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Ship Collision and the Farø Bridges

Collisions de navire et ponts de Farø

Schiffsanprall und Farö-Brücken

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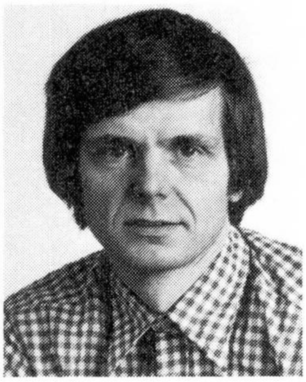

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SUMMARY
The paper describes the navigational situation at the Farø Bridges, at present under construction, and further describes how the design assumptions for the ship collision loading case have been derived from recordings of the present ship traffic in the area by means of theoretical analyses and prognoses. The calculated effect of the ship collision load on the elements of the substructure is mentioned and compared with the results of independent calculations based on different principles.

RÉSUMÉ
L'article décrit la situation de la navigation sous les ponts de Farø actuellement en construction. La probabilité de collisions de navire a été estimée sur la base de la densité du trafic maritime actuel dans la région, au moyen d'analyses théoriques et de pronostics. L'effet calculé de la force de collisions de navire avec les éléments de l'infrastructure est mentionné et comparé avec les résultats de calculs indépendants basés sur différents principes.

ZUSAMMENFASSUNG
Der Artikel beschreibt die Navigationslage an den Farö-Brücken, die sich im Bau befinden. Die Lastannahmen eines Schiffsanpralls wurden aus Aufzeichnungen über den gegenwärtigen Schiffsverkehr im Gebiet sowie theoretische Analysen und Prognosen getroffen. Die berechnete Einwirkung des Schiffsanpralls auf die Elemente des Unterbaues ist erwähnt und mit den Ergebnissen von unabhängigen Berechnungen verglichen.

1. INTRODUCTION

1.1 General Briefing

The Farø bridges are two motorway bridges, one leading from Sjælland to the small island of Farø and the other leading from Farø to Falster. They will form part of the motorway connection from Copenhagen to Rødby and Germany, see Fig. 1. Since 1965 Christiani & Nielsen A/S has been acting as consultants to the Danish Road Directorate for these bridges. A great number of studies, sketch proposals and preliminary designs have been worked out, concluding in a tender project presented in April 1979. Since the construction contracts were signed in May 1980, Christiani & Nielsen A/S has worked out the detailed design for all the bridge piers, pylons and abutments including the foundations, and is also performing the supervision of the site construction. The bridges are scheduled for completion in 1985.

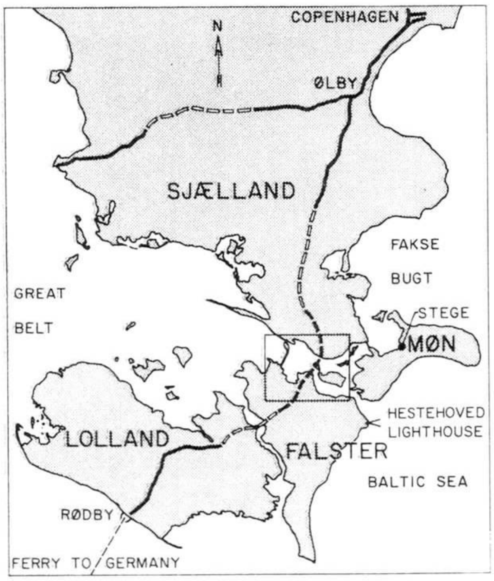

Fig. 1 Location map

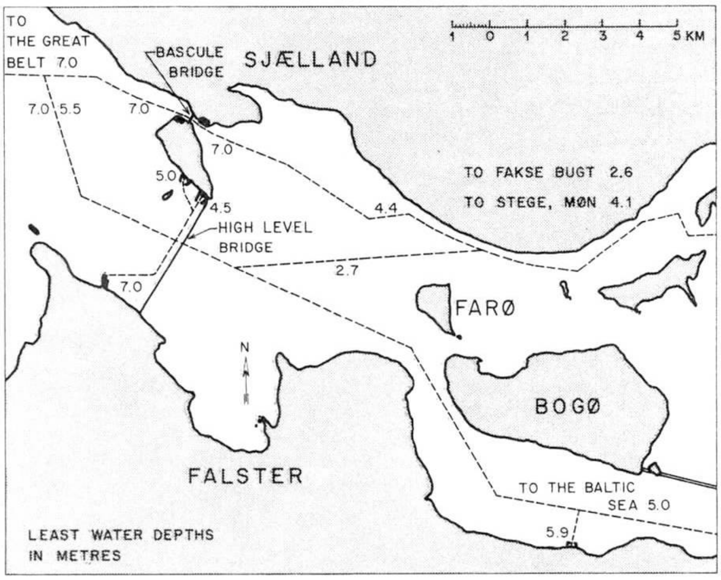

Fig. 2 Present navigation pattern

1.2 Physical Conditions for Shipping

The natural water depths in the area vary considerably, from extended shoals of about 3 m water depth to deep channels of 10 to 38 m water depth. The present navigation pattern in the area, which could possibly influence or be influenced by the linkage structures, is shown in Fig. 2, where the main fairways are indicated with dotted lines. The water depths restricting the shipping in the fairways are also given. Fig. 2 shows, moreover, the existing rail- and road connection between Sjælland and Falster, consisting of a bascule bridge with a 25 m wide navigation opening, and a high level bridge with a 26 m high and 111 m wide main navigation opening. The northern fairway towards east is passing another high level bridge with a 26 m high and 80 m wide navigation opening.

1.3 Navigational Aspects of Selected Linkage

The finally selected linkage lay-out is shown in plan and elevation on Fig. 3 and 4 respectively. From Fig. 3 it is seen, that the fairways can be straigth-lined for adequate lengths before and after passing the bridges and intersect the longitudinal bridge axes close to right angles. In the bridge between Sjælland and Farø with a general span length of 80 m, two 20 m high navigation openings for one-way traffic are arranged in the two spans next to pier No. 6,

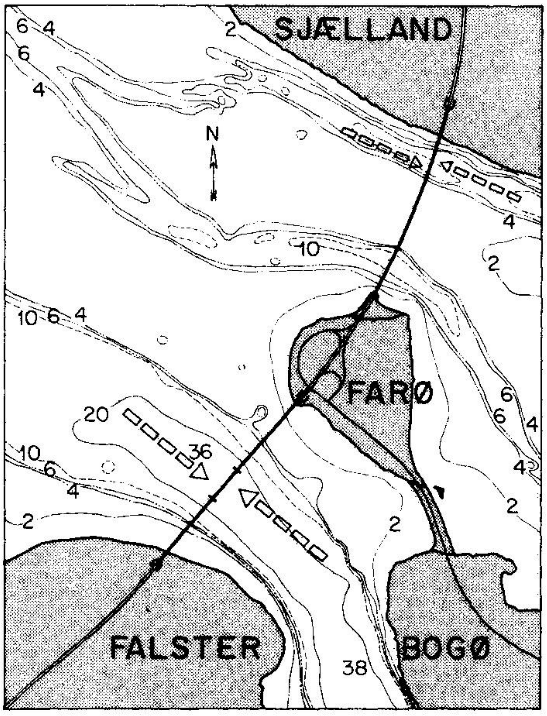

Fig. 3 The Farø Bridges, plan

whereas in the bridge between Farø and Falster an integral cable-stayed bridge part provides a main span of 290 m length between piers Nos. 9 and 10 with a 26 m high navigation opening. The deep channel just north of Farø has a blind ending towards east and is, therefore, not used for navigation.

The ordinary R/C bridge piers all have pier shafts with a uniform outer shape, hexagonal in cross section, in the full height from the foundation block to the bridge bearings, see Fig. 5. The pier shafts are solid below level +2.00 m and above that level, hollow with a wall thickness of 0.40 m to 1.00 m, depending on the loads and height of the pier. Fig. 5 further shows one of the two R/C pylon piers for the cable-stayed bridge. The pylons are also composed of a lower, solid and an upper hollow part. The R/C foundation blocks are all placed either entirely below sea bed or below the possible draught of ships.

The design philosophy adopted in respect of ship collision was on the one hand that the piers shall be the strong and unresilient part of a collision, and, on the other hand that ships, whether large or small, shall not meet any unexpected, submerged structures.

Other design philosophies were contemplated, for instance to diminish the effects of ship collisions by providing the piers with resilient fenders or to surround the piers by embankments or "islands". However, these ideas were abandoned due to high costs and adverse hydraulic effects.

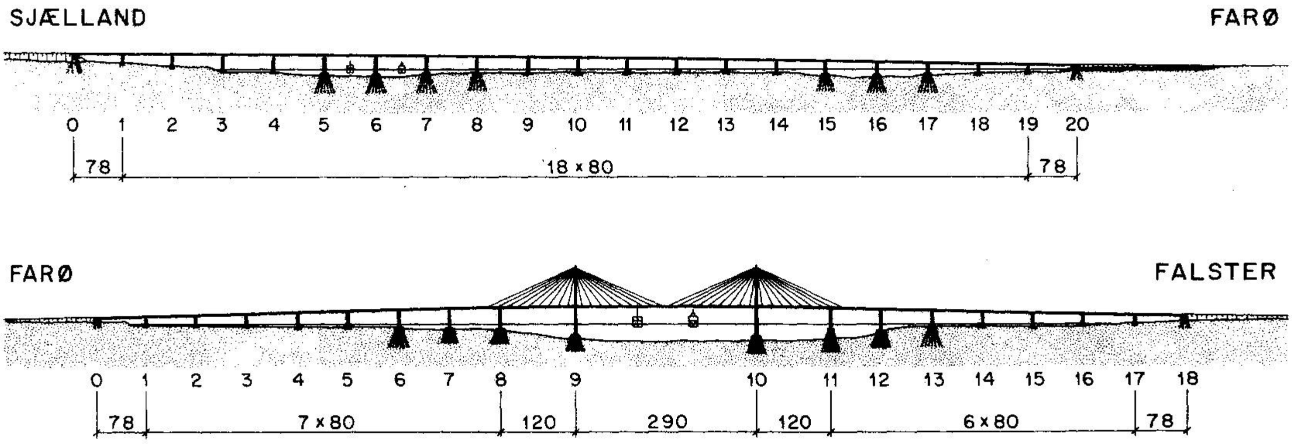

Fig. 4 The Farø Bridges, elevation

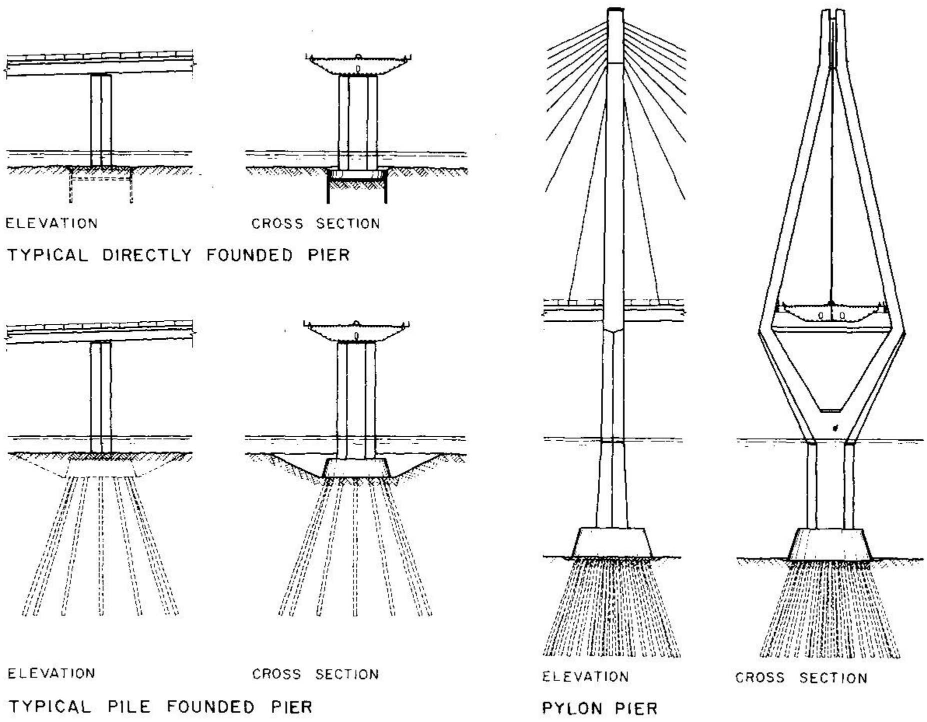

Fig. 5 Bridge piers

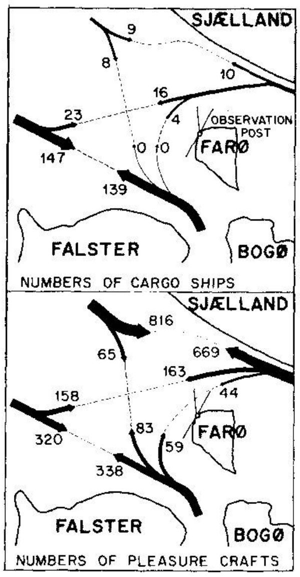

Fig. 6 Ships recorded from Farø 12.July-2.Aug.72

2. DESIGN SPECIFICATIONS FOR SHIP COLLISION

2.1 Recording of Shipping

A basic impression of the shipping was obtained in 1966 by questioning the harbour authorities of seven harbours in the area on the annual traffic in 1965 for different ship categories.

When the alignment at Farø was finally selected a more comprehensive recording was arranged in 1971-72 as follows:

- From Hestehoved lighthouse at the easternmost point of Falster all passing ships, cargo ships as well as pleasure crafts, were recorded with estimation of size. This should cover the major part of the ships passing south of Farø. Duration 18 months.
- In the harbour of Stege on Møn all berthing cargo ships were recorded and their sizes were noted. This should cover the major part of the bigger ships passing north of Farø. Duration 15 months.
- From a point on Farø, see Fig. 6, all ships were recorded by means of a specially developed instrumentation allowing determination of position, direction,speed, length and mast height. Duration 3 weeks in July-August.

All the recordings were statistically treated. Fig. 6 shows the distribution of ships recorded from Farø. It appears that the traffic with pleasure crafts is quite considerable.

For determination of the dead weight of the cargo ships recorded from Farø the following formula was developed on the basis of the compiled information:

$$DWT = 55 + \left(\frac{L}{6.2}\right)^3 \text{ tons, where } L = \text{ship's length in m}$$

The biggest ship recorded was determined at 2200 dwt, going at 5.5 m/sec.

The inherent collision force for the cargo ships recorded from Farø was calculated from the recorded data by the formula given in [1] :

$$P = \frac{v^{2/3} \times L^2}{1100} \text{ MN}$$

where v = ship's velocity in m/sec

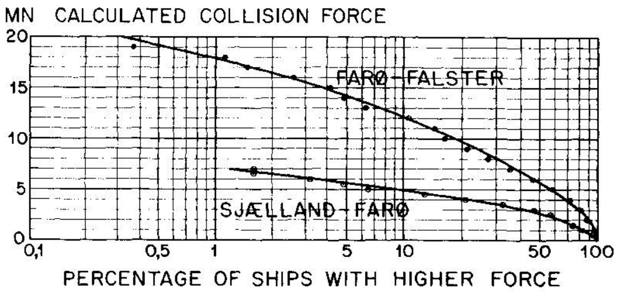

Fig. 7 Inherent collision force of cargo ships recorded from Farø

2.2 Determination of Characteristic Collision Load

Based on experience from the English Channel Macduff [2] proposes a "causation probability" of 0.0002 for ships in an area with platforms in the North Sea, meaning that there is one chance in 5,000 that a ship will be out of normal control due to such causes as poor visibility, rudder or engine failure or faulty navigation. Assuming the same causation probability for the Farø Bridges and considering that, due to the geometrical relationship between pier dimensions, span lengths and possible approach angles, the chance that an uncontrolled ship in the area will collide with a pier is about one in 7, the real probability of a ship collision on a Farø Bridge pier is one in 35,000.

Based on all the ship recordings and assuming "status quo" conditions it can be expected that, during 100 years, approx. 65,000 cargo ships will pass a bridge from Sjælland to Farø, and approx. 500,000 cargo ships will pass a bridge from Farø to Falster. Consequently, during 100 years 65,000/35,000 ~ 2 ships will collide with a bridge pier between Sjælland and Farø, whereas 500,000/35,000 ~ 14 ships will collide with a bridge pier between Farø and Falster. However, due to the relatively low standard of navigational aids at the fairway between Sjælland and Farø, and in view of the uncertain assumptions, the number for this bridge is arbitrarily increased from 2 to 10.

Defining the maximum load P_m as the force to be exceeded once per 100 years the following was found from Fig. 7, thus still assuming "status quo" conditions:

- Sjælland-Farø: One of the 10 colliding ships, i.e. 10% of them, will exert a collision force higher than 5 MN, hence P_m = 5 MN.
- Farø-Falster: One of the 14 colliding ships, i.e. 7% of them, will exert a collision force higher than 14 MN, hence P_m = 14 MN.

The effect of future development of the shipping was then evaluated by a sensitivity analysis and a prognosis for the navigation. Based on this investigation it was decided to assume for the next 100 years an unchanged number of ships, a 10% increase of speed and a 50% increase of dead weight.

Based on the statistics and the formulas mentioned in 2.1 was then found a characteristic collision load of 7 MN for Sjælland-Farø and 20 MN for Farø-Falster.

The characteristic load for Farø-Falster corresponds to collision by a "characteristic ship" of 2250 dwt with a speed of 6.25 m/sec, which data, incidentally, are very close to those for the biggest ship recorded from Farø.

2.3 Load Specifications

The ship collision load specifications finally adopted for the individual piers were based on the above theoretical considerations, but regard was, of course, also made to the fact that the actual water depth at some piers restricts the size of ships to hit them. Furthermore, for bridge piers more than 240 m away from any of the navigation openings in the Sjælland-Farø bridge, it was decided to neglect ship collision loads, as it was found that the very unlikely event of a ship collision on one of these piers would cause only local damage to the pier shaft.

Thus, the following ship collision loads P_1, acting in a direction perpendicular to the longitudinal axis of the bridge, are specified:

- Piers Nos. 4 to 9 in the Sjælland-Farø bridge and piers Nos. 4 and 5 in the Farø-Falster bridge P_1 = 7 MN
- Pier No. 6 in the Farø-Falster bridge, 4 m water depth P_1 = 14 MN
- Piers Nos. 7 to 12 in the Farø-Falster bridge P_1 = 20 MN
- All the remaining bridge piers P_1 = 0

Alternatively is specified a collision load P_2 acting parallel to the longitudinal axis of the bridge, where $P_2 = 0.5\ P_1$.

Based on compiled information regarding dimensions and ultimate strength of ships' hull and superstructure, it is specified that the loads P_1 and P_2 shall be assumed to act as uniformly distributed loads p as follows:

For P_1 = 14-20 MN and P_2 = 7-10 MN the width of the loaded area shall not exceed 10 m, and the load p shall be

- From 10 m to 15 m above sea level p = 50 kN/m^2
- From 5 m to 10 m above sea level p = 500 kN/m^2
- From 5 m below to 5 m above sea level p = 1,000 kN/m^2

For P_1 = 7 MN and P_2 = 3.5 MN the underlined dimensions are multiplied by 0.6, whereas the loads p are unchanged.

The loads shall be arranged so as to produce maximum stresses in the members investigated. However, for the calculations of the pier foundations the resultant loads P_1 and P_2 are assumed to act at sea level and as shown on Fig. 8 in plan.

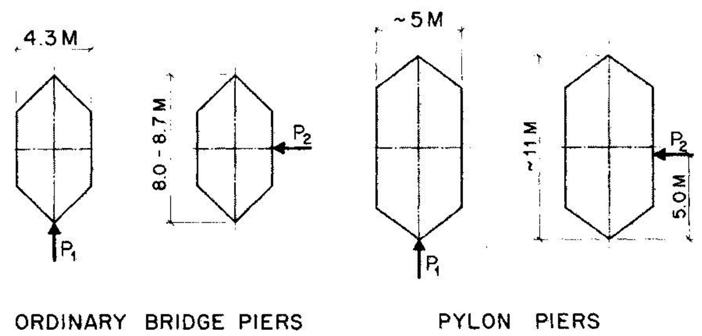

Fig. 8 Location of resultant loads for design of foundations

Referring to 2.2 all the above ship collision loads are characteristic loads. They shall be combined with dead weight of bridge structures only, and the combinations are considered extreme and random assuming a partial coefficient of safety of 1.0 to the loads.

The sea level shall be assumed to vary +/- 0.5 m from mean sea level, which covers about 99% of the time.

3. DETAILED DESIGN OF SUBSTRUCTURE

3.1 General

The following design assumptions were agreed upon with the Road Directorate:

- Ship impact to be considered as static load.
- Structural behaviour in accordance with the theory of elasticity.
- Pier shafts and pylons to be designed with as well as without lateral stiffening effect of the superstructure.
- Foundations to be designed only without lateral stiffening effect of superstructure.

3.2 Pier Shafts and Pylons

The ship collision loads have determined the thickness and horizontal reinforcement of the walls of the upper hollow part. They have also determined the vertical reinforcement of the ordinary piers designed for 14 and 20 MN ship collision load, whereas the vertical (longitudinal) reinforcement of the pylons is mainly determined by the construction phase.

3.3 Pier Foundations

The project consists of both directly founded piers and piers founded on piles. Direct foundation is used only at water depths less than 4 m and the relatively modest ship collision load (viz. zero or 7 MN) being specified here, has not been dimensioning for the foundation. The same applies to the pilefounded piers of the Sjælland-Farø bridge, whereas the ship collision load has been dimensioning for the Farø-Falster bridge piers Nos. 6-12, all pilefounded. A typical, piled foundation is shown in fig. 9.

The chosen form of the pile groups with the piles radially placed in respect to the pier centre means that part of the load on the pier will be taken up as shear and bending moment in the piles. Therefore, knowledge of the axial as well as the lateral bearing capacity in the soil is necessary. Assumptions for the soil-pile interaction in the form of load-deflection curves for both lateral and axial resistance have been established in co-operation with the Danish Geotechnical Institute, whereupon C&N has made the calculations by means of EDP-programmes capable of taking into consideration the variation of the soil properties with the depth and the non-linear course of the load-deflection curves.

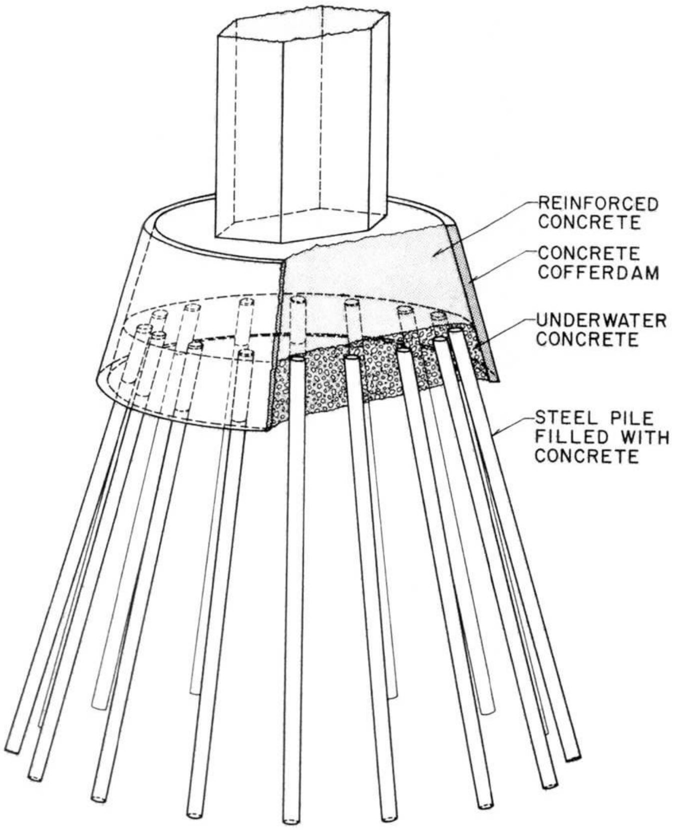

Fig. 9 Piled foundation of bridge pier

For all load combinations, including the one with ship collision load, the criterion for acceptance of the piled foundation has been that neither axial force, shear force nor bending moment in the most heavily loaded pile must exceed the design value of the bearing capacity of the soil or the design strength of the pile. Regarding the bending moment in the piles the exception has been made that plastic deformations have been accepted in some cases, as long as the subsequent loadings could be taken up without exceeding the design strength of the pile.

4. SUPPLEMENTARY INVESTIGATIONS

4.1 General

To check the validity of the results from the detailed design, the Road Directorate had supplementary investigations of ship collision on some selected piers carried out, as described in 4.2 and 4.3.

4.2 Investigations According to the Theory of Plasticity

The investigation of some selected piers according to the theory of plasticity has been made by the Danish Geotechnical Institute by means of an EDP-programme especially developed for this purpose. The collision load and the partial safety factors used were the same as those applied for the theory of elasticity. When comparing the results it was found that, because of the less strict rupture criterion, the pile foundations could withstand 20% to 50% higher ship collision loads when calculated in accordance with the theory of plasticity than when calculated in accordance with the theory of elasticity.

4.3 Ship Collision as a Dynamic Load

These investigations have been made by B. Højlund Rasmussen and we refer to B. Højlund Rasmussen's paper on this issue.

In the main series of these calculations the stiffening effect of the superstructure was taken into account, and it was found that the pile forces were somewhat lower than those calculated for the detailed design in accordance with 3.1, whereas bending moments considerably higher were found in pylons and pier shafts. Nevertheless, the sections in question, determined by other load combinations and structural criteria, proved to be sufficiently strong to withstand also these moments.

A calculation not considering the stiffening effect of the superstructure was also made for pier 11 in the Farø-Falster bridge to try to get a more comprehensive comparison between static and dynamic applications of ship collision load. This calculation showed that the dynamic collision load will give slightly higher pile forces than the static collision load, but considering the other supplementary investigations this was accepted.

5. FINAL REMARKS

In designing the Farø bridges respect was paid to the shipping, in the planning phase as well as in determining the shape and strength of the structures. Thus, strengthening had to be made of pier shafts and pylons, which were assumed to be exposed to ship collision load and of the foundations for pylons as well as for piers, which could be hit by ships with a draught of more than about 4 m.

Control calculations, based on different principles, revealed that a certain extra safety might exist in some of the structures.

This had to be utilized for one of the so-called anchor piers for the cable-stayed bridge, viz. pier No. 11, where especially poor soil conditions were found. The resulting low tension resistance of the piles would make it very expensive to obtain the full prescribed safety using the design assumptions in accordance with 3.1, so a somewhat lower factor of safety was accepted in this case.

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