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Evolution of Bridge Foundations for Constructability, Economy, Sustainability and Safety

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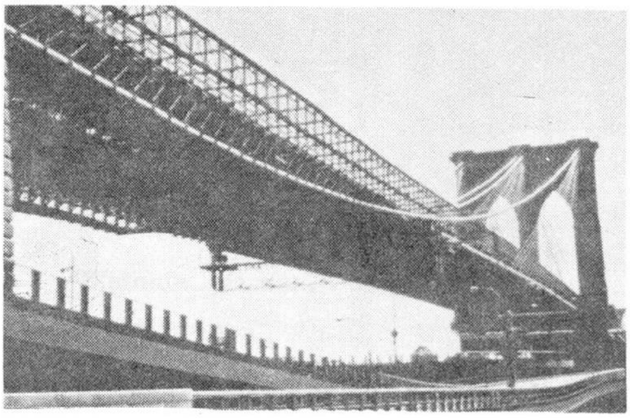
SUMMARY

Bridge foundation has been subjected to significant evolutions from earlier risky techniques with high losses of human lives to modern safe and economical foundation engineering. The use of float-in caissons, large diameter piles in concrete or steel, adapted from the offshore oil industry, and grouting techniques have reduced material quantities, energy consumption and been beneficial to environmental impact. This evolution is described by examples from resent major bridge projects.

1 INTRODUCTION

A bridge component, which has been subjected to significant development and innovation over the last 30 years, is bridge foundation. The foundations were traditionally the most complicated and difficult part to built of any major bridge structure. Unexpected difficulties caused delays, extra costs and sometimes required project changes caused by the need for altered positions. Loss of human lives was normal rather than the exception. The compressed air chamber caissons for the Brooklyn Bridge claimed the lives of many workers at the end of the last century because the unknown effects from compressed air, the bends, were believed to be some sort of a bacterial decease. This technique has also resulted in many accidents and difficulties several times later. It was regularly used, however, up to the mid 1960'es, when new techniques appeared.



The Brooklyn Bridge.

2 NEW TECHNIQUES

Important progress within the offshore industry has led to vast improvements in foundation techniques for bridges over the last 30 years.

Two fundamentally different techniques, inherited from offshore, dominate modern bridge building today:

- Offshore gravity base structure method (GBS).
- Large diameter steel pile foundations, driven to refusal, or large diameter prestressed concrete bored piles.

The first technique was initially developed for offshore oil and gas fields in the North Sea, pioneered by the Ekofisk tank in 1973 for 70 m water depth. The second has been developed for offshore steel jacket structures, initially in the Mexican Gulf, later in the North Sea on medium water depths up to 40 m, and many other places.

Common for these techniques is that they eliminate complicated, weather dependent and sometimes very risky manned operations in the water under pressure. This risky work is substituted by onshore fabrication of reinforced concrete caissons in the GBS case and steel or concrete fabrication onshore, to be installed offshore by floating, and then sinking respective driving or boring techniques with heavy equipment from above water level.

These techniques have proved their reliability in a number of major bridge projects, and have reduced unexpected delays considerably and minimised technical and financial difficulties in the substructure work.

Further, significant progress of analysis and design has made it possible to make use of the potential detailed knowledge of soil structure interaction, including interface behaviour.

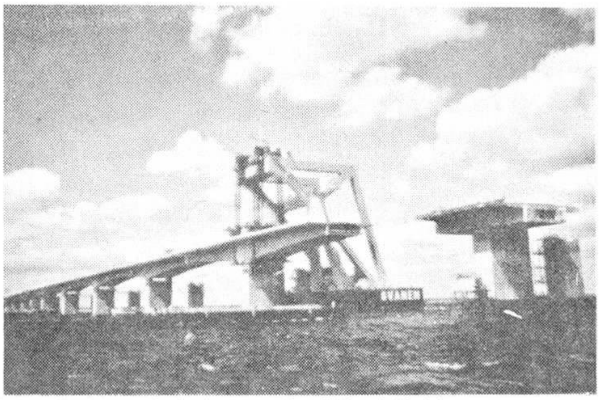
This progress in foundation technologies has, in keeping with time needs of today, considerably reduced quantities of material required for adequate foundations, as well as energy consumption and environmental impact, and thereby contributed to sustainability of modern bridges.

It is often seen that optimum spans for certain applications have been reduced compared to previous more risky and material consuming foundation techniques.

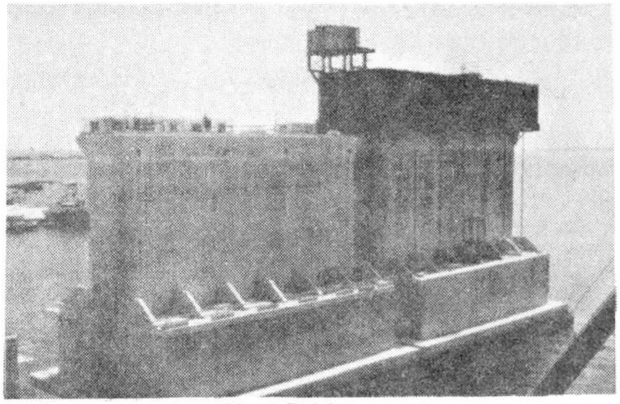
3 THE STOREBÆLT WEST BRIDGE

One of the most recent major bridge projects, where the GBS method has been used to its full potential, is the Storebælt West Bridge, a 6.6 km multi-span bridge, comprising 51 identical spans of 110 m, built as a huge prefabricated building block system.

The bridge contains altogether 324 concrete elements which have been pre-fabricated on shore close to the bridge site and without use of heavy gantry cranes or dry docks. Sliding surfaces were used to move the units.



Installation of girder on the West Bridge.



Caissons for the West Bridge.

The caisson fabrication was carried out parallel in two lines. A base plate was cast first, followed by slipforming of the walls and casting of the cover slabs and plinths. The dimensions were 34 m x 22.5 m maximum and 31.1 m x 6.4 m. Only one slipform was used, suspended from a special gantry and served each line alternatively. A catamaran crane vessel lifted out the caissons from a jetty and transported them to their position in the bridge site.

Each bridge pier is resting on a stonebed which has been constructed after excavation to a prefixed level, determined by detailed site investigations and subsequent cleaning and inspection. The stonebed consists of a lower, well-compacted about 1.1 m, 5-70 mm thick layer, followed by an upper about 0.4 m thick screeding layer with a grain size of 70 mm. During construction, great care was taken to produce a plane surface, and after placing the stones, substantial checks were carried out to ensure that this goal had been met. As the caissons were constructed with a plane base plate, no grouting underneath was carried out.

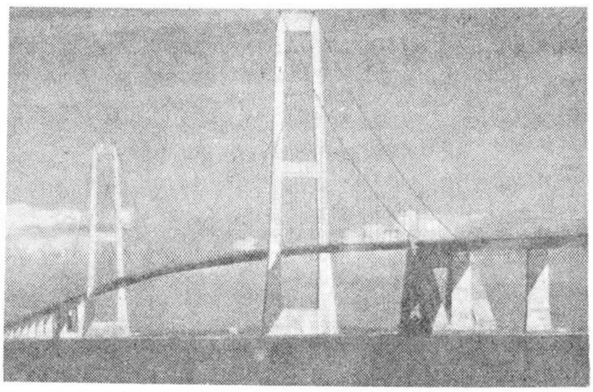
All piers were installed within a few centimetres of accuracy laterally, and vertical settlements have been within a few centimetres as predicted. Further, the method substituted complicated and time-consuming work on the critical path offshore. The West bridge was completed in 1997 and subsequently opened for rail traffic in June. A year later the motorway part was opened.

4 THE STOREBÆLT EAST BRIDGE

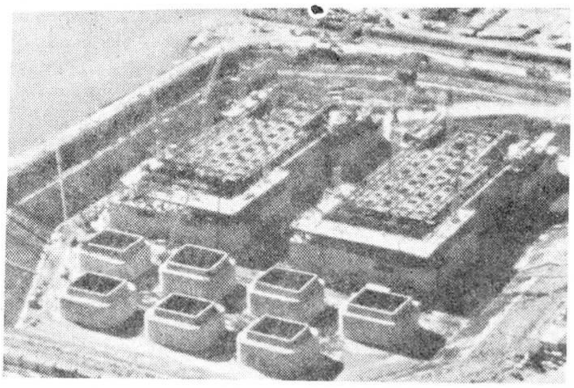
The main bridge across the navigation channel of the Storebælt has similarly employed modern foundation techniques following the success of the West Bridge.

The caissons for the pylons, the anchor blocks and the approach spans were constructed at a prefabrication site about 30 nautical miles from the bridge site. The larger caissons were cast in two dry docks, using the GBS technique, and the smaller caissons on a nearby quay area. The pylon caisson weighed 32,000 tonnes and the anchor block caissons 36,000 tonnes when they were towed by tug boats to their position in the bridge alignment.

The pylon caissons are equipped with 0.5 m high skirts. A very high friction angle for the crushed stone bed materials gave rise to some concern about whether sufficient skirt penetration would be achieved. However, by placing a screed, looser layer at the top of the stone bed, the predicted load penetration response was received with full skirt penetration and the desired base contact prior to grouting of the interface.

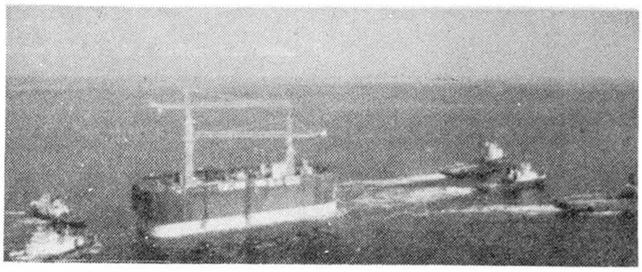


The East Bridge.



Anchor block caissons for the East Bridge.

Each anchor block, which must be able to resist a cable force of 600 MN, has a 121.5 m x 54.5 m rectangular base which is divided into three parts: a front pad of 41.7 m, a middle part of 39.1 m, and a rear pad of 40.7 m. Only the front and the rear pads are in contact with the supporting soils. As a result of excavation, the top part of the clay till was expected to be disturbed and to have a reduced sliding surface. This problem was compensated for by introducing a wedge shaped fill of compacted crushed stone below each of the two pads.



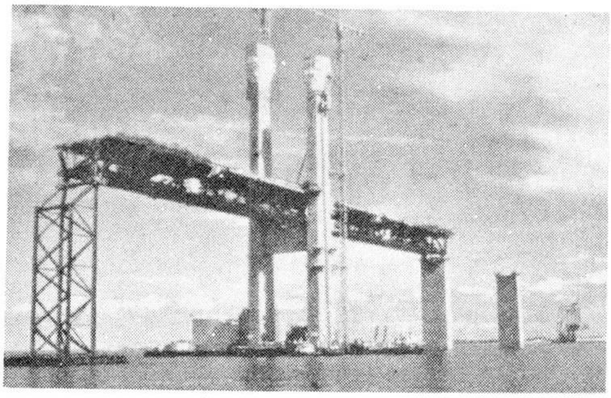
Pylon caisson towed by tug boats.

Settlements and movements after force transfer have been carefully monitored and have been within predicted limits. The bridge was inaugurated in 1998.

5 THE ØRESUND BRIDGE

For the 8 km long Øresund Bridge between Denmark and Sweden, which is presently under construction, the concept has been further refined and optimised. All piers have been prefabricated, including the pylon foundations. All pier foundations have been completed, and the bridge is scheduled for inauguration in year 2000.

The accidental load from ship collision is one of the governing load cases in the design of the pylon foundations for the cable-stayed bridge with has a main span of 490 m. The pylon caissons have a base area of 36m × 38m and are founded directly on Copenhagen limestone at a water depth of 18m. The caissons are buried 2m into the limestone to obtain the necessary horizontal bearing capacity as a combination of base shear and passive resistance in front of the caisson.



The Øresund Bridge.

The quasi-static design ship collision force of 550-600 MN, acting 2m above sea level, was determined from a dynamic global analysis. Several finite element models with advanced elasto-plastic models describing soil behaviour were defined. By means of quasi-static push-over analyses, the horizontal bearing capacity and the associated movements were calculated. These results were compared to the maximum force, and the expected permanent displacement was determined.

The use of an advanced soil model, which was carefully calibrated, made it possible to obtain a very competitive foundation design by avoiding excessive conservatism for this rather unlikely event of collision from a large vessel.

6 THE JAMUNA RIVER BRIDGE, BANGLADESH

The projects mentioned above have all employed derivatives of the GBS offshore foundation technique, because the subsoil condition did not require piled foundation.

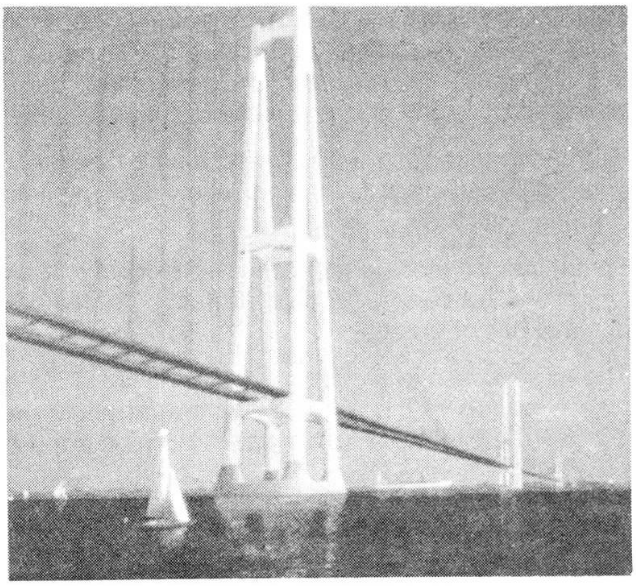
Ground conditions for the Jamuna Bridge in Bangladesh were far so friendly as for the Storebælt and Øresund bridges. The geological conditions at the site consist of about 70 m deep deposits of sands which have a low capacity to resist lateral loads. The bridge is furthermore built in a seismically active zone.

Thus the foundation conditions were extremely difficult, and previous studies in the 1970'es indicated that huge and very deep well caisson foundations would be required. Such foundations would, of course, be extremely costly, and the optimum span would consequently be of a magnitude which would require cable stayed or even suspension bridge spans. The total cost of the project would be considerably beyond a financially feasible level and could therefore not be justified.

During the subsequent evaluations in the World Bank expert panel of the technical and financial feasibility of the project, the experience from large diameter piled foundations of offshore steel jackets were brought in as an element that completely changed the concept and thereby the cost of the bridge.

Substituting huge caissons of concrete to very large depths - more than 80 m - by tripod-like, large diameter steel pile foundations, connected by a pile cap at the bridge deck soffit level, saves the overall per foundation unit costs considerably, whereby the optimum span length decreased to the use of well proven pre-stressed concrete or steel girder techniques. The final optimisation of the project resulted in an overall cost reduction of the bridge project by more than 50% compared to the previous studies using 100 m spans and approximately 3 m diameter steel piles, driven to 60-80 m depth using large capacity offshore pile driving equipment.

At the same time this foundation type reduced the use of resources considerably and was beneficial to environmental impact. The long piles cater for the risk of liquifaction of the uniformly grained, fine sand of the Jamuna River bed during earthquakes as well as allowing for the sand wave risk and very deep scour characteristic of the changing river bed of the Jamuna River bed.

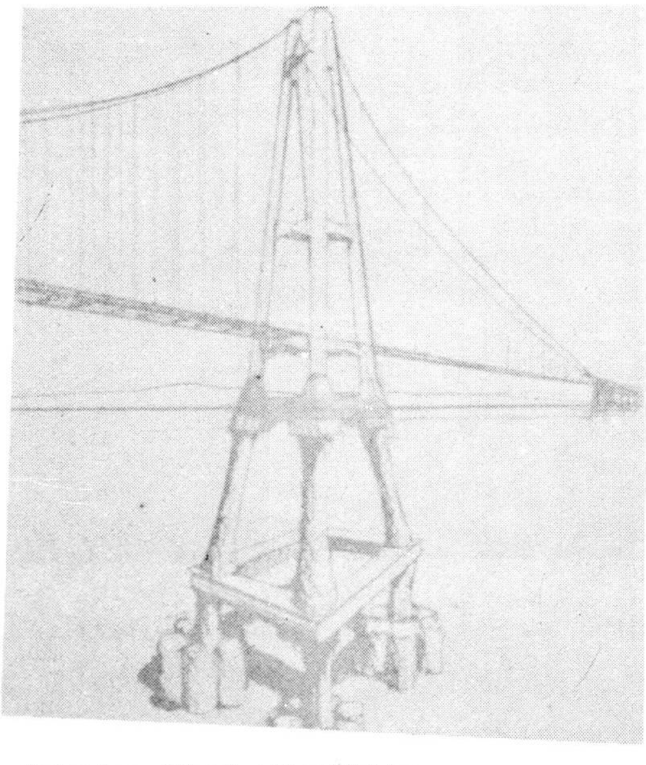


Artist's view of a Gibraltar Strait Bridge.

7 THE GIBRALTAR STRAIT BRIDGE

Since 1981, the United Nations have been interested in investigating the feasibility of a fixed link across the Strait of Gibraltar. The strait is characterised by large water depths, at the narrowest crossing between 500-1000 m, and 250-350 m at a slightly longer alignment along a subsea sill.

The extrapolation of the Ekofisk GBS technique to the Troll Field in Norway with more than 300 m water depth has made it conceivable to build a bridge on fixed foundations across the Strait. Costs of foundations would, of course, be very high as for the offshore platform, and the optimum spans therefore very long. 10 years of studies of alternative configurations have resulted in a technically feasible concept of a series of suspension spans 3500 m each with 450 m tall A-frame pylons founded on a GBS-type prefabricated concrete structure, installed on the sea bottom by towing out and subsequent sinking using skirts and underbase grouting.



Pylon for a Gibraltar Strait Bridge.

The concept would enable initial base construction to take place close to the shore in dry docks, float out and continued construction above water with simultaneous sinking of the caisson as the load increased until completion in a floating condition at an intermediate construction site. After completion the foundation would be towed to position and sunk, where after pylon construction could take place.

The concept being physically transparent in its nature with few cylindrical or conical legs, allows a relatively free and unhindered water flow, thereby minimising wave and current forces as well as reduces the waterforces from earthquakes and minimising environmental impact. The structure would be optimised structurally for minimum material consumption and thereby use of energy and resources.

The Gibraltar Bridge brings to an extreme the huge potential of GBS-based bridge foundations for a case where a bridge on fixed foundations would be unthinkable without such a technique.

8 THE RICHMOND-SAN RAFAEL BRIDGE

Another field within foundation safety is retrofitting. As part of the seismic retrofit of the Richmond-San Raphael Bridge, a concept of using precast concrete jackets to strengthen the existing concrete piers has been developed by Ben C. Gerwick Inc.

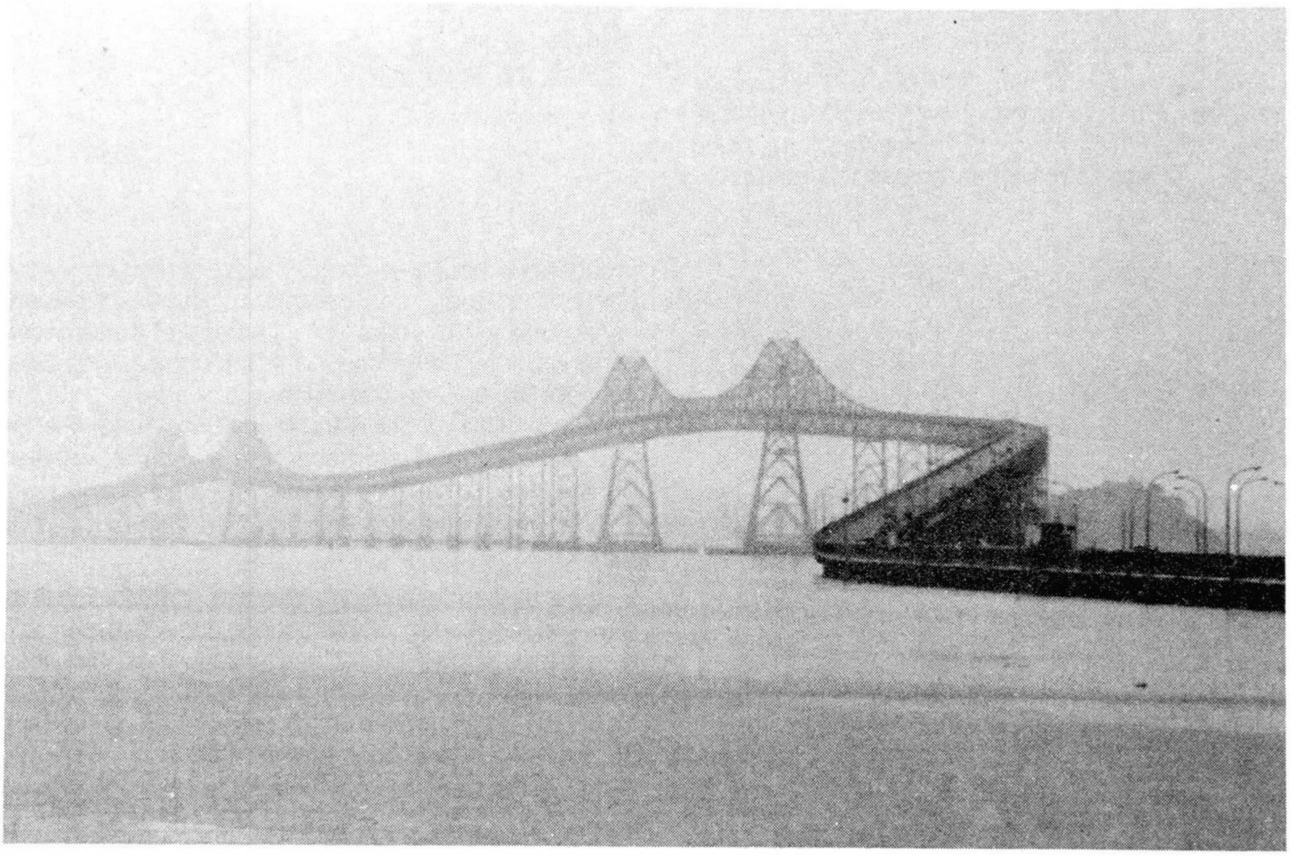
Unlike steel jackets, concrete jackets can be designed to resist corrosion in the aggressive tidal-splash zone for the remaining 100-year life expectancy of the bridge.

A concrete mix with a low water-cement ratio, fly ash, and moderate amounts of an active pozzolan has been specified to allow the jackets to be constructed with a 6.35 cm minimum cover with un-coated reinforcement. In the splash and tidal zone, the concrete will be polyurea-coated which reduces cover impedes micro cracking and reduces the weight of the jackets.

The concrete jackets will be matchcast horizontally and placed around the existing shafts, spandrel beam and diaphragm wall in halves, connected by transverse HS rods which will also connect the precast segments vertically.

Two thirds of the precast concrete jackets will be submerged when placed in their final position. The precast jacket concept allows for a high degree of off-site prefabrication followed by a wet erection with a minimal use of divers.

The existing shafts are cleaned by high-pressure jets before the jackets are placed. An erection frame is placed on top of the existing shafts that allow two precast segments to be placed on each side of the concrete substructure above water. HS rods are used to connect the segments on the outside of the shafts.



The Richmond-San Rafael Bridge.

9 CONCLUSION

The examples illustrate how huge potential in new construction techniques and methods, often generated in other fields, can be employed in bridges with many advantages for the owners, and sometimes even making unprecedented projects feasible.