Design of protective dolphins in demanding geotechnical conditions

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ABSTRACT
Many existing bridges are faced with urgency to increase safety due to vessel collision. A number of different approaches are possible depending on the set of constraints which are almost unique for a given project.
This paper describes the design of independent protective dolphins for the Sallingsund Bridge in Denmark. Two concrete structures, supported by tubular steel piles were designed to resist impact of vessels of up to 6000 deadweight tonnage (DWT) and prevent collision with the bridge piers. The design of the dolphins was preceded by risk analysis based on monitoring of the ship traffic through the channel and a concept study which narrowed down the choice of structural system. The final solution was greatly influenced by the 15m water-depth and presence of a 15m thick layer of gyttja found immediately beneath the seabed, providing very little geotechnical resistance against lateral loads. The solution also had to fit many other constraints such as a limitation of the size of the structures, proximity of existing raked piles below the bridge pier, restrictive budget, etc.
Structural verification was done using state-of-art calculation methods, which took into account time history of the collision event, plastic behaviour of all structural elements (including the vessel) and second order effects for piles and pile - group effect. Furthermore, the design was streamlined to maximize the dolphins overall energy dissipation capacity and is optimized with regards to the constructability in the near-shore environment.

Keywords: vessel collision, protection dolphin, gyttja
1 INTRODUCTION

Ship impact to a bridge from a larger vessel is a rare hazard which may have catastrophic consequences. A number of existing bridges do not have sufficient capacity required to resist the collapse of superstructure in the event of critical collision.

For any such bridge, a design of additional provisions is required in order to reduce the risk level below the requirements given by the society and applicable codes. In recent years, Vejdirektoratet (Danish Road Directorate who is the authority and main owner of roads and bridges in Denmark) has initiated assessments of 4 large marine bridges having unacceptably low safety against ship collision. Ramboll and COWI worked together with Vejdirektoratet on establishing the appropriate acceptance criteria to be met by protective measures following the principles of Eurocode system.

The largest of the analyzed bridges is Sallingsund bridge, which was opened in 1978 in order to improve the traffic connection between the island of Mors and the Salling peninsula on the Danish mainland (Jutland). The total length of the bridge is about 1700 metres, the span length is 93 metres between the piers and the maximum vertical clearance to the sea is 26 metres. The bridge is constructed of reinforced and prestressed concrete. The bridge deck is carried by 18 concrete piers, founded on driven tubular piles.

1.1 Risk analysis

The design was preceded by a comprehensive risk assessment which included a cost-benefit analysis in order to choose the right solution for the task at a given budget. The assessment included analysis of vessel traffic through Sallingsund by collecting of Automatic Identification System (AIS) data and incorporated mathematical models of vessel deflection upon the impact with a protection structure.

The overall findings were that acceptable level of protection would be achieved by placing two independent protection structures south of piers 8 and 9 in order to protect...
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Figure 4 Placement of dolphin in relationship to the pier, overview (left) and detail (right)

these two piers against ship impact from northbound ships.
The design vessel was adopted to represent the largest ship that can enter the Limfjord taking into account planned deepening of the entrance channel from the North sea.

Table 1 Design vessel characteristics

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (partly loaded)</td>
<td>6000 t</td>
</tr>
<tr>
<td>Width</td>
<td>16 m</td>
</tr>
<tr>
<td>Length</td>
<td>97 m</td>
</tr>
<tr>
<td>Bow depth</td>
<td>16 m</td>
</tr>
<tr>
<td>Draft (partly loaded)</td>
<td>4.7 m</td>
</tr>
<tr>
<td>Rake length of bow</td>
<td>4 m</td>
</tr>
</tbody>
</table>

The design speed of the ship was determined based on the AIS data and adopted as 4.8 m/s.
The dolphins were designed to absorb the kinetic energy from the moving ship and prevent it from hitting the pier.

2 SITE CONDITIONS

2.1 Geotechnical conditions
The water depth at the location of the dolphins is around 15 m. The topsoil consists of a layer of gyttja reaching 15m below the seabed.
The gyttja is followed by a sand layer (17-30m in vicinity of piers 8 and 9) under which there is a layer of mica clay - see Figure 5.
The gyttja layer is very porous and with almost negligible strength and stiffness.

Therefore scour was not considered as an issue that affects the design assumptions. The depth of the sand layer varies between pier number 8 and pier number 9. Preliminary design determined that the tip of the piles at the dolphin near pier 8 will end in sand with sufficient depth to clay to insure the full tip bearing capacity. The reduced thickness of the sand layer near pier 9 (in comparison to thickens at pier 8) meant that piles had to be extended into the clay layer making them considerably longer, much like those of the bridge.

Figure 5 Overview of geotechnical layers which govern the foundation of the bridge

2.2 Existing piers and their piles
The bridge piers are founded on circularly distributed groups of driven piles in two rows fanning out with 9% and 32% inclination outwards. The piles are constructed as driven steel pipes with outer diameter of 711.2 mm and maximal bearing capacity of 6000kN in compression.
Tip of the existing piles at pier 8 extends between levels -45.20 and -47.50. At pier 9, the piles for the foundation of the bridge had to be extended into the clay to achieve required bearing capacity. Tubular piles end in sand (levels -40.0 to -43.0) with steel H pile driven further down into the clay (tip level between -54.13 and -57.80).

3 GEOMETRY AND DESIGN

Preliminary studies eliminated cylindrical sheet pile caissons filled with gravel as unsuitable to the geotechnical conditions. Instead, concrete dolphins on piles were chosen as the concept capable of meeting the capacity required for stopping the design vessel. This solution also provided flexibility regarding the shape in plan and construction methods. As the dolphins are placed with 10.5° out of the perpendicular axis of the bridge (see Figure 4), their size and distance affects the available width of navigation passages. A requirement from the Søfartsstyrelsen (authority in charge of ship safety) was that a minimal navigable channel width of 60m had to be maintained. The width of the dolphins was adopted as 16m to ensure sufficient shading of the piers. The distance between the dolphins and the piers was adopted based on minimal allowable distance between newly installed and existing piles taking into account driving tolerances and mutual influence. Concrete superstructure is identical on both dolphins.

In plan, the dolphin has elongated shape, with their southern edges rounded to increase the deflection capability. As the piles are loaded by vertical forces, the longer edge is adopted as 24.4m to maximize the lever arm between the opposing rows of piles.

Figure 6 Isometric view of the dolphin and pier 8 (left) and 9 (right)
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piles. The concrete cap is a box-like structure, which consists of a concrete base slab, four walls and a top slab. Each dolphin is founded on 18 steel piles, 1200mm in diameter.

From the beginning, the design included active consideration of the available construction methods. For example, maximal sizes of floating cranes and other construction vessels which can enter the Limfjord were taken into account when the size of prefabricated sections of superstructure was decided. Piles were adopted as driven tubular steel piles with diameter of 1.2 metres. Bored piles were also considered in the preliminary design but discounted due to estimated higher price of execution and less availability of the necessary construction equipment.

Driven piles offered the added benefit that the driving log allows for a precise estimate of the bearing capacity without additional testing.

One other important feature of the chosen pile system is that the largest part of pile’s vertical/axial capacity originates from the skin friction (both inside and outside), which is governed by ductile post-yield behaviour. As shown later in this paper, this is an important feature in the system which allows for vertical yielding of piles (plastic portion of the diagram) during the collision. Increase of the pile tip area by under-reaming and filling with concrete was excluded as the larger tip resistance obtained in such way is hard to verify and produces more brittle post-yield behaviour.

As the combined depth from water surface to load bearing soil layers is around 30m due to presence of gyttja, design with a pinned connection between piles and superstructure with chosen diameter of the piles would require too large deformations in order to stop the colliding vessel. This challenge was met by designing a cap with extended height to shorten the free length of the piles, and by providing a fixed connection between piles and bottom slab.

By incorporation of the vertical resistance of the piles through the lever arm between the rows in tension and compression, the overall stiffness of the structure was increased.

The ability of the piles to retain maximal moment in the post-yield stage was addressed by designing the wall thickness to satisfy requirements for compact cross-section class (class 1). The required thickness wall of 40mm is reduced below the fixation level in the sand where piles are subjected only to normal forces.

4 MODELLING AND ANALYSIS

The general approach to the design of independent protective structures is to demonstrate that the kinetic energy of the ship can be dissipated through plastic work and acceleration of the mass.

The working curve of the dolphin was obtained by creating a full static model of the structure in the FE-program LUSAS. In the FE-model, several nonlinear effects were taken into account: horizontal and vertical response of the soil, nonlinear behaviour of the steel in the piles and second order effects (geometric nonlinearities).

4.1 Modelling of geotechnical conditions

The horizontal response of the surrounding soil was modelled by use of PY-curves. The PY-curves describe the dependency between reaction force, \( P \), in the soil and lateral deformation, \( Y \), of the pile. Group effect was taken into the consideration by reduction of the \( P \)-values of the PY-curves for given deformation. Different reduction factors were used depending on the geometric position of the piles. Typically the reduction factors have values between 0.6 and 0.95. The PY-curves also vary with type and strength of soil and depth beneath the sea bed.

The gyttja provides negligible resistance against lateral load compared to the sand layer below which ensures shallow depth to the fixation with its relatively high strength and stiffness. The lateral resistance in the clay layer (which is found beneath the sand
The vertical resistance of the piles is a combination of skin friction and tip resistance. For a plugged pile, the skin friction acts on the outer circumference of the piles, whereas the tip resistance acts on the cross sectional area of the piles and the area of the enveloped soil. For an unplugged pile, the skin friction acts on the inner and outer circumference of the piles and the tip resistance acts on the cross sectional area of the piles. However, to simplify the modelling of the dolphins, the sum of both skin frictional resistance and tip resistance was applied at the tip of the piles, by use of a piecewise linear spring, a “tzQz-curve”.

The lateral response of the soil (PY-curves) was implemented in the FE-model through use of multi-linear springs (as shown in Figure 7) applied to the embedded part of the piles. The vertical response of the soil (tzQz-curves) was implemented in the FE-model through use of multi-linear springs (as shown in Figure 8) applied to the tip of the piles.

4.2 Modelling of structural elements

The static model of the dolphin is in essence a sway frame with piles fixed to the concrete super structure and fixation developed in the sand layer. Yield hinges are expected to develop in the piles at the zones of maximal moment.

The global overturning moment caused by the impact load acting over the vertical distance between the top slab and the level of fixation, augmented by the second order effects, is resisted in two ways: - 1) through compression / tension action of the opposing pile rows and 2) through moment in each individual pile at the fixation level. The load-deformation diagram of the structure has a steep linear shape until the two front and rear rows of piles yield in compression / tension and yield hinges have developed in all of the piles. This point marks the peak load factor that the structure is able to resist. Afterwards, the deflection continues to increase and the global overturning moment is kept constant. Since the influence of second order effects...
increases with deflection gain, the load factor will decrease simultaneously so that the global overturning moment is kept constant.

The steel piles are modelled as beam elements with perfect elasto-plastic behaviour. This means that bending moment can only increase in the pile until the von Mises yield criterion is reached. Thereafter, the moment is kept constant (or decreases if the normal force increases) with increasing rotation and a yield hinge is formed. Geometric imperfections were taken into account through applying horizontal loading to the beam elements. All concrete parts were modelled as shell elements with linear material properties. The concrete structural elements were designed to transfer the loads from the ship impact without considerable plastic deformations to appear in the concrete.

A horizontal point load of 1000 kN was applied at the top slab (level +1.5), as shown in Figure 9. The load was multiplied by a load factor, which was gradually increased. Based on the horizontal deflection of the top slab and the load factor, a working curve of the dolphin was found. This working curve was used to determine the required deflection in order to dissipate the energy from the collision and the capacity of the structure was verified for the relevant load factor.

4.3 Energy exchange and dissipation concept

Apart from plastic work of the dolphin, during the collision, energy is absorbed in several other ways. For most is the crushing of the ship’s bow, which is described with non-linear curves in both AASHTO and Eurocode. Determination of this dependency based on the physical experiments (Woisin and Meir-Dornberg). Simplified curves and maximal values of quasi-static impact forces show considerable disparity. This is discussed in AASHTO and there is awareness that this is an area of ongoing research.

In this project, energy exchange between vessel and the dolphin was assessed using time series analysis based on the conservation of momentum at the moment of impact and conservation of energy for motion after the impact. The model is described as two-degrees-of-freedom system connected by piecewise linear longitudinal springs. The ship’s bow force-deformation curve is adopted from Eurocode.

Figure 10 Simplified model for collision analysis
5 RESULTS

5.1 Dolphin capacity
Iterative elasto-plastic analysis of the FE-model was performed with increase of the load factor in each step. Deformed configuration of dolphin 9S is shown on Figure 12.

Displacement of the impact point on the top slab is plotted against the applied force to form a “work curve” for the entire structure shown on Figure 11. The area beneath the diagram is equal to the dissipated energy of the system through plastic work.

Prior to reaching the peak value, the curve drops in angle from the previous linear load-deformation response of the dolphin. At this point (marked with “a”), front piles have almost exhausted their normal bearing capacity in skin friction which has a steeper T-z curve compared with the tip.

Point 2 represents the deformation at which is the required kinetic energy of the colliding vessel dissipated by the plastic work of the system. Displacement of the top slab is around 2.9m for both dolphins.

The corresponding values of the normal forces in piles are shown Figure 13.

5.2 Load-displacement curve of the dolphin 8(red) and 9 (blue)

Point 1 marks the peak load value for the dolphin. Outermost two rows of piles, both at the front and at the back have reached their vertical capacity.

Figure 11 Load-displacement curve of the dolphin 8(red) and 9 (blue)

Figure 12 Successive deformed configurations of the dolphin (LI – load increment, LF – load factor)

Figure 13 Overview of the development of normal forces in the piles compared to the load factor (each coloured bar corresponds to one row of piles and positive values represent compression)
The working curve shows that dolphin is capable of deforming further which could indicate that the design is conservative. However, the overall stiff behaviour of the dolphin ensures stopping of the vessel on safe distance from the pier. Also, in the marine environment susceptible to ice loads, stiff structure is less susceptible of inducing unintended damage.

Apart from the results shown for head-on collision, oblique impact was analysed with a deviation angle of 30° to insure sufficient lateral stiffness of the dolphin. This issue, together with their results are the subject of a future publication.

5.2 Energy exchange

The interaction between the ship and dolphin is simulated using time series analysis performed with in-house developed program. The working curve of the ship’s bow was adopted from annex C4.4 of EN 1991-1-7.

Due to relatively large mass of the concrete superstructure compared to the displacement of the vessel, it was assessed that up to 60% of the collision energy could be dissipated by deformation of the bow. However, the assumptions regarding the ship’s bow behaviour incorporate substantial uncertainties. Furthermore, recent studies based on detailed FEM models of ship’s bow, indicate lower yield load. Collision with deformable structure could limit the deformation of the bow, thereby reducing the amount of energy dissipated in this way. For this reason, dolphin’s pile system, is verified without relying on this mechanism of collision energy dissipation.

Concrete superstructure is dimensioned for the difference between maximal forces in the bow and dolphin shown on Figure 15. The assumption of the peak quasi static force to act on the concrete structure is in this case a conservative assumption. As the peak force is larger than maximal force that can be taken in the pile system, separate model was made where the piles were given unyielding vertical support. In this way, it is ensured that impact load can be transferred by the superstructure and distributed on the pile group as assumed.
6 CONCLUSION

The presented solution successfully meets multiple-constrained design requirements through integration of all available structural and geotechnical energy dissipating components.

The presence of a thick layer of weak organic soil excludes a number of solutions and poses execution and design challenges. With limitation on pile diameter and construction method, the required response of the structure is achieved by an extended concrete superstructure and moment-coupling connection to the piles.

This was facilitated by a concurrent geotechnical and structural design process which verified ductile post-yield behaviour of all elements.

Further possibilities for optimization of future similar structures can be explored through more advanced modelling of energy transfer between the ship and the dolphin.

7 REFERENCES
