Submerged tunnels, examples of marine structures

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Tunnels immergés, exemples de structures maritimes

Absenktunnel, Beispiele von Offshore-Bauwerken

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SUMMARY

Submerged tunnels have been constructed since the beginning of this century. They represent the wide range of engineering practice required for offshore structures, such as: deep water dredging and seabed preparation, marine transport and installation operations, large scale fabrication in drydocks and waterproofing. The paper explains these different items including the most up-to-date solutions.

RÉSUMÉ

Les tunnels immergés sont construits depuis le début de ce siècle. Ils mettent en oeuvre une grande partie des techniques de construction en mer par exemple: dragage en eaux profondes, préparation des fonds marins, transport maritime et opérations d'immersion, fabrication à grande échelle en cale sèche et imperméabilisation. Cet article expose ces différents problèmes et les solutions les plus récentes qui leur sont apportées.

ZUSAMMENFASSUNG

Absenktunnel werden seit Beginn dieses Jahrhunderts gebaut. Ihre Realisierung verkörpert einen breiten Umfang an Bauweisen und Technologien, die zur Herstellung von Offshore – Bauwerken erforderlich sind. Dazu zählen Nassbaggern in tiefen Gewässern und Unterwassergründungen, Überseetransporte und Absenkoperationen, sowie grossformatige Vorfertigung in Trockendocks und Bauwerksabdichtung. Der Beitrag verdeutlicht die einzelnen Bauabschnitte und beinhaltet deren neueste Lösungen.

1. INTRODUCTION AND HISTORICAL BACKGROUND

On request of the chairman of the scientific committee this paper has been introduced in the session on offshore structures of unconventional nature. It serves the purpose of demonstrating that many techniques required for such structures are not only proven art, but are also up to date controllable procedures. It further shows to many engineers present, not being familiar with these techniques, that submersed tunnels can be a solution to many communication problems.

Since the construction of the Michigan Central Railroad Tunnel in Detroit, completed in 1909, almost 100 submersed tunnels have been built. The idea to construct structures like bridgepiers, quaywalls and tunnels in a sheltered dock instead of in an exposed pit, being an obstacle to shiptraffic as well, at location, is even far older. It dates back to the end of the 18th century [1].
It is remarkable to notice that the way the Michigan tunnel was built, still represents the "American" way of constructing tunnels. This is characterized mainly by the way the construction takes place. The "american" or "Steel" immersed tunnels are constructed on a shipyard as a single or usually double steel hull, with some concrete for stability as a keel. This structure is than immersed, towed to location, and locally filled with usually non structural concrete, to obtain the required weight and soundness for immersion and in situ functions (Fig. 2).
The "European" tunnel dates back to 1936, when the Maastunnel under the shipping lane to Rotterdam was constructed. The authorities selected, amongst others, two 2-lane American type tunnels, leaving pedestrians and bicycles, temporarily on one or two of the four lanes available. A contractors alternative, involving just one huge reinforced concrete cross section, containing 2 x 2 lanes plus a double deck pedestrian and bicycle channel, was offered for a lower price and accepted. In this way the "European" or "Concrete" immersed tunnel was born. It was completed 50 years ago, in 1942 (Fig. 1).

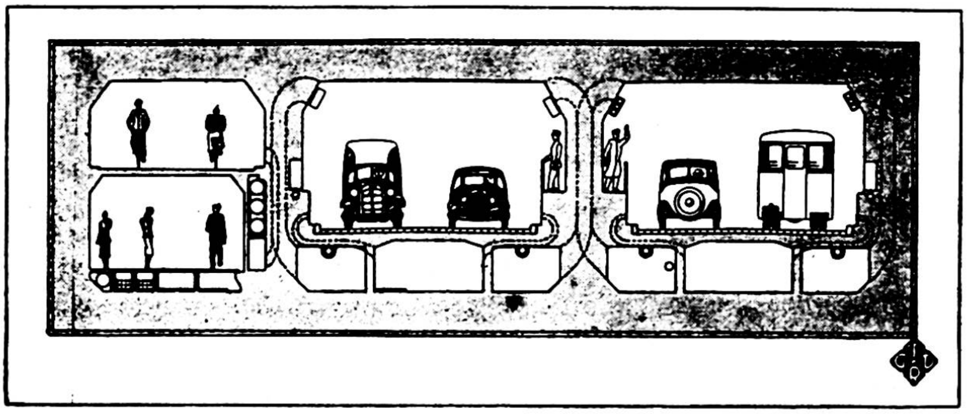


Fig.1 The Rorterdam maastunnel as constructed

At present 42 reinforced "concrete" tunnels and 34 "steel" tunnels have been constructed. 14 of them are constructed in Japan, where both systems are used.[2] Many more submersed tunnels are planned, such as in Greece, Ireland, Hong-Kong, USA, Uk and Holland.

2. BRIDGING, BORING AND IMMERSING

There are of course, like in every engineering discipline, rules of thumb to decide on methods to solve a problem; in this case, how to cross a channel. These rules are however, changing by the development of technology and new public requirements and values. The rules further provide a large area, where all three methods, to cross, have to be considered and evaluated on the basis of costs and quality.
Bridges have been replaced by tunnels because of the impact on shiptraffic. The height of the bridge above the waterline governs the allowable shiptraffic. Today, allowing offshore equipment or large sea going ships to pass, free heights are required of 60 meters and over.
The introduction of an opening span reduces the traffic capacity of the bridge not just during the time of being up, but also before and after the actual opening time. As traffic usually increases, an opening span bridge is no sound solution that will last for long, downstream of cities with a harbour.
The introduction of bridgepiers in shipping channels is a potential danger to shiptraffic that can be quantified quite well with modern simulation techniques.

Last but not least bridge approaches consume scarce space in usually dense industrious areas. All of this makes bridges comparatively less attractive compared to tunnels in a large range of circumstances (Fig. 3).
Bored tunnels need substantial cover underneath the mudline, which usually dictates an overlength of tunnel, especially when the slopes are of limited steepness. They further require suitable soil for drilling to reduce substantial construction risks. As more techniques become available, the feasibility of drilling tunnels increases. Bored tunnels further require substantial length compared to immersed tunnels, in order to depreciate the investment in the shield over sufficient length, to arrive at a competitive price per unit length.

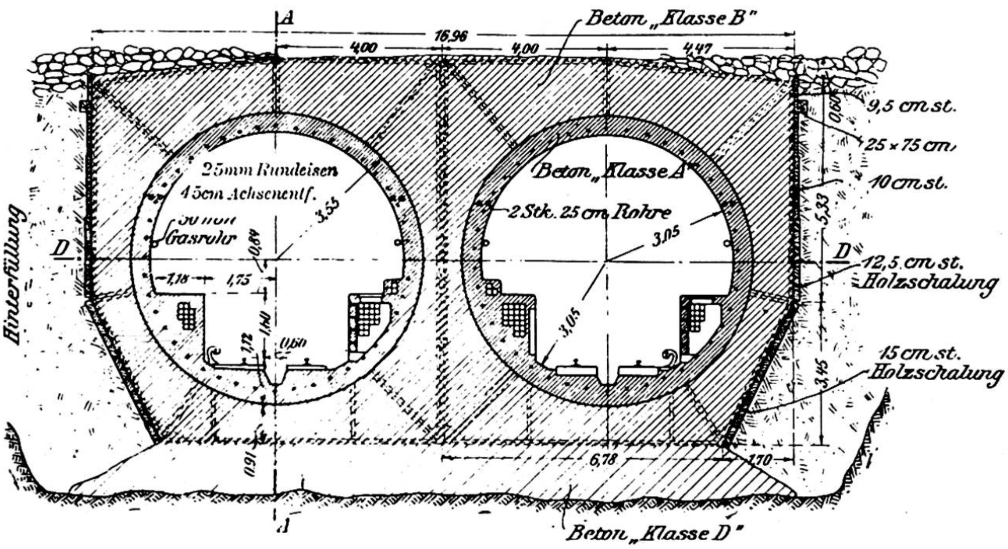


Fig.2 Cross section: Michigan Central Railroad tunnel in Detroit

Immersed tunnels are quite flexible in cross section, they only require a dredged trench to be installed and a simple drydock, sometimes located in the future approaches, to be constructed.
All of this explains that immersed tunnels are of increasingly interest for the solution of traffic communication within and around cities. From the number of

tunnels, mentioned in chapter 1, 10 have been completed during the last 5 years. Although no real offshore immersed tunnels have been constructed yet, many plans are under consideration. The Channel tunnel was just not built as an immersed tunnel as the limited width in cross section, being a raillink only and the favourable soilconditions for boring, just ruled out an immersed tunnel. For the Great Belt Link in Denmark, things were different. Although an immersed tube tunnel was offered as more expensive and initiated the potential risk of dredging contaminated soil, it presented less risks compared with a bored tunnel through the geologically complex soilstructure.
The bored tunnel was selected, but presents actually major escalations in time and costs. This may influence the decision process in future offshore tunnelling jobs.

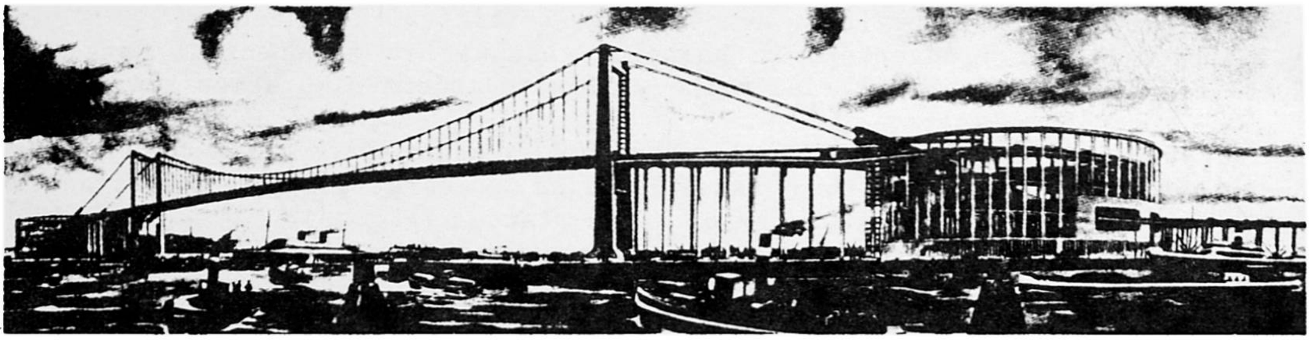
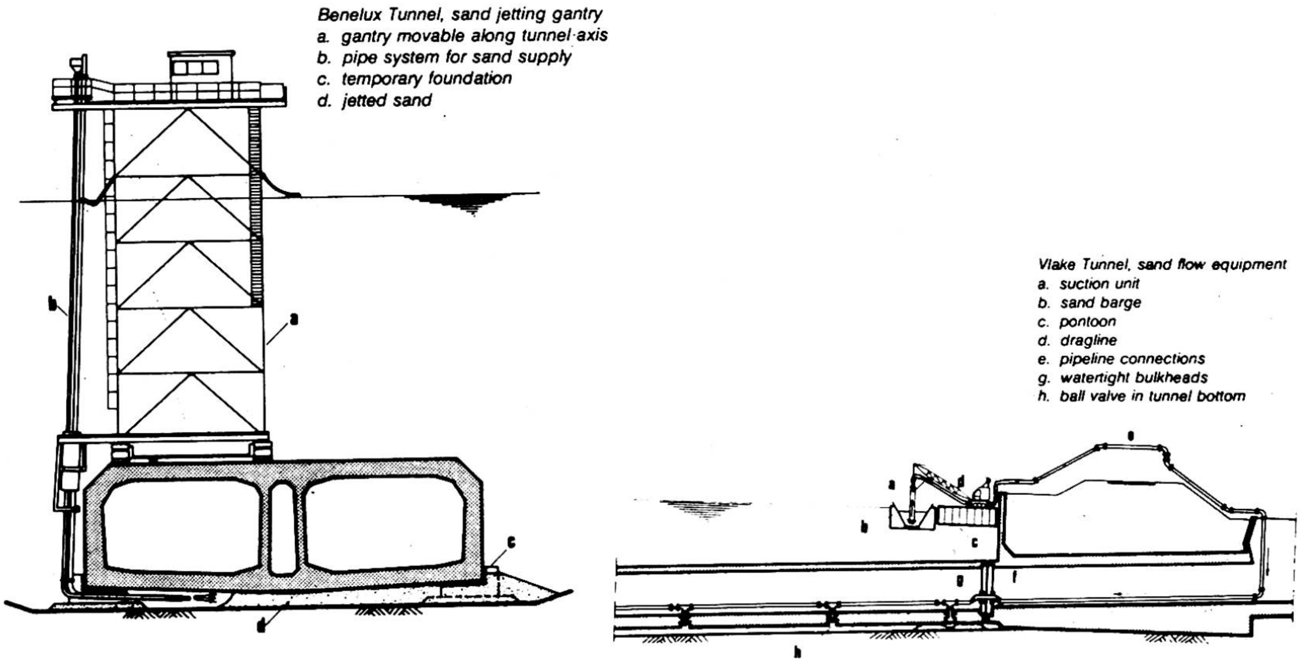


Fig.3 A bridge with spiraltype access structures as proposed for the Maastunnel in Rotterdam.

3. FOUNDATION

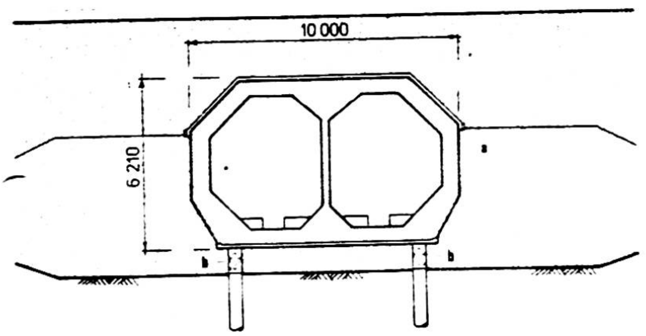
Although immersed tunnels, like most offshore structures, float temporarily, they are to be installed on a proper foundation.
It is here where all kind of techniques are used. Tunnels are founded on piles, on a pre-installed gravel or rock beds and on provisional foundations, to be replaced by undergrouting or underbase sand jetting.
This variety of engineering solutions to provide a sound foundation for the immersed tunnel is not only a consequence of geotechnical circumstances at the tunnel location, but also addresses the structural system of the tunnel in longitudinal direction.
The "American" tunnels are usually founded on a gravel or rock bed, being layed on top of a usually quite stiff bottom of a dredged trench. Such a bed, having a minimum depth, provides obviously sufficient elasticity, to safeguard acceptable foundation reactions for tunnelelements of lengths and size as installed in the USA. There is only little information on tolerances being measurable and consequentially tolerable using this method. The record is good and does not show any major problem. The method has been used in Europe as well in a limited scale, especially for service tunnels where uneven subsidence did not raise major problems.
Far more popular in Europe is the method of providing a temporary foundation by means of concrete tiles, on the bed of the dredged trench, on which the tunnel is temporarily founded and geometrically positioned up to quite fine tolerances by means of jacks. The remaining space in between the tunnelbottom and the bed of the trench is than filled with sand. This was originally done by jetting a mix of sand and water from the side of the tunnel through a system of pipes, from which two served the supply of sand and one caused suction in order to

drain the superfluous water (Fig. 4).
At present, the method of just injecting a sandflow through the bottom of the tunnel became more popular, as it avoids any disturbance of shiptraffic and can be applied fast after immersion. This has the advantage, that silt has none or anyhow quite reduced changes to settle in the trench before the final foundation is realized. The sand flow method is based on the principle that velocities in and around a cone of sand being built up underneath a hole in the tunnelslab on the bottom of the trench are such, that the sand settles in a proper way on the outside of the cone. With a centre to centre distance of around 10 m for a 1 m thick void, a sufficient foundation can be realized (Fig. 4) [4].

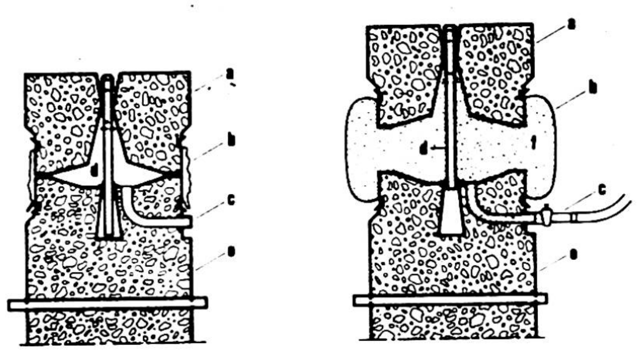


<u>Fig.4</u> Sand jetting equipment and sand flow equipment in action.

On locations where poor soilconditions would cause unacceptable uneven settlement in the tunnel, or above the tunnel at covered parts outside the actual river, foundations on piles have been provided. This was for instance the case for the Rotterdam subway line (Fig. 5). To meet tolerances, a system was developed with jacks on top of the pre-driven piles.
It should be realized, that for most offshore structures, these methods will not provide a valid solution, as the ratio of horizontal reaction over vertical reaction is basically larger, because of wave forces acting on the structure. Therefore either foundations directly on the seabed or on a prepared seabed are used. In case this is not possible for technical reasons, a skirt is provided around the perimeter and across the bottom of the structure is provided. This skirt penetrates into the seabed. The remaining space is filled by injection of materials that can be mixed with seawater, such as cement and silicate, giving smooth flow characteristics.



Rotterdam Metro Tunnel, cross-section
a. concrete tunnel structure
b. foundation piles with adjustable head



Rotterdam Metro Tunnel, adjustable pile head
a. pile head
b. nylon sleeve
c. grout pipe connection
d. guide rod
e. prefab pile section
f. grout injection

Fig.5 Cross section of Rotterdam subway tunnel and piling system

4. WATERPROOFING AND DURABILITY

A most important aspects of marine structures is the waterproofing and durability. Here again immersed tunnels offer a large record of satisfactory behaviour. There seem to be quite some different approaches towards waterproofing, but most of them just exist, based on historical background.
In the first place the "American" type tunnel had a steel lining. This was not essentially for watertightness or durability, but was there as a consequence of the fabrication method and the structural system. But being there, it was taken for a waterproof hull as well. Many tunnels and other marine structures, including the above mentioned Maastunnel were consequentially provided with a steel or carbohydrants based skin, to provide watertightness.
The construction of tunnels and parts of tunnels by means of pneumatic excavated caissons raised some concern about the resistance of waterproof layers on the outside walls against the soilfriction during placing. It was decided for that reason, to omit the waterproof layer in some cases in Holland and Germany. This decision was further supported by the fact that existing tunnels with watertight coatings were leaking anyhow, because of failing details in joints and details of penetrations. Such leaks were usually quite difficult to trace at their source and to stop.
Since about twenty years now, tunnels in the Netherlands are constructed without an extra watertight layer. The performance is extremely well and can be an example worldwide, provided that a few things are noticed. This concerns concreting including treatment, detailing of joints and penetrations and the provision of back up measures where relevant.
When the concrete has to be the only and consequentially reliable way of defense against leakage, the whole process of concreting with all its aspects has to be controllable in order to provide the required reliability. This has been improved in several ways during the last decade, especially by the ability to study all aspects influencing the hardening process of concrete in one computer model [5]. These aspects concern mix-design, hardening parameters like cooling and heating, environmental aspects like temperature and wind and construction parameters like formwork and time of stripping.
Working with such a model, stresses during the hardening process of concrete can be predicted and controlled, enabling us to select an effective way of construction in view of costs and durability (fig. 6).

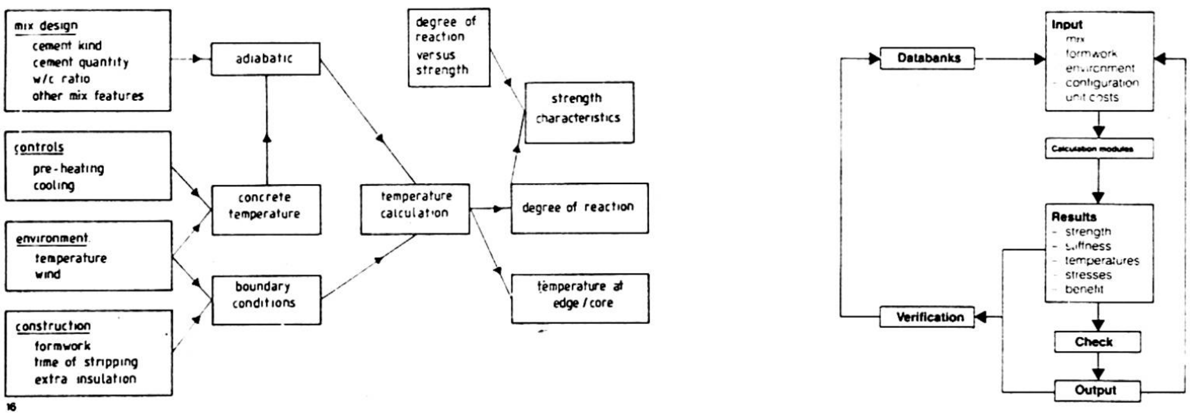


Fig.6 Relation in between construction parameters and concrete characteristics. Flowsheet of a computerprogram analyzing this.

With concrete being sufficiently impermeable by good design, practice and control, only the details, such as construction joints, joints to be provided for expansion and rotation and joints to link independently immersed units together are left for attention.

For construction joints good practice, such as jetting fresh stripped surfaces, is quite common and satisfactory. Joints in between independently immersed elements are usually carried out with double waterstops. Most remaining trouble in the past has been caused by joints to provide expansion and rotation freedom within one tunnel element. It is common practice today, to take special measures during pouring of concrete around such joints, to avoid honeycombing and air entrainment, in the vicinity of the waterstop in the joint. On top of that, means are provided to inject possible leaks in between the concrete and the waterstop anyhow, with some back up for injection after final installation (see fig. 7).

Elastic strip for reinjection   Injection tube

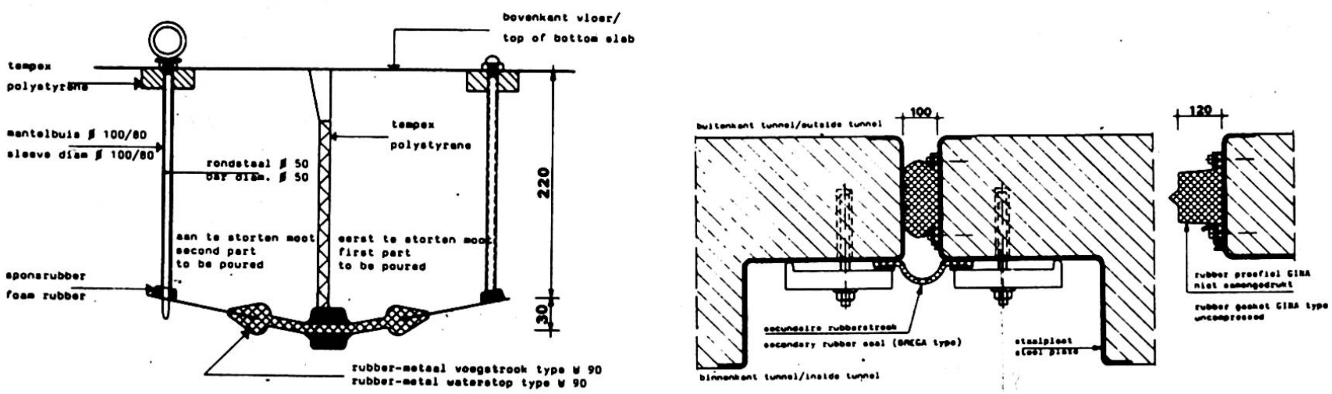


Fig.7 Joint details for joints within and at ends of submersed units.

It can be concluded that watertightness for concrete marine structures is no problem anymore, provided that sufficient know-how is being made available and sufficient quality control is being applied to the job. As durability of the structure requires more or less the same effort, it can be concluded that this can be assured in the same way.

5. STRUCTURAL SYSTEM

The American type tunnels have always been solid structures in longitudinal way for the length of one immersed unit. Connections in between units have also been designed quite stiff, not allowing rotations.
In Europe, where tunnels have been constructed on soils of less stiff nature, the concept of hinges within the units at distances interfering with the casting joints came up and is commonly used. The elements are made stiff by prestressing from bulkhead to bulk-head during float up, tow and immersion. After installation the prestressing cables are removed and the element can follow the differential settlement of the riverbed without forces being introduced in longitudinal direction of the tunnel element. A secondary benefit of this system is the fact, that less than minimum reinforcement in longitudinal direction can be applied in the tunnelelement as no mechanism to cause brittle failure in longitudinal direction is present. In some cases, the temporary prestress is only provided in the area of the joint. In such a case the longitudinal reinforcement should of course have a minimum value as required for membrame tensile stresses in the cross section.
An other aspect of the structural system for reinforced concrete tunnels is the internal force distribution in transverse direction. As shear usually governs the design of the cross section, several systems are available to decide on dimensions of the cross section. In case of low waterdepth, say less than 15 m, or small spans as in case of railtunnels or two lane tunnels, just normal reinforced concrete plate type structures can form roof, bottom and sides of the tunnel. In case of larger depths and wider tunnels, with 3 lanes, sizing roof and bottom will not result anymore in tunnels of minimum cross section still being able to float. In such cases a selection has to be made in between a larger cross section, requiring more concrete, dredging and tunnellength, or solutions with transverse prestressing, providing stirrup reinforcement in roof and bottom or bent up bars in roof and bottom. It may be clear, that an approach for an effective solution now requires more partners in the construction process than just the designers.
Such choices, to be obtain the most effective structure, in a discussion in between designers and constructors, are quite common and even required during the design of offshore structures.

6. CONSTRUCTION FACILITY

Large offshore structures as well as immersed tunnels have been constructed in both existing shipyards and dedicated "polder" type drydocks. Availability, soilconditions, local law, and an increasing impact of environmental aspects govern the choice of a construction facility for a specific job. It is quite possible in certain cases where more tunnels have to be built in a small area, that the same facility will be used several times. In Holland, the Hijnenoord dock, in the vicinity of Rotterdam, was used for seven immersed tunnels, since its construction in 1966.
Sometimes tunneldocks are provided temporarily in the future approaches to the tunnel. This reduces extra dredging work in case of small projects and low draft access to the tunnel trench.
Just as for offshore structures, parts of ship repairdocks, or abandoned drydocks, are sometimes made available for the construction of immersed tunnels. Fast construction becomes quite important in that case.

7. IMMERSION SYSTEMS

Whereas the construction of the elements for an immersed tube tunnel is still of a comparatively conventional character, the marine operations, containing float up (will it float ?, etc.), tow (can it be towed regarding draft, tide, waves and current, etc.) and immersion (will stability be sufficient in all stages; is the time frame sufficient, etc.) are not.
Recent practice has shown, that it is quite useful to consider the skills required for the immersion procedures as an integral required experience in the design and construction of an immersed tunnel job. This means that immersion and the preparation of immersion has so many effects on the total construction of an immersed tunnel, that it can not be considered as a subcontract in the whole procedure.
Apart from design and integration of embedded items for float, tow and immersion, of the elements, unconventional disciplines like weight control, required strength for operations and possible impacts during operations are to be considered.
Beyond this, two basic design philosofies are valuable for the selection of the main parameter of the immersion system. The tunnel elements may have sufficient buoyancy for float and tow and will have to be ballasted for immersion and provisional installation. This method requires quite light immersion equipment, but involves substantial work in the elements before, during and after installation.
The other method, as quite frequently used in the USA involves floating up, towing and immersing tunnel elements without any floating capability. The equipment is consequentially more expensive, but savings are made by having no ballast equipment for storage and pumping within the elements and having no need for the installation of ballastconcrete after installation.

8. CONCLUDING REMARKS

It is clear from the few aspects being touched in this paper, that there is not a thing like an ideal design for a submerged tunnel. Project parameters, like draft, type of traffic, length and depth will provide different challenges to the designers. The design parameters, like structural system, waterproofing and foundation still offer a wide variety of solutions. Both project and design are having an impact on the construction method.
Quality control, especially where information technology plays a role, provides means of simulating construction processes, like marine operations for towing and immersion, like concrete hardening for strength and stress development and like surveying for weight control. This will reduce risks and provide new technologies for faster construction of cheaper and more durable structures.
This is the case in the offshore industry as well. The present record of immersed tunnels in the world proofs it.

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