CONTRACTOR-DESIGNER TEAMWORK, THE KEY ELEMENT OF SUCCESS IN DESIGN-BUILD

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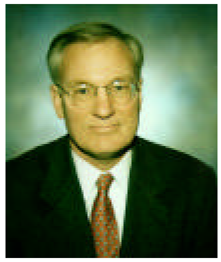

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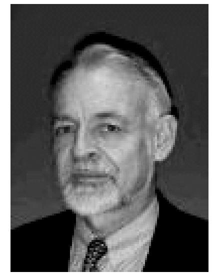

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Abstract
The success of the Oresund Tunnel is based on a foundation of effective teamwork between the contractor and his designer. This article describes how teamwork was developed during the tender period and focuses specifically on the consequences of this effective teamwork to the design and construction of the tunnel elements.

Keywords
Oresund Tunnel
Design-Build
Immersed Tunnel
Incremental Launch
Prefabrication
Launch Systems

Introduction

The Oresund Tunnel is considered a success today because it has been completed ahead of schedule, within the owner's budget, and to a high level of quality. This success raises two questions: How was it accomplished; and can the experience from the Oresund Tunnel be applied to future large-scale projects?

Figure 1
Aerial view of Oresund Tunnel Casting Yard

The project's success can be attributed to a number of factors including the excellent management of the project by the owner's and the contractor's staff during the detail design and construction of the tunnel. However, the foundation of this success was the effective teamwork developed during the tender period between the contractor and his designer. This teamwork was made possible by the owner's decision to select the design-build contracting method. However, it was the owner's proper implementation of the design-build process that gave the contractor and his designer the freedom to work effectively as a team to develop the successful design and construction methods used on the Oresund Tunnel.

Two other factors during the tender stage played a key role in the projects eventual success: these were the effective control of risk by the owner and contractor; and the contractor's ability to effectively communicate the innovative concepts proposed for the project.

Effective Team Work Between Designer and Contractor

The Oresund Tunnel Joint Venture was effective in developing teamwork between the contractor's personnel and the design team. The tunnel design firm was selected approximately one year before release of tender documents, and members of the design team attended all pretender meetings dealing with proposed construction methods and evaluation of potential fabrication sites. Two months before receiving tender documents, a project office was setup in Malmo, Sweden, and a team of construction engineers, estimators and design engineers was assembled. Team personnel where assigned to Malmo on a full-time basis through the tender period.

Perhaps the central challenge facing the tender team was to find a way to build the tunnel elements that exploited the unusual scale of the project. The solution eventually chosen, the key elements of which are described below, certainly achieved this, offering higher quality, faster construction and lower cost than conventional alternatives. However, this solution did not arise easily or quickly, and would probably never have emerged without the exceptionally open-minded approach taken to design development by the tender team.

Many meetings were held during the early stages of the tender period to discuss the tunnel element construction problem. At these meetings, innovative ideas and solutions were encouraged from all individuals, without regard to individual expertise or seniority, and regardless of whether an idea looked promising on first inspection. Through this process, many apparently implausible suggestions were explored. A number of these, although unworkable in their original form, either appeared in the final solution in a new guise, or acted as catalysts to spark off new lines of enquiry.

This critically important conceptual design process is perhaps best illustrated by way of examples. One early idea was to construct each section of tunnel beside an existing dry dock, then slide it onto a floating pontoon within the dock, which could then be lowered to take the tunnel section down to sea level. This concept suffered from a number of flaws, but the basic idea - to lower tunnel elements to sea level by raising and lowering the water level in a dock - was adopted.

Another idea was to precast very short sections of tunnel on end, then rotate them to the correct orientation and connect them together. For the very large cross section of the Øresund Tunnel, this ultimately proved impractical, but it forced the team to think about ways of moving sections of completed tunnel without floating them in water. The final solution did precisely this, albeit by a very different method.

Finally, when existing dry docks were being considered as construction sites, it became apparent that in-situ fixing of reinforcement would not be practical due to space restrictions at these sites. The final solution did not use an existing dry dock, but the concept of prefabricating reinforcement cages off-line (and hence off critical path) was adopted.

The procedure for developing new ideas once raised was to first collect and disseminate all relevant information on the issue in question. Prior to any meetings, a preliminary solution was then developed and distributed to all members of the team. The purpose of the preliminary design was to challenge the team's imagination and help define the scope of the task. Each member of the team was then given time to develop his own ideas of how to solve the problem. The objective of this step was to stimulate the imagination of the team and, for each team member to create a clear picture in his mind of a perfect solution without trying to answer all the questions regarding how to get there. A meeting was then held to openly discuss the potential solutions and compare the relative merits of each. The team then took the best elements of each solution and combined them into one that the team felt best solved the problem. After jointly agreeing on the best solution, the team then focused on addressing how to make it work.

The tunnel designers played a key roll in this process. They contributed potential solutions, and most importantly, identified potential benefits and negative impacts that the various solutions could have on the completed tunnel. The designers for example, were able to confirm early in the tender period that full section casting not only reduced the risk of early age cracking in the freshly cast tunnel segments, but also completely eliminated the need for all artificial cooling of the concrete. They were also able to confirm the need for a hydraulic support system for the newly cast tunnel segments to ensure the segments would not crack as they were skidded from the casting bed to the outfitting site.

The designers were also instrumental in showing how the tunnel design could be modified to accommodate the innovative construction methods. As an example, a significant cost advantage was possible with the use of fixed rigid jigs for the pre-assembly of the reinforcing cages, but the use of jigs was only made viable because the designers where able to standardize the spacing of the bars to accommodate the jigs.
To summarize, the essence of the approach was:

- To encourage everybody to contribute ideas, regardless of whether their expertise was in permanent works design, temporary works design or construction methods;
- To encourage imagination and creativity;
- To accept ideas with an open mind, even if they made little sense on first inspection, and to explore whether they could be improved by exposure to other ideas from different sources;
- To compare ideas as they developed in open discussion, using as far as possible objective criteria for comparison.

Consequences of Effective Team Working
The Owner selected the design-build process over other forms of contracting that typically separate design from construction. This decision allowed the designer and contractor to work together during the tender stage. This had many beneficial effects. For example:

During the tender period, the designer and contractor shared the common goal of minimizing construction cost. The contractor was able to provide reliable and current cost data to the designers and helped the designer to more readily see the cost implications of their design decisions. The designers made effective us of this information because they fully realized that a price would be attached to their design before submittal to the owner, and that the joint proposal for the project could be rejected because the price was too high.

The final permanent works design not only minimized materials, but also focused on ease of construction and customization to this particular contractor's preferred methods of working.
The choice of construction methods was perceived by all as an input to the overall tunnel design process, rather than as something to be determined after design was complete. Many of the construction methods adopted are not intrinsically, easy or cheap in themselves, but were chosen because they fundamentally improved the tunnel design, affording indirect, but very significant cost and schedule benefits.

Bringing the contractor and designer together allowed both parties to develop a better understanding of the risks inherent in the project, and to adopt designs and construction methods which helped to minimize risk.

The net result of this exchange of perspectives and ideas was numerous innovations for tunnel design and construction that reduced costs while improving quality. The success of this process is illustrated by the following examples where quality was improved while costs were reduced:

<u>Standardization and Assembly Line Production</u> – It was recognized early in the tender stage that tunnel elements and segments should be as uniform as possible, and that there were significant cost and quality control advantages if the tunnel segments could be produced in a continuous flow of work with a relatively even and steady demand on labor. It was also recognized that the Oresund Tunnel would be the largest immersed tube tunnel ever built, and that the number of segments to be fabricated would justify the high cost of setting up an assembly line facility. (See Figure 2 on following page.)

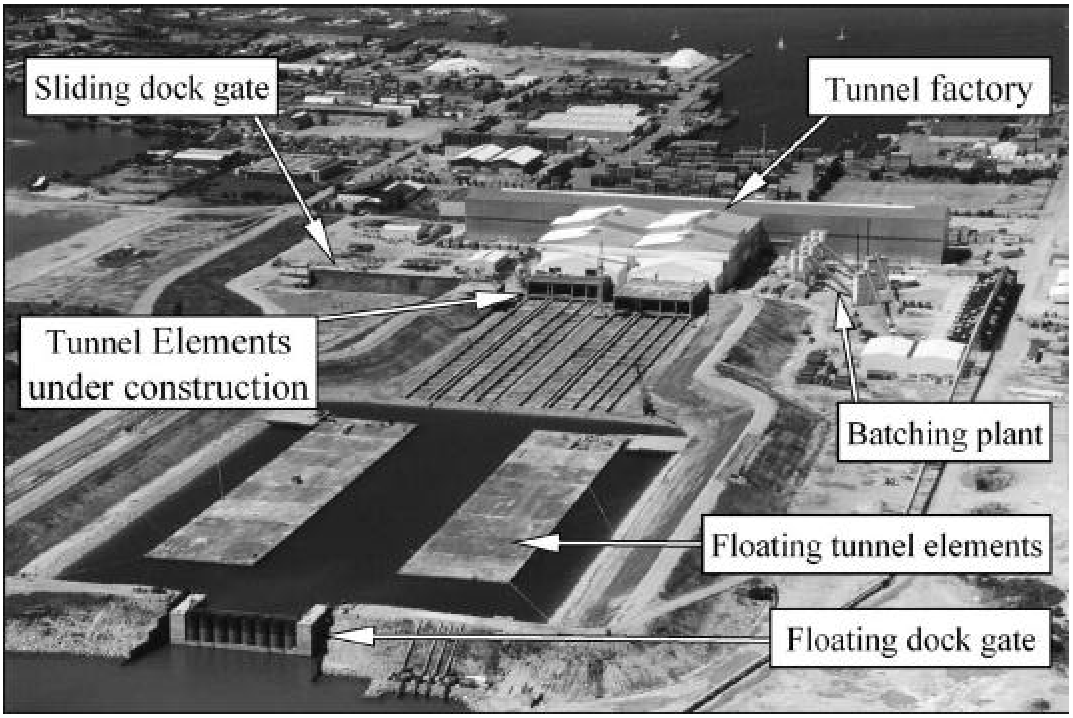

Figure 2 Assembly line facility for precast tunnel segments

This type of fabrication facility greatly improves material flow and labor productivity while allowing a systematic monitoring and control of quality. This combination helped to assure lower construction costs while improving quality of the tunnel construction.

<u>Prefabrication of Reinforcing Cages</u> - Prefabrication allowed most of the reinforcing to be placed and tied at chest height, the optimum position for manual assembly of reinforcing. At the same time, the rigid templates (used to build the cages) helped ensure precise and consistent spacing of the individual bars. The prefabrication also allowed complete inspection of all reinforcing before the cages were placed in the forms. (See Figure 3 below.) The end result was 40,000 tons of reinforcing steel efficiently placed to tight tolerances. In addition, this approach took the entire reinforcement assembly process off the critical path for tunnel construction.

<u>Enclosed Fabrication</u> – The winters in Scandinavia can be long and cold. The Danish and Swedish contractors and their work forces have effectively adapted to this environment and take the winter in stride. However, cold, wind, rain, snow and ice all have an impact on productivity and the quality of construction. The contractor/designer team was fully aware of this and saw that the large scale of the project in combination with the relatively fast flow-through of tunnel segments along the assembly line would make it economical to completely enclose the fabrication and casting facility. (See Figure 4 below.) This decision allowed work to proceed 24 hours per day, year around, without disruption or impact from weather. This helped provide a continuous flow of work and a consistent increase in productivity. From a quality standpoint, it provided a controlled temperature environment that helped to minimize the risk of early age cracking of the newly cast tunnel segments.

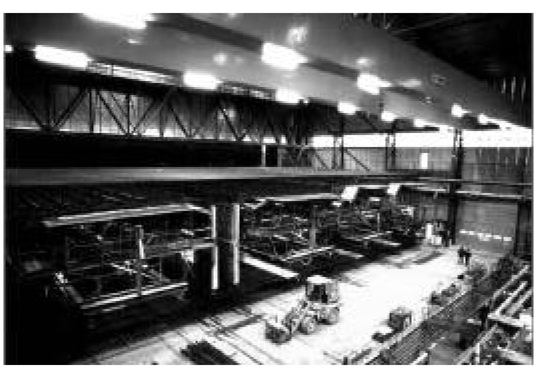
Figure 3
Completed reinforcing cage


Figure 4
Aerial view of enclosed casting facility

Element Fabrication Above Sea Level – The conventional way of casting tunnel elements is in the bottom of a large graving dock. The graving dock is excavated to a depth below sea level, sufficient for launch of the tunnel elements. A gate is provided to shut the basin off from the sea and allow dewatering. This type of facility is subject to potential flooding from high water or failure of the dewatering system. Additionally, this type of basin is not suited for continuous casting operations since all work must stop in the basin during flooding, launching of the elements and dewatering. In order to avoid these problems, the casting bed and skid beams were located above sea level, a berm was constructed around the basin to allow flooding, and a sliding gate was constructed to separate the casting area from the launching area. This design allowed the cost advantages of continuous production and the quality advantage of dry land construction. It also offered a significant environmental advantage in that long term dewatering of the casting area was not necessary.

Figure 5
Element fabrication above sea level

Use of Fixed Casting Bed with Steel Forms – The concept of assembly line production is based on the premise that the item of production moves, and the means of production remains fixed in location. To apply this process to the production of 7,000-ton tunnel segments implies the use of fixed casting beds and forms rigid enough to withstand high re-use. This same process (on a smaller scale) has been used successfully on the incremental casting and launching of bridge segments for over 30 years, where it has been shown to be highly economical and conducive to high quality. This system significantly reduced labor by mechanizing the form placing and stripping operation with hydraulic controls. In addition, the steel forms provided consistent and tighter casting tolerances, which reduced concrete waste and helped to provide minimum cover on all reinforcing steel. (See Figure 6 below.)

Figure 6
Steel form system for full section casting

Direct Placement of Concrete from Plant to Forms
The most economical way of placing concrete is to pump it directly from the concrete plant to the forms. The large volume of concrete made it economical to setup a concrete batching facility within 100 meters of the casting beds, and the centralized location of the casting beds made it feasible to setup a permanent pumping system. The net result was an economical concrete delivery system with the high quality associated with freshly placed concrete.

Full Section Casting – Full section casting of the tunnel segments was first considered by the designer/contractor team because it allowed tunnel segments to be cast on a weekly basis. However, it was recognized early in the tender process, that artificial cooling of 460,000 cubic meters of concrete for the purpose of controlling early age cracking in the tunnel would be a major cost factor on the project. It was also realized that the most common cause of early age cracking is the temperature differences between the staged pours in conventional casting operations, and that the temperature differences could be eliminated by the use of full section casting. Consideration was first given to casting the tunnel segments vertically (with the axis of the bores vertical). This offered the advantage that all concrete on a given section would be of uniform age and temperature. However, it was concluded that lifting and turning 7,000-ton segments after only a few days of curing without cracking them would be too expensive and too risky. As an alternative, the team turned to the incremental cast and launch techniques that had been successfully used on previous bridge projects by members of the joint venture team. These techniques involved full section casting of four to six-meter bridge segments and launching them within 48 hours of casting. The application of these techniques to bridge construction were cost effective and conducive to high quality, and it was assumed that they would be of equal benefit for tunnel construction. However, the main anticipated advantage of the full section casting was the potential elimination of the differential temperatures in the tunnel cross-section, and thereby, elimination of artificial cooling for the in-place concrete. A thermal analysis of the tunnel cross-section using a finite element model was conducted during the tender period, and the results confirmed that early-age cracking could be avoided with this process. The end result of this innovation was 460,000 cubic meters of crack free tunnel concrete without the use of artificial cooling.

<u>Elevated Casting</u> – Immersed tube tunnel segments are typically cast on the ground or on a prepared surface bearing directly on the ground. During development of the method for clearing the segments from the casting bed, it was recognized that the segments should be supported directly under the longitudinal walls, and the best method for doing this was to use pile supported grade beams. During the thermal modeling mentioned above, it was recognized that the elevated support provided by the grade beams also allowed the underside of the tunnel segments to cool at the same rate as the walls and roof. This necessary component of the assembly line process had the added benefit of further minimizing the risk of early age cracking.

<u>Hydraulic Support of Tunnel Elements</u> – To meet the requirements of the contract deadlines, it was concluded that each production line of the casting facility would have to produce an average of one tunnel segment per week. This required moving the tunnel segments 48 hours after casting, and entailed the risk of cracking the young concrete. In order to control the support forces going into the segment and avoid this risk of cracking, a concept was developed to support each tunnel segment on 36 hydraulic jacks. The jacks were divided into three groups and piped together to form a three-point support system that provided complete control of the support forces. (See Figure 7 below.)

Figure 7
Hydraulically supported tunnel segments exiting the enclosed casting facility

Owner's Definition of Contract Requirements
The tender documents prepared by the owner and his in-house consultant included specific design and construction requirements as well as an "Illustrative Design" that specified alignment, elevations and clearances for the rail and highway bores. The "Illustrative Design" left open such question as:

- whether the tunnel elements would be designed with a waterproofing membrane or not;
- whether the rail bore would be in a separate structure or combined in one structure with the highway bores;
- the length of each tunnel segment and element;
- the thickness of all walls and slabs;
- the amount of reinforcing in all tunnel sections;
- location of the tunnel fabrication yard;
- the selection of all construction methods;
- the method and material for underbase support of the tunnel elements.

At the same time, the construction requirements were very precise and explicit on issues relating to concrete durability, specifying: a maximum water-cement ratio of 0.40 for the immersed tubes, very strict limits on the alkalis reactivity of aggregates, and a prohibition of early-age cracking of the tunnel's exterior walls and slabs.

The degree of freedom afforded to the designer/contractor team was highly beneficial in that it permitted significant construction method innovation. However, the tight specifications included in some areas of the contract, notably with regard to concrete, created constraints in some instances where arguably none were needed.

A further interesting question was the necessity of the owner's "Illustrative Design". Given that the "Illustrative Design" was not contractually binding, it could reasonably be argued that it was unnecessary, or even that it might have distracted tendering contractors from finding inventive design solutions of their own. Certainly, for this project, many aspect of the "Illustrative Design" were not adopted by the designer/contractor team. However, on the other hand, from a contractor's point of view, the "Illustrative Design" was extremely helpful in allowing the tender team to focus its limited time and resources on the area of the tunnel where they could have the highest impact on cost. As an example, the primary focus of the designer/contractor team during the tender period was the fabrication and launch of the tunnel elements, and most of the innovations developed pertained to the tunnel elements. The approach structures represented a significant part of the work and risk on the project, but in the end, the illustrative design was closely followed.

The tender documents also contained a precise division of risk on the project. The owner had identified and evaluated a number of risk parameters covering site conditions including sea, weather and geotechnical conditions. The tender documents provided clear definitions of the range of expected or normal conditions for which the contractor was to assume risk, and the corresponding range of unusual conditions, for which the owner was to assume risk. Events falling outside the contractor's area of assumed risk were compensatory in either additional time allowed for construction or money, or in some cases both.

The level of detail and the focus of the owner's "Design and Construction Requirements" provided with the tender documents made it clear that the primary evaluation criteria for contract award would be:

- assurance of quality construction;
- cost;
- schedule;
- conformance w ith environmental restrictions.

Effective Risk Control by Owner and Contractor
The owner and contractor were both effective in minimizing and controlling risk on the project by avoiding the unknown. For example:

- Given the exceptional scale of the project, the owner opted to place the special risks associated with dredging the tunnel trench in a separate contract, so that these risks did not dominate the tunnel contract.
- The owner provided clear definitions in the tender documents of the risks to be assumed by the contractor and the risks to be assumed by the owner.
- The contractor selected his tunnel designer after evaluation of several firms, and only after confirming the designer's successful track record of several completed immersed tube tunnel designs.
- The contractor's joint venture team contained two firms knowledgeable of local environmental and labor conditions.
- All members of the contractor's joint venture team were experienced in marine construction, and five of the six firms had successfully built immersed tube tunnels in the past.
- The contractor selected methods and equipment that allowed over 99% of the structural concrete for the entire underwater tunnel to be constructed on dry land. This eliminated the unknown of future sea conditions for most of the tunnel construction.
- The large scale of the project and the contractor's selected casting method for the tunnel segments allowed all work to be performed within an enclosed structure. This eliminated the unknown of future weather conditions for a significant portion of the total project.
- The contractor selected only proven methods and technologies for construction of the tunnel. The contractor proposed and used a great many innovations on the project, but the innovations were in scale or field of application. The use of the incremental launch method for tunnel construction is an example of innovation in both scale and field of application. This technique has been effectively used on a smaller scale in bridge construction for over 30 years, but it had never been implemented on tunnel construction. To confirm that these proposed technologies were applicable and viable for tunnel construction, the contractor formed a technical review committee to pass judgment on all proposed construction methods. This committee was made up of experienced technical experts from each of the joint venture companies.

Figure 8
Crack free tunnel elements at time of launch

Effective Communications by Contractor
The tender submittal prepared by Oresund Tunnel Contractors proposed a number of new and innovative concepts for construction of the Oresund Tunnel. Effective communications played a key role in conceiving, developing and selling these concepts. The use of videos was one of the best examples of effective communications by the contractor. Early in the tender period when various casting concepts were first being discussed, one of the team members proposed the use of incremental cast and launch for the tunnel segments. The method had been used successfully by one of the joint venture partners on a bridge project in Paris. The idea seemed to have merit; however, there was not a great deal of enthusiasm for the idea until a video was provided that showed a step-by-step

process of the actual casting, pushing and launching of the precast bridge segments over a length of one kilometer. After watching this video, all members of the contractor/designer team immediately saw the applicability and viability of the concept for casting of the Oresund Tunnel. Before proceeding to the design and pricing of this concept during the tender period, the same video was used to sell the concept to the upper management of the individual joint venture companies.

A few weeks before submittal of the proposal to the owner, it was realized that there could be difficulties selling the innovative concepts to the owner (and eventually, difficulty for the owner selling the concepts to the public). Therefore, it was decided to prepare a video of the new tunnel casting facility showing in a step-by-step process how the segments would be fabricated on the production line, and how the completed elements would be outfitted and launched. This video was submitted with the tender and proved highly effective in communicating the new concepts to the owner.

After contract award, when construction began at the casting site, this same video became a very important training tool for quickly showing the entire work force, managers and craftsmen, the concept. Within 15 minutes, each member of the construction team who saw the video immediately had an idealized picture in his mind of how the entire process should work, and each member of the construction team knew the end objective.

Conclusion

The final success of the Oresund Tunnel had its origins in the early decision by the owner to use design-build as the contracting method and in the owner's proper implementation of design-build concept. The owner provided the contractor and his designer with a clear picture of what was wanted and the contractor/designer team was given the freedom to develop a design and construction plan that optimized both economy and quality. The contractor/designer team made the most of this opportunity by jointly developing innovative solutions while at the sam e time minimizing risk.

The Oresund Tunnel Project provides a successful design-build case history for future application on major projects. Experience from the Oresund Tunnel shows that when contractors and designers work as a single team, it is possible to reduce cost while improving quality and reduce risk while using innovative construction methods.

Figure 9
Completed tunnel element exiting the launch basin