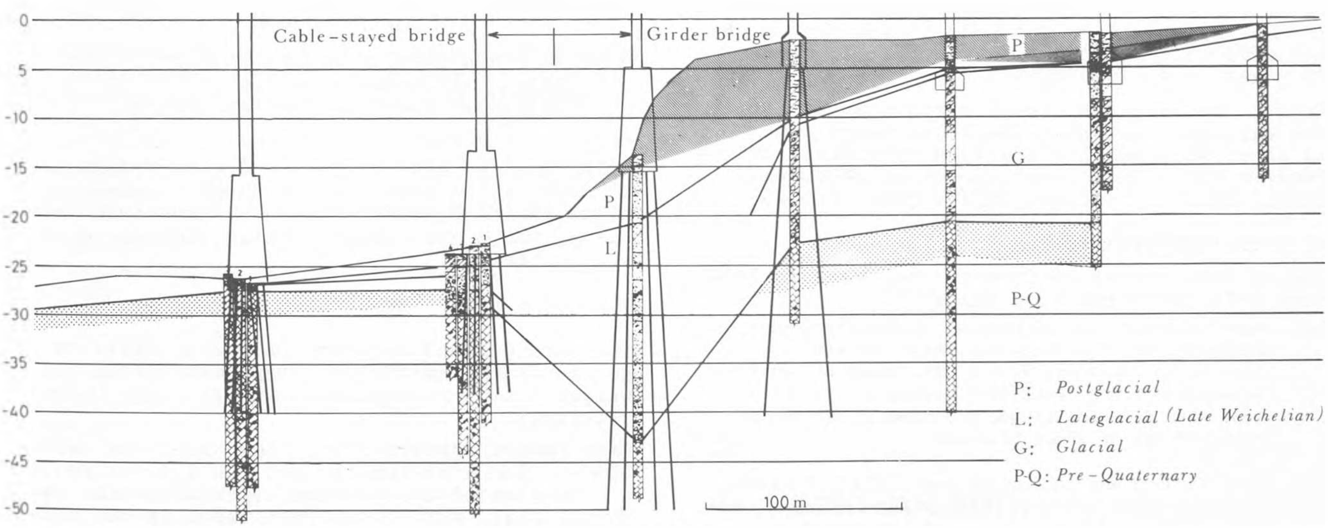

Fig.2: One pylon and one side span pier for the cable-stayed bridge and two piers for the girder bridge to be founded on piles in weathered white chalk. The figure also shows the characteristic geological structure.

The geotechnical investigations comprise 60 borings, from which the method of foundation, foundation levels and soil characteristics has been extracted. Fig.2 presents the foundations of a few piers (vertical scale enlarged 5 times compared to the horizontal scale).

All pile foundations are designed with battering piles placed in one or two concentric circles and the pile tips are in most piers planned to be stopped in the stronger part of the chalk.

GEOLOGY AND CLASSIFICATION

The borings have shown Quarternary deposits of varying thickness, lying on the Pre-Quarternary which occurs as only slightly lithified white chalk of Senonian age. The white chalk represents a level in the Senonian about 200 m below the original Senonian surface. This is interpreted as being caused by extensive erosion throughout most of the Tertiary and Quarternary. The chalk surface in the area as a whole is a level plane, dissected by a few deep valley depressions. The surface appears to have been formed by glacial processes.

The Quarternary consists of deposits from, and after, the last ice age (Weichselian).

The white chalk consists of coccoliths and it is very fine grained. Scanning electron microscopi have shown that the grain size generally lies between about 0.5 and 10 µ varying from single crystals to crystal aggregates. The fragmentation of the coccoliths throughout many millions of years has formed the chalk and several hundreds of meters were deposited. The physical compression and chemical reactions between the pore fluid and the adjacent particles are the processes by which loosely consolidated chalk ooze is converted into lithified chalk. The chalk encountered varies from unconsolidated to partially lithified, i.e. it is less compact than typical chalk.

Generally, the weathered chalk is located from 20 meters below sea level, deeper seabed level or valley depressions. The upper zone of the chalk is strongly weathered with a water content w of 25 % which is a little lower than the water content of the stronger chalk below (27 - 30 %). The corresponding void ratios e are 0.68 and 0.73 - 0.81, and the bulk densities γ are 20.2 and 19.4 - 19.9 kN/m^3.

From a visual classification and a few SPT-tests the strongly weathered chalk has been classified as grade VI gradually changing into grade III (medium hard) from about 35 meters below sea level. The SPT N-values varies from 3 to 25.

IN SITU INVESTIGATIONS

The in situ investigations in the chalk include bore hole tests and load tests:

(i) Bore hole tests in 33 borings in 25 pier positions including 150 pressuremeter tests (Menard, 1975), vane tests covering 120 m, 6 SPT, about 60 meters of cone penetration tests (SPT) using an electrical cone with friction sleeve and finally two dynamic ramsoundings of about 15 m each.

(ii) Test driving and loading of two 0.35 × 0.35 m reinforced precast concrete piles with ABB joints, see fig.3. Before driving with an Åkermann M14 (5 t drop hammer, drop height 1 m), the piles were lowered through ø 0.50 m casings prebored through the glacial deposits to the chalk surface. The pile tips were instrumented with strain gauge force transducers monitoring the tip resistance.

(iii) Load tests on circular plates, ø 0.12 to ø 1.12 m, some 20 km from the bridge site in an open chalk pit. In this area, the chalk is very similar to the grade V - VI chalk in the line of the bridge.

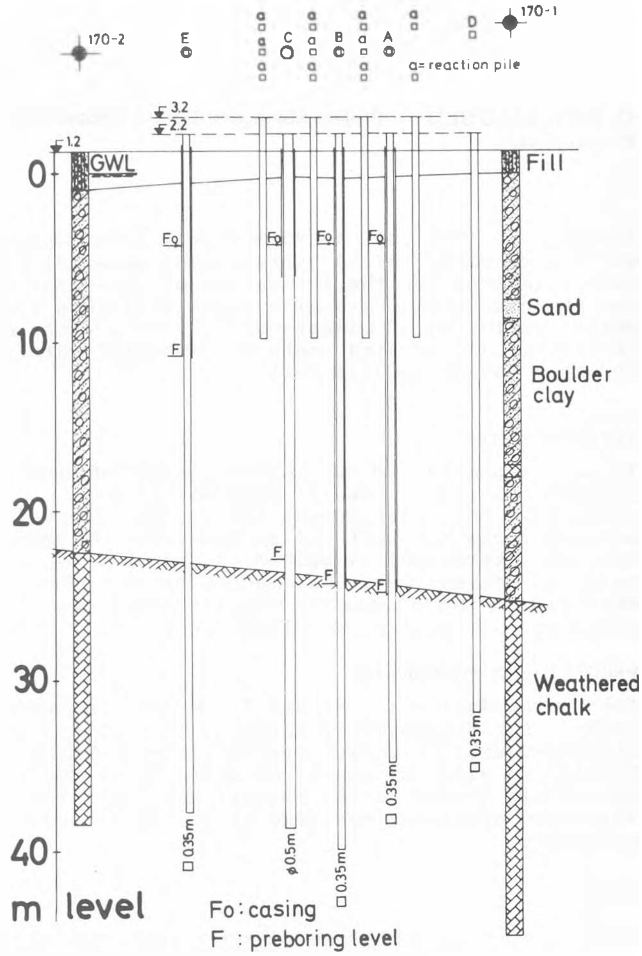

Fig.3: Pile load tests. Plan and section.
Pile C has not been tested yet,
pile D and E were used for test driving.

Additionally, several laboratory tests have been carried out in order to establish a connection to the Danish experience in foundation on the white chalk, which has caused serious problems at several occasions.

BORE HOLE TESTS, RESULTS.

The strength and deformation characteristics of the chalk are remarkably homogeneous within the bridge site, although the local variation is considerable.

This result appears quite clear from the variation of the pressiometer modulus E_{pr}. In fig.4 E_{pr} is plotted against the depth below the senonian chalk surface as registered in the borings or as estimated from the vertical variation in the chalk in a few borings where the Senonian chalk surface probably has been eroded.

To a certain extent, trends similar to the ones in fig.4 have been recognized in any other in situ test, see fig.5, including test driving of 0.2 m^2 precast concrete piles with a Mench MRB1000 steam hammer in 18 pier positions.

The local as well as the overall variation is more or less dependent on the size of the soil volume influenced by the test equipment, and the best correlation to the performance of the piles has been established from the pressuremeter tests (ø 70 mm prope).

International, as well as Danish experience shows, that the weaker chalk is unfitted for pile foundation of a bridge and consequently, the relatively well-defined transition into the stronger chalk has great importance to the project in question.

LOAD TESTS, RESULTS

The load tests on piles and plates are carried out as maintained load tests (duration of each load step greater than 4 minutes) as well as constant rate of penetration tests (rate of settlement varying from 8 to 400 mm/hour).

In spite of great variations in the test procedures no significant difference has been detected on the load settlement curves. This is interpreted as a reasonable confirmation of the high permeability of the chalk, which allows us to consider all tests as perfectly drained (changes in pore pressure = 0). Consequently, any time dependent deformation is believed to be due to creep in the chalk skeleton.

Concerning the pile load tests the interest has been concentrated on the tip resistance, because the tests have shown that the skin friction only has a secondary influence. Some 40 days after driving the skin friction τ has been measured within the interval of 15 - 40 kN/m^2, more or less independent of the chalk grade. This is in agreement with several other investigations (Hobbs and Healy, 1979).

It is emphasized that any attempt to correlate the friction sleeve resistance from CPT with the skin friction τ has failed, while the remoulded vane shear strength seems to be a reasonable measure of τ.

The load tests show a surprisingly uniformity in the relation between the mean stress $\bar{\sigma}$ = (load Q/ area A) for the first time load (Q greater than any previous Q) and the relative vertical settlement $\bar{\varepsilon}$ = (settlement δ/diameter d). Figs.6 and 7 present characteristical test results for a plate and a pile. Fig.7 shows the $\bar{\sigma}$-$\bar{\varepsilon}$-relation of the pile top as well as the tip (compression test, pile B).

In a dimensionless form all $\bar{\sigma}$-$\bar{\varepsilon}$-curves may be described within an acceptable accuracy by the equation:

$$\bar{\varepsilon} = \bar{\varepsilon}_b (\bar{\sigma}/\bar{\sigma}_b)^n \quad , \quad (2 \lesssim n \lesssim 3) \qquad (1)$$

$\bar{\varepsilon}_b$ is the value of $\bar{\varepsilon}$ at $\bar{\sigma} = \bar{\sigma}_b$, which in this connection has been defined as the stress $\bar{\sigma}$ giving a permanent settlement $\bar{\varepsilon}$ = 0.1 after unloading to σ = 0. $\bar{\sigma}_b$ is then equal to the characteristical ultimate bearing capacity according to the Danish code of practice DS 415, from which applicable safety factors have to be used, too.

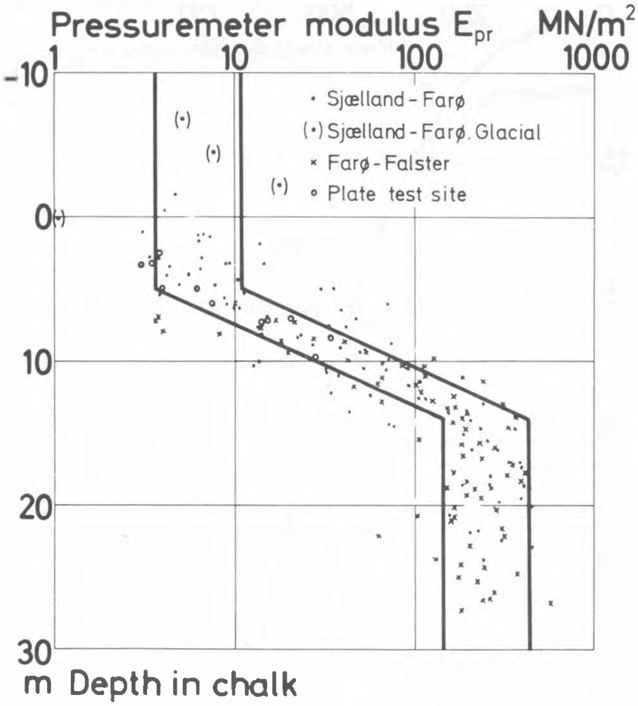

Fig.4: Pressuremeter modulus E_{pr} vs. depth in chalk. The curves limiting 85 % of the tests correspond with a factor 3 between min. and max. E_{pr}.

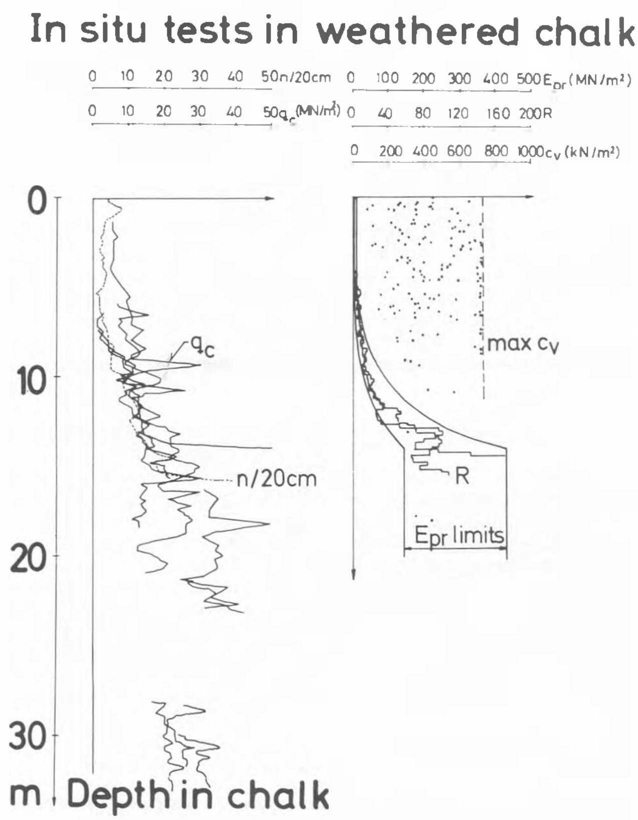

Fig.5: In situ tests in chalk. The driving record shown is a typical one. The maximum measurable c_v is 720 kN/m^2.

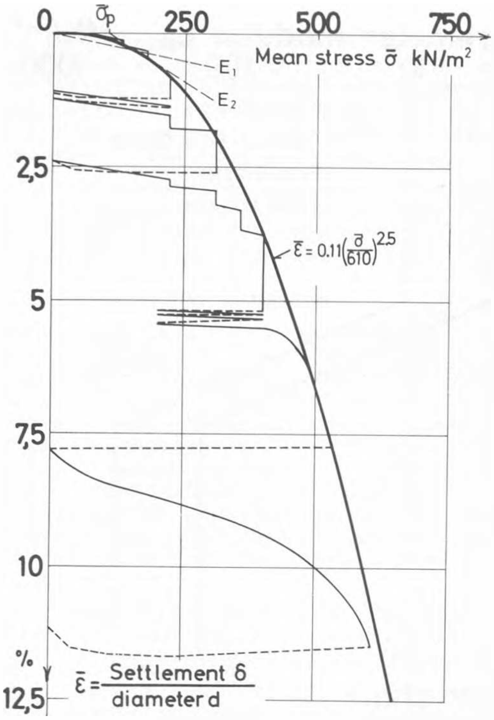

Fig.6: Plate load test, ⌀ 1.12 m. Measured load/settlement curve (1) fitting primary load points. Calc.load/settlement relationship acc. to proposed model, lines E_1 and E_2.

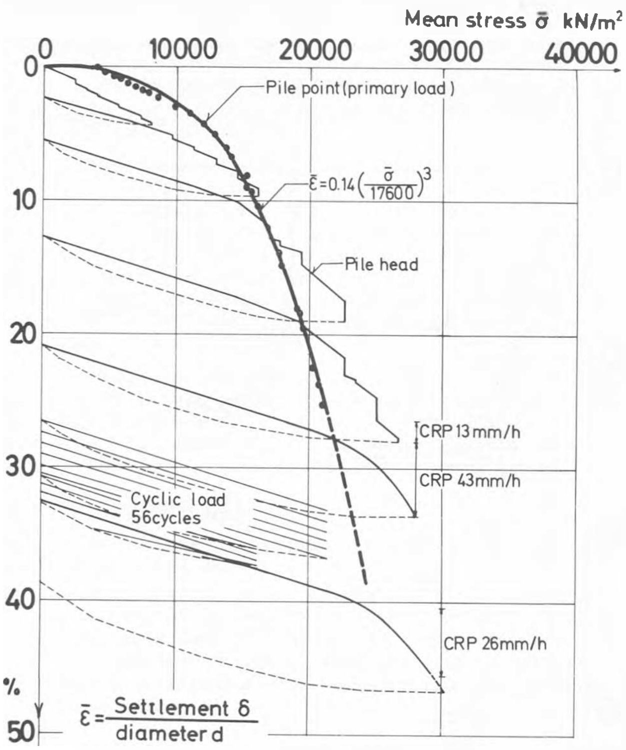

Fig.7: Pile load test, pile B. Measured load/settlement curve for the pile head, primary load points for the pile point and curve (1) fitting these.

Equation (1) has been confirmed by 10 tests covering $(0.12 \leq d \leq 1.12$ m), $(500 \leq \bar{\sigma}_b \leq 18{,}000$ kN/m²), $(\bar{\varepsilon} \leq 1)$ and chalk grade III - VI.

The pile load tests A and B give $\bar{\sigma}_b = 13400$ resp. 17600 kN/m² and $n = 3$, while the plate load tests give $520 \leq \bar{\sigma}_b \leq 1500$ kN/m² and $2 \leq n \leq 3$.

As mentioned, the results of the load tests indicate that $\bar{\varepsilon}$ calculated from (1) includes initial settlements and settlements due to consolidation. Additionally, the creep has to be considered and for normal engineering purposes the creep (expressed as the relative settlement $\bar{\varepsilon}_s$ per time decade at a constant stress level $\bar{\sigma}$) may be calculated from $\varepsilon_s = 0.1 \times \bar{\varepsilon}$ from equation (1).

PILE DESIGN

The design problem is to establish a relation between $\bar{\varepsilon}_b$ and $\bar{\sigma}_b$ and the in situ test results, a problem which has not been solved theoretically yet.

The ultimate end bearing capacity (defined as $\bar{\sigma}_b$) has been compared to theoretical or empherical capacities calculated from the strength parameters of the chalk. An acceptable approximation is determined by the Janbu driving formula (Janbu, 1973) or by the theoretical bearing capacity in cohesionless soil using the "undrained" shear strength c_u calculated from the pressuremeter limit p_l (Baguelin et al, 1978).

These methods including conventional bearing capacity formulas based on CPT, SPT, vane tests or triaxial tests (reference 2 and 3) give bearing capacities between 30 and 80 % of the values measured.

Conservatively, a skin friction τ of 20 kN/m² may be assumed, independent of the grade of the chalk.

CONCLUSION

From the extensive test program of weathered white chalk a reasonable design bases has been established. Although several problems concerning the properties of the chalk have not been solved yet, the foundation project of the 15 piers is based on ⌀ 0.711 close-ended steel pipe piles loaded by 5 MN in compression and about 1 MN in tension (expected settlement < 30 mm).

In order to verify those capacities, compression/tension load tests will be carried out in all pier positions using the steel pipe piles and during the driving an extensive stress wave monitoring program is planned.

REFERENCES

Ménard, L. (1975). The Ménard Pressuremeter. Interpretation and Applications of Pressuremeter Test Results. Sols-Soils 26.

Piles in weak rock. Second Géotech.symp.in print. Géotechnique. Vol.XXVI, No.1, March 1976.

Recent developments in the design and construction of piles. Proc.Conf. London, March 1979.

Code of Practice for Found.Engng. (1978). (Trans.into English of DS 415), Danish Geotech.Inst., Bulletin No.32.

Janbu, N. (1951). Beregning af frittstående pelers bruddlast og tillatte belastning. Teknisk Ukeblad, b.98, nr.26.

Larsen, G., Bæk-Madsen, C., Foged, N. (1978). Storstrømmen. Geological conditions in the Farø-line. Danish Geotech. Inst., Bulletin No.31.

Hobbs, N.B., Healy, P.R. (1979). Piling in Chalk. Direct. of Civ.Engng.Services. PSA Techn.Guide No.24.

Baguelin, F., Jézéquel, J.F., Shields, D.H. (1978). The Pressuremeter and Foundation Engineering. Trans Tech Publications, Clausthal.