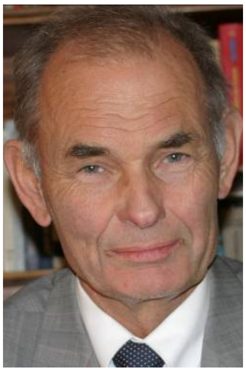
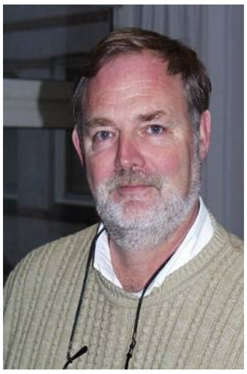
Odin´s Bridge

Kjeld THOMSEN
MSc
ISC Consulting Engineers
Copenhagen, Denmark
kt@isc.dk
Kjeld Thomsen born 1936, grad. 1960 from Copenhagen Technical University. Founder of ISC Consulting Engineers A/S in 1967. Specialist in bridge design and steel structures. Honoured with ECCS steel design award 5 times and IABSE bridge design award 2001.



Hilmer JUNG LARSEN
MSc
ISC Consulting Engineers
Copenhagen, Denmark
hjl@isc.dk
Hilmer Jung Larsen, born 1948 grad.1973 from Copenhagen Technical University. Chief Engineer, Project Manager. Specialist in design of airports, bridges and other large infrastructure and turnkey projects.



Summary

The new bridge crossing the Odense Canal on the island Funen Denmark is named Odin’s Bridge. Odin was a god in Nordic mythology and was the name giver to the city Odense. The bridge has closed a long missed gap in the infrastructure of the road system surrounding Odense which is the third largest city in Denmark.

An international competition was opened in December 2008 according to the EU´s service directive and 6 groups were pre-qualified to compete for being successful in obtaining the contract for design of the bridge.

ISC Consulting Engineers A/S and their sub-consultants were finally in September 2009 selected as winners of the international design competition for a 900 m long bridge connection comprising a bridge crossing the 80 m wide Odense navigation canal and on the western side of the canal an approximately 540 m approach bridge and dam joining the main circular road.

Fig. 1 Swing Bridge - Visualization

On the eastern side an approach span and a short dam have been included in the total contract. The key part of this connection is the 194 m long swing bridge -the longest yet in northern Europe with several outstanding features in the design. The main structure is designed in steel as a twin box girder bridge with a 3 m clearance between the box girders. The centre span of the bridge is 120 m and the side spans are 37 m each. The bridge shall be constructed in an environmental sensitive area which requires as little impact on the surrounding nature as possible. Another prime requirement for the bridge solution crossing the canal was to choose a solution providing the maximum navigational width opening.

The present twin swing bridge with the centre supports pulled back from the quay side full-filled these requirements. The bridge should also have an esthetical link with a new administration building for Odense Harbour in which also the operating centre for the bridge should be located.

The prime goal for the solution proposed by the consulting group was to minimize damage to the surrounding nature, which was achieved by letting the canal pass untouched under the bridge as well as letting the surrounding roads on the canal sides pass under the bridge.

A parameter study of alternative bridge concepts for instance hydraulic operated bridges was cored out to prove that the selected bascule swing bridge was the utmost feasible.

Keywords: Swing Bridge; Rotating support; Slide bearings; Monoplane structure; Box section; Pile foundation; Dowel joint; Abutment; Mechanical system; Hydraulic system

1. Introduction

The swing bridge, which will be described in the present paper, is a central part of a 900 m long combined bridge-dam connection between two main roads and part of the circular road system around Odense and thereby an important improvement to the infrastructure. The twin swing bridge has from the end abutments a total length of 194 m. The main span is 120 m and the side spans are 37 m.

An outstanding feature for the solution of the present structural system was primarily to prevent any blocking effect of the Odense Canal as this would seriously affect the sensitive environmental conditions and therefore no pillars or supports are placed in the canal, even if this might have presented a more economical solution. Consequently the two main supports for the swing parts are located pulled back from the embankment. This in order to assure that no part of the bridge would be located within the shores of the navigation canal in the open condition to prevent any ship impact and thereby assuring the safety of the system These basic requirements have led to the present solution for the structure overall.

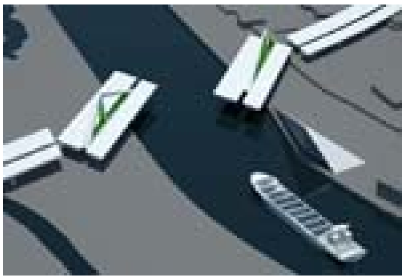


Fig. 2 Swing Bridge - Opening

The superstructure of the two nearly equal swing parts in steel is designed as a twin box girder bridge with 3 m clearance between the box girders. The spans have, as mentioned, been selected to protect the environment, and the bicycle paths running along the shore of the canal. The superstructure is a monoplane support structure triangular shaped with an elevation of 20 m above the road surface. Compared to existing swing bridges with this width of approximately 28 m, the monoplane system is quite outstanding. The main supports carrying the permanent bearings and the bearings for rotation are designed in concrete and have a diameter of 12 m. They are designed as reinforced concrete cylinders. The hydraulic system that rotates the bridge to the open position as well as the electrical installations is placed inside these cylindrical supports. The dehumidifying system is located in the box girders.

The swing bridge consists of two equal rotating parts which in the closed position are linked to the end abutments with hydraulic operated shear bars. In the centre of the bridge shear bars are provided as well. It should be mentioned that the bridge is skew in relation to the navigation canal and crosses the canal in an angle of 64^{o}. The bridge carries two lanes in each direction as well as pedestrian and bicycle paths of 4.6 m width.

The twin box girders are provided with orthotropic steel deck floors and an asphalt surface in the car traffic lanes and a polyester coating in the bicycle and pedestrian lane.

The selection of the monoplane support structure meets the requirements to a simple and logical configuration of the bridge structure which can be seen with its monumental shape from all directions – both from the bicycle paths as well as from the canal and further off. Artificial LED lighting is provided for the superstructure and the hand railing to visualize the shape when it is dark.

2. Design basis

Due to the fact that the European Standards for bridges have not yet been introduced and certified for application in Denmark – the Danish standards basically have been the basis for the design of the bridges. These standards cover standards for safety classes, material control as well as loads on structures and foundations. However, the European standards in the preliminary editions have been applied as a supplement in cases where the local Danish Standards do not cover the issue. The general loading conditions are supplied with the loading conditions issued by the Danish Road Directorate for bridges. Attention has also been brought to the European Standards 1-3 Design Basis for Loadings on Bridges part 3. The same applies for the Mechanical and Hydraulic installations which have been based on Danish Standards and the EU Directives covering the subject.

Apart from traffic loads, wind loads have a certain importance on the design as well as ship impacts. Wind loads are due to the irregular shape of the bridge, determined by means of wind turbine tests. Ship impact on the bridge has been fixed to 150 ton.

All primary structures in the steel superstructure for the swing bridge have been designed in S355 steel in the appropriate quality class depending on the location of the structure. The concrete quality for the foundations has a characteristic strength of 40 MPa, and as laid out for the requirements of aggressive environmental class. The reinforcement bars in the foundations and in the central cylinder will be tentor or ribbed bar steel with a characteristic yield strength of 550 MPa. In cases where Euro Codes have been applied, the safety regulations have been replaced by the national application document.

3. Approach spans and dams

The western dam is the first part of the Odin’s Bridge from station 0 to 280 m, where the road shall pass over a very soft meadow Bispeengen. The first part of the dam is built up to the fauna passage west as a pile founded earth dam corresponding to a similar method applied for the intersection where the Odin’s road starts. Due to the soft soil it is necessary also to arrange piling to carry the junctions to the main road. At the eastern side of the fauna passage west and forward to the crossing at the Stavid´s creek, the dam is carried out as an earth dam with preceding pre-consolidation.

The meadow bridge west carries the road from the dam across the Bispeeng to the western

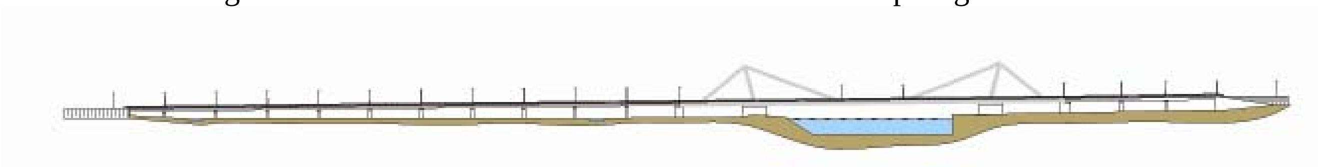


Fig. 3 Whole Bridge - Elevation

abutment of the swing bridge. The approach spans have at total width of 28.14 m. The two bridge girders are separated by a 3 m opening primarily arranged to provide light and tempt the animals to pass through under the bridge. However, the gap is closed just before the abutment for the swing bridge to allow any vehicles, in case of traffic accidents, to turn around before reaching the swing bridge. The approach spans are designed as pre-stressed continuous concrete girders with a width of 15.14 m and 10.08 m. The northern bridge part, with a width of 15.10 m, is laid out for two traffic lanes and 4.6 m width for pedestrian and bicycle paths, whereas the southern bridge is laid out for only two traffic lanes. The heights of the pre-stressed concrete girders are maximum 1.5 m near the centre of the bridge.

Each continuous concrete girder supported on one row of columns located near the centre of gravity. They are stabilized by cross girders in the centre of the spans as well as above the column supports.

The westerly meadow bridge has nine spans of 26 m and one end spans towards the swing bridge with a length of 25 m and further an 18 m end-span towards the dam. The stability of the system is provided by bearings fixed in the longitudal direction on the two centre columns. The load in the bridge direction is transferred through to the columns restrained in the foundations.

The approach bridge east has only three spans. Due to the curved line for the bridge and the skew crossing of the harbour road the spans are unequal and vary between 21 m and 36 m. The bridge is fixed in the longitutal direction on the wall under the southern part of the bridge.

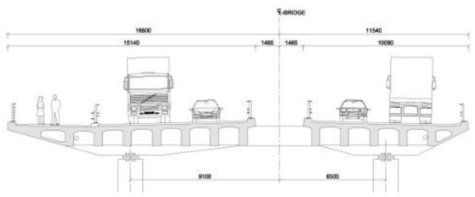


Fig. 4 Cross Section in Concrete Approach Span

The design concept selected for the approach spans was an open beam structure as this structure was considered more economic than a closed box. The decks are designed for in situ casting of the concrete girders. The bridge is post- tensioned in the longitutal direction and the pre-stressing cables in the bridge line are located between the hollow sections in such a way that the vertical placements of the cables in the cross section can vary from the centre of the span towards the cross girders over the columns. The cross girders are post-tensioned as well, both the cross girders in the centre of the span and those over the columns. Transversely the bridge girders are reinforced with ordinary reinforcement bars.

4. Swing bridge

The bridge over Odense Canal is a twin swing bridge with two equal spans and a total length of 194 m. The supports are located in a distance of 120 m in the bridge line. The supports are located in such a way that no part of the bridge reaches into the canal zone when the bridge is open. When opening the eastern part the bridge rotates counter clockwise and the western part as well turns counter clockwise and visa versa when closing. Due to the skew crossing of the canal in a 64^o angle, the two bridge sections have to rotate no more than the 64^o.

4.1 Structural system

Each of the swing sections consists of two steel monobox girders separated with a 3 m opening. In order to improve torsional rigidity of the whole structure the two box girders are mutually connected with cross girders in a distance of 14 m. In the closed condition for the bridge, the monoplane structure is simply supported on two neotopf bearings on each of the two main supports. The bridge is further supported with a twin dowel system on the end abutments just as they are hinged together with two dowels in each box girder at the centre of the bridge.

The southern box girder in the swing section has a total width of 10.1 m and carries two lanes each of 3.5 m width including shoulders and box edges the width reach a total of 9 m between the crash barriers. The northern box girder has a total width of 15.2 m as it also includes a two way shared pedestrian/bike lane.

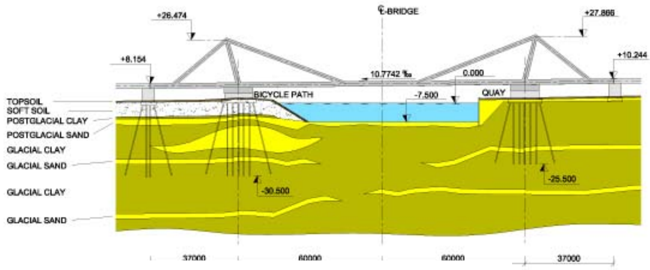


Fig. 5 Swing Bridge - Elevation

The permanent support for the bridge consists of two neotopf bearings with a diameter of approximately 1.2 m. The bearings rest on a circular sliding surface with a diameter of 12 m. In the rotation situation the bridge is supported on four neotopf bearings located 90^o apart. The support on the four bearings is achieved by a hydraulic lift of the two bearings in line with the bridge until the load in all four bearings attain the same load – thereby initiating that the bridge can commence the rotation.

To reduce the friction on the circular sliding surface the centre bracket is jacked up with about 1000 t. These jackets rests on a circular neotopf bearing with a sliding pad placed between the bearing and the concrete foundation.

The horizontal load is transferred to the steel floor welded at adequate height to a circular steel swing beam on the top of the circular concrete support via a circular shell bracket fixed to the bridge girders. These loads comprise wind load as well as accidental ship impact.

In the opening operation, when the dowels at the end abutments and the centre of the bridge have been pulled back, the bridge structure is balanced by counter weights cast as scrap concrete in the side span ends of the swing bridge sections. A complication in the geometry is that it has been necessary to provide the bridge with a slope of nearly 11‰ from east to west.

Geometrically the canal bridge can be considered as a machine where special requirements to precision under fabrication and a clearance to restricted geometry tolerances compared to traditional standard tolerance requirements in stationary bridge structures.

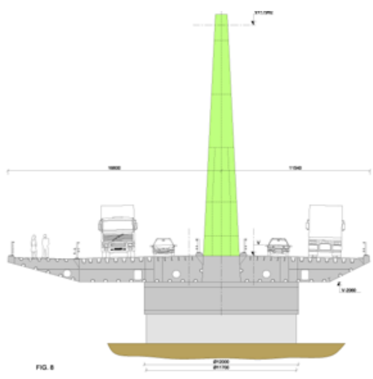


Fig. 6 Swing Bridge - Cross Section

4.2 Box girder design

The box girders are all welded with a total height of 2 m and include an orthotropic steel deck and are stiffened by trapezoid shaped bent stiffeners of 6 mm thickness. Diaphragms have been provided per each 3.4 m for support of the orthotropic deck and also for the transfer of torsional moments into the section. Above the supports special structural stiffening arrangements have been provided to carry the load out to the bearings. The torsional rigidity in general is used in the structural system to carry the load to the monoplane structural support system. This support system is arranged to minimize the height of the structure to obtain the required free clearance demands over the canal surface.

4.3 Triangular monoplane system

The triangular lattice system is located in the opening between the two box sections. It is shaped as a simple triangular lattice structure with a front stay and a back stay and an inclined column transferring the resultant axial force straight into the circular foundation.

The elements of this triangular structure are designed as welded box sections. These are restrained fixed in the bridge floor and the width of the box section has the same width as the opening – 3 m between the box sections. A static subtlety with the monoplane structure is thereby also achieved, because the vertical load during the deflection of the centre column will have the direction of the joint restraint in the bridge floor when starting a horizontal deflection, thus preventing any second order bending moments in the connection of the centre column to the bridge floor. The two swing sections have their fixed point in the centre of the twin supports, between that any deformation freely can take place in the longitudinal direction of the bridge towards the centre and towards the abutments.

Adequate openings are provided at the abutments as well as by the centre of the bridge to allow for these horizontal temperature deformations in the bridge line. The centre joint shall allow for temperature deformations in the length of 120 m - the span of the bridge. The expansion joint has been designed to achieve an exceptional noise reducing solution.

4.4 Structural analysis

The analysis of the structural system has been carried out by means of the FEM calculation program Ansys on a detailed developed diaphragm model. All major primary structural joints such connection between the triangular structure and bridge box girder, have been analysed by means of FEM analysis and to verify hotspots entering the fatigue investigations to assure a lifetime of 100 years for the bridges superstructure as required.

For accidental loads such as ship impacts, it has been arranged in the design, that the hydraulic system will be weaker than the torsional ultimate resistance of the centre column and its pile support configuration. This to ensure that in case of a ship impact the machinery may be ruptured, but the main foundations of the centre structure shall resist in order allow for short term repairs.

A detailed analysis of all deformations in the structural system has been carried out to verify that the needed slip and tolerances during opening as well as in the service condition are met.

4.5 Swing support

The twin bridge system is supported on the two centre supports for the bridge and further at the abutments on two bearings – one located under each box girder. In the closed bridge situation, lift loads at the abutments are transferred by means of two spring supported brackets, hydraulically activated into the abutments. Vertical downward loads are carried by the two neotopf bearings in the centre of the bridge; two hydraulically operated dowels in each box girder are activated from one section to another. The dowels in the centre of the span 2 off for each girder part only transfer sheer forces vertically as well as horizontally.

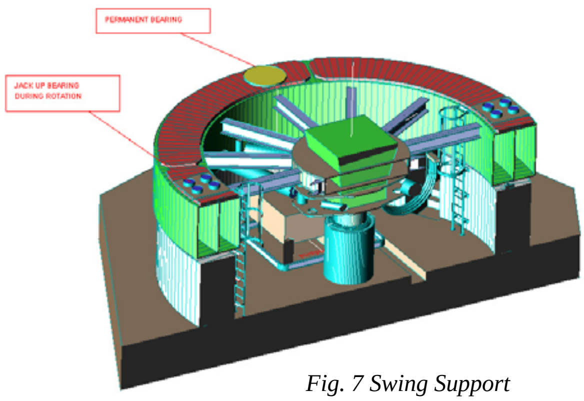


Fig. 7 Swing Support

During the rotation the swing section is controlled by the hydraulic rotation machinery in the centre columns and friction in the rotation bearings. The horizontal load is carried by the centre cylinder transferring horizontal loads to the concrete slab in the centre foundation. For the accidental loads from ship impact during rotation the hydraulic machinery will be the weak link compared with the ultimate torsional strength of the pile foundation for the centre support. During rotation the swing section will be fully balanced by counter weights placed in the far end of the two bridge sections near the abutments.

Due to poor geotechnical conditions with approximately 30-35 m piles it is considered necessary to provide easy access to adjustment of the bearings levels to compensate for any settlement or rotation of the circular cylinder foundation. To meet this requirement a 1.8 m deep and 1.5 m wide circular steel box girder has been inserted between the concrete foundation and the steel superstructure. This girder is anchored into the foundation, however, with easy access to install jacks between the girder bottom flange and the concrete base for adjustment.

The maximum vertical load overall in the service condition will be 3,300 ton in the centre supports and the maximum vertical load during rotation will be 2,300 ton. The vertical load during rotation will be carried by means of the two permanent bearings and the two bearings jack activated only during the rotation operation. The bearings have been designed also for an unbalanced load due to unsymmetrical wind loads on the bridge section in the opening situation.

4.6 Centre support

The centre cylinder bracket, welded to the bridge floor structure, has three functions. One is to transfer torsional moment to the bridge from the hydraulic machinery. The other is to fix the bridge section horizontally. The third is to provide support for the central jack lift. The horizontal plane bearing is located in level with the centre of the concrete deck.

The central lift which reaches about 1,000 ton is activated to minimize the required torsional moment needed in order to rotate the bridge section. The jack has a diameter of 800 mm (250 bars) for the lift. The jack is placed on the concrete support of the centre of the foundation. Between the jack and the cylinder tap is placed a low friction bearing.

The slide bearing placed on top of the concrete cylinder is designed with a corrosion resistant steel surface on which PEHD 1000 slide blocks are arranged. This particular type of bearing has been developed especially for the Odense Canal Bridge and is adequate for easy alignment. Compared with a traditional roller bearing this solution is much cheaper and has a shorter delivery time. Furthermore it is much easier to handle in case of needed replacement.

4.7 Mechanical system

A conventional type of hydraulically activated dowel connections has been used at the centre of the bridge. At the abutments a new concept has been developed as wedge activated spring support. A special mechanical system has been developed for the centre columns. To assure stability during opening, the two permanent bearings are supplied with two bearings in the bridge line supported on the concrete cylinder foundation. These bearings are activated by means of four hydraulic jacks until equal loads are achieved in all four bearing locations.

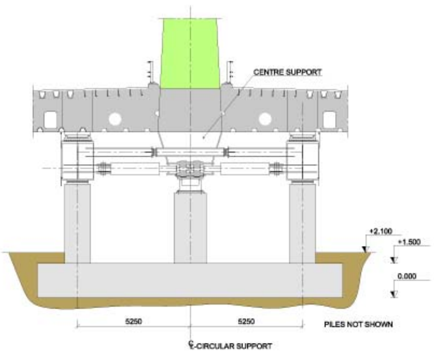


Fig. 8 Circular Support East

The jack bearings also provide a minor slope to allow the bridge section's movement out of the centre joint. In the permanent service situation these bearings in the bridge line allow for the angle of the rotation of the bridge during service load. The torsional load to be applied by the hydraulic system is minimized by means of the above mentioned lift from the central jacks on the vertical cylinder. The rotation machinery in the cylindrical foundation comprises four hydraulic cylinders of Ø 470/Ø280, which are close the maximum size which can be built into the space available in the concrete cylinder. The maximum torsional moment which can be provided by these hydraulic cylinders in the shown set-up is 21 MNm with a 300 Bar pressure is sufficient for the opening of the bridge.

The shear connection of the centre of the bridge is permanently fixed in the eastern section because the western shall be tilted and rotated first. The two bearings at the abutments shall resist considerable vertical reactions both upwards and downwards. As pressure bearing a neotopf bearing is mounted on the abutment. The top bearing is provided by a single bracket and a spring supported plate which can be pressed in and press the bearing down into position by means of hydraulic installations in the bridge. The reason for using a spring loaded plate, is partly that the bearing does not become wedged, and partly because there are no slackness with normal load on the canal bridge. The top bearing is built into the rotating section, and when in use is pushed forward by one hydraulic cylinder.

4.8 Operation

It is anticipated, based on statistical figures from earlier registrations, that the swing bridge shall have 3,000 opening sessions a year and that the operational time of each opening session is estimated to last 7 minutes. The hydraulic systems and necessary electrical installations are designed for a service life of 25 years. The guiding and controlling components are designed for a lifetime of at least 15 years.

The power supply for the operation requires provision of two 630 kW transformers for service of both the swing bridge and the harbour administration building. The transformer-station is located in a separate building located close to the bridge, in order to minimize the distance to the centre support foundations for the swing bridge. Power to the bridge's machinery is, during possible failure of power supply, provided by an emergency diesel generator with capacity of 500 kW for short break supply for the swing bridge and the bridge guard. The generator system is designed for supply in 4 hours full service and for 48 hours of idle. The diesel generator system will be located in the same building as the transformer. The operation for opening and closing session for the swing spans takes approximately 2 minutes each. It is assumed that a ship passing will take approximately 2 minutes included in the total of the 7 minutes.

Certain requirements have been set for the key part of the structures under a ship impact. The bridge girder is designed to be able to survive the impact of a ship, whereas the hydraulic system is designed in such a manner in the centre piers that they will fail before the foundation piles due to the torsional moment. This is to assure that any accident can be repaired promptly whereas if the foundation suffers rupture, the bridge could be held out of service for a much longer period of time.

4.9 Fabrication

Fabrication of the steel superstructure is very similar to the production of ship sections with the panels manufactured by partly automatic welding. It is obvious that the fabrication in a yard with quay facilities such as a ship yard or offshore steel production facility will be suitable for fabrication of the twin section in one piece.
The inside of the box girders will not be corrosion protected but will be protected with dehumidification systems. These will be located in the centre of each bridge section – one in each box. The dehumidification systems will be designed to absorb a maximum humidity of 40 % relative humidity.

The outer surfaces of the steel structure will be corrosion protected by a painting system corresponding to corrosion class C5 in DS/EN 12944.

4.10 Transport and installations

Fig. 9 Visualization - Bridge and surroundings

A fabrication shop the nearby quay facilities will allow easy load out on barges and transportation of the structures to the construction site. The barges can easily be towed to the bridge site at Odense Canal where the twin sections of 97 m length can be mounted and slided into place, supported on a temporary structure along the canal. The twin sections will be supported on temporary jacks which assures an exact position before final grouting of the bearing. It is anticipated that the entire erection procedure for the two swing sections will be done in ten working days. During this period the ship traffic may be subject to certain restrictions.

5. Foundation

The environment and the soil condition are poor for an economical and effective direct foundation. The entire meadow area is located on soft soil and moraine layers with adequate strength are not met before 13 m under the ground surface on the western embankment. This requires pile foundations for all columns and for the centre columns for the swing bridge as well. Another difficulty, not least for the carrying out of subsoil drilling tests, is that there are very limited access to possible temporary supports during construction. Even during the hard winter in 2010 it was not possible to access the meadow area without establishing temporary roads for driving vehicles.

On the eastern embankment moraine clay is found only few m below the ground surface which means that all column foundations in this area have been directly founded. The abutments and all the columns are supported on foundations on which the top is located near the ground water level and the bottom of the foundation located at a level coming from as small a depth from the foundations as possible due to ground water level at level zero. All the column foundations on the eastern approach bridge are supported on 20 piles.

The foundation bases each have a dimension of 14.5 x 14.5 m. The foundation base level is also placed as high as possible to minimize the cost of the drainage and suction systems during construction. The bridge support foundation are tapered on reinforced concrete piles with dimensions 40x40 cm at a total of 56 piles of which 32 piles are vertical piles and 24 piles are tapered with a slope of 1 to 4. The bottom levels of the foundations are located at the mean water level of the canal.

From the bottom of the foundation to the topside of same, there are only 1.5 m. The centre supports for the bridge, located on the square foundation slab is circular with an external diameter of 12.0 m as earlier mentioned. Despite the fact that the geotechnical conditions are somewhat better on the east side, it has been decided that the 2 centre foundations should be designed alike.

It is most essential to calibrate the foundations in such a way that no displacements will take place between the eastern and the western supports. Thorough settlement investigations were therefore performed, and during the lifetime of the bridge a thorough monitoring of the evolution of the displacement will take place.

The bearing capacity of the concrete piles will be based on driving tests on piles during the construction.

6. Conclusion

The twin swing bridge crossing the 80 m wide Odense Canal in Denmark, named Odin's Bridge has some outstanding features to be highlighted.

- With a 120 m span it is the largest swing bridge ever built in Northern Europe.
- The structural system characterized with the triangular monoplane structure carrying a four lane highway.
- The support concept applying sliding bearings instead of the traditional roller bearing leading to low cost and easy short time adjustment and replacement.
- The transition from the in service two bearings support to a more sophisticated five point support in the rotating situation.
- The bridge proposal was selected as the most feasible and economical attractive as the result of an international design competition.
- The detailed design will be issued for tender in the autumn of 2010 and the crossing open for traffic is planed to be in spring 2014.
- The total cost of the 900 m bridge including the 194 m long twin swing bridge has a budget of approximately 40 Mill. Euro.