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Advantages of British Steel Bi-Steel in Immersed Tunnel Construction

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Hugh Bowerman, born 1960, has a degree in civil engineering from Manchester University. Working initially in the design of offshore structures, he then focussed on subsea production systems which introduced him to mechanical and controls technology. The past 4 years he has been developing Bi-Steel, his work covering the production technology, product R&D program and the writing of the Bi-Steel design manual.

John Pryer, born 1962, has a degree in civil engineering from Nottingham Polytechnic. He worked for over 10 years for a civil engineering contractor gaining extensive experience both on site and in the design office. He joined British steel in 1994 as a piling advisory service engineer, moving to the Bi-Steel business in 1996 to lead the sales and marketing activities.

Summary

There has been interest in the use of steel-concrete-steel sandwich composites in immersed tube tunnel construction for over 10 years. Research has shown this form of construction to have good structural performance. Despite this, its use has been limited owing to difficulties in construction. British Steel Bi-Steel is a new, unique and patented composite construction system comprising two parallel steel plates held together by transverse bars welded at each end to the plates. The void is filled with concrete. Bi-Steel overcomes the construction difficulties, offering rapid construction times. It also offers opportunities to design and construct immersed tunnels in ways which are impractical with conventional methods. If these benefits can be realised in a project, then the use of Bi-Steel will result reduced costs. This paper explains what Bi-Steel is, and suggests how the material may be advantageously used.

1 Introduction

Immersed tube tunnels are usually constructed in a dry dock or casting basin in a number of segments. These are floated to the tunnel location where careful ballasting lowers them onto a prepared foundation. Adjacent elements are sealed together by welding, grouting or rubber seals. Permanent ballast is applied to ensure on-bottom stability. Most immersed tunnels are located in dredged trenches and are subsequently covered up.

For applications where water depth makes the construction of conventional immersed tube tunnels impractical, the concept of the immersed floating tunnel has been developed. The tunnel section is designed to have slight positive buoyancy, thus supporting its weight by floating. Segments are joined together and sealed as previously. However, the tunnel is held underwater and at the required depth by being tethered to the sea or river bed.

A number of different construction methods are used for immersed tube tunnels. These fall broadly into two categories: concrete or steel.

In concrete construction the tunnel tubes are usually rectangular cross section. The flat sides are heavily reinforced with steel to withstand the bending forces. Water is excluded by an external coating of bitumen, although some recent tunnels have deemed this unnecessary. Occasionally an outer layer of steel is used to exclude water. Tunnels of this type have been in use for many years - the Maas tunnel in The Netherlands was first opened in 1942 [1].

Steel immersed tunnels have been in use even longer, the first example being under the Detroit River in 1910 [2]. Whilst there are many variations on the general theme, all steel tunnels use a stiffened steel shell construction. Mass and additional strength is added by casting concrete around the shell, either on the inside or outside. Such tunnels are usually round in cross-section and the strength issue is not so severe as in the rectangular concrete tunnels. Thus, whilst some composite action between the steel and the concrete is assumed, the technique has never needed to develop the full strength potential available by utilising an inner and outer steel skin.

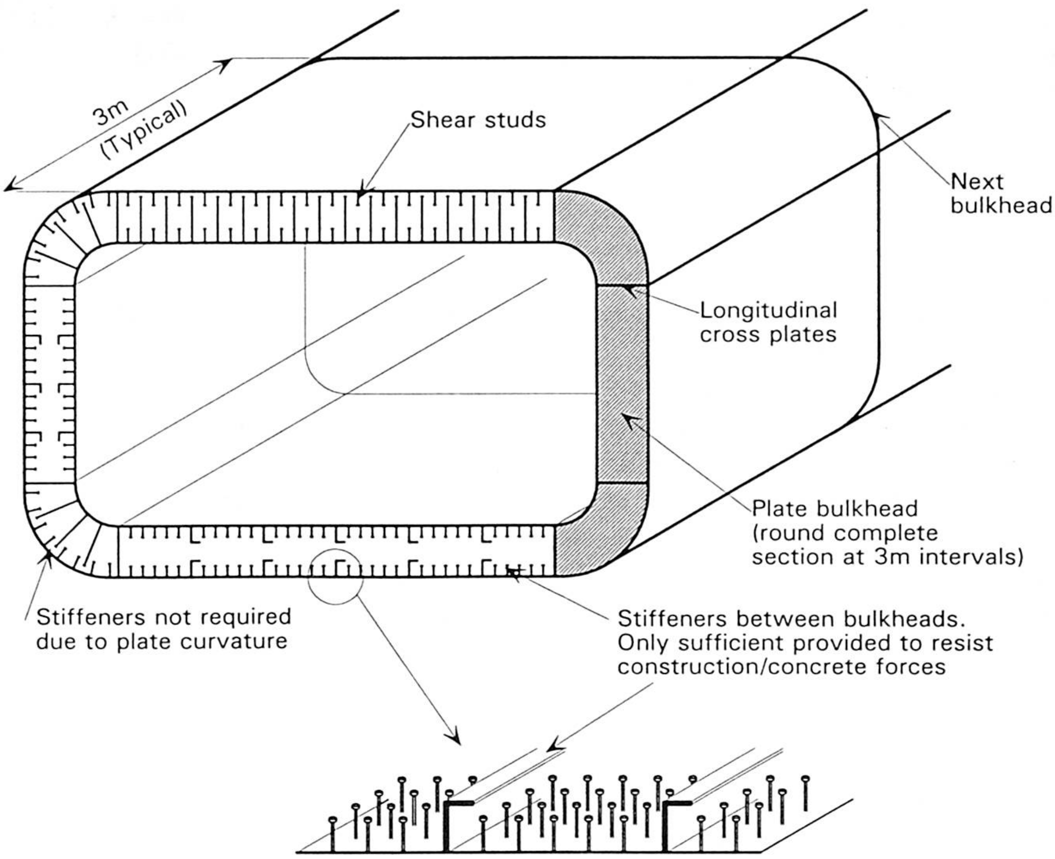

Fig.1 Steel-Concrete-Steel (SCS) construction using shear studs.

The interest in the use of double skin composite where both an inner and outer skin are fully utilised is more recent. As for steel construction, there are a variety of forms. That of concern here is referred to as SCS. This comprises of two steel plates with shear studs attached to each, see figure 1. The idea was first postulated for tunnels by the Tomlinson Partnership in response to preliminary work being carried out for the Conwy river crossing project in North Wales. Although essentially a concrete tube, the proposal was to enclose the concrete with an external steel skin. Why not make the skin work for you by keying it to the concrete using shear connectors? And why not provide a similar inner skin and dispense with most of the concrete reinforcement? Preliminary work indicated the scheme to be economically viable, and a program of research was instigated to provide the necessary design data.

Research continued for about 10 years, resulting in the publication of two design documents [3,4]. However, SCS has yet to be used on a major project. There are many reasons for this, a major one being the apparent mixing of steel and concreting trades on one project. But a second reason is undoubtably because it is not as easy to construct in SCS as had been anticipated. In particular, the relatively thin face plates need to be rigidly held in position during concreting. This substantially negates one of the major advantages of SCS which is that the steel plates act as permanent formwork. Either the plates must be stiffened, as in figure 1, or extensive temporary works are required. British Steel Bi-Steel, which is the subject of this paper, resulted from attempts to solve these construction problems. It is a patented construction system and the objective of this paper is to introduce Bi-Steel and thereby stimulate the designers of immersed tube tunnels to consider how it can be applied to these types of structures.

2 What is Bi-Steel?

2.1 Product description

Bi-Steel comprises of two parallel steel plates. Transverse bars are welded between the plates to hold them apart. The resulting panels can be considered as semi-rigid - they are stiff and strong enough to hold their shape during handling, but not so rigid as to prevent panels being fitted together.

The initial range of panel sizes available are summarised in figure 2. Note that it is possible to manufacture both flat and curved panels. The availability of curved panels opens up a number of interesting possibilities for immersed tunnel construction.

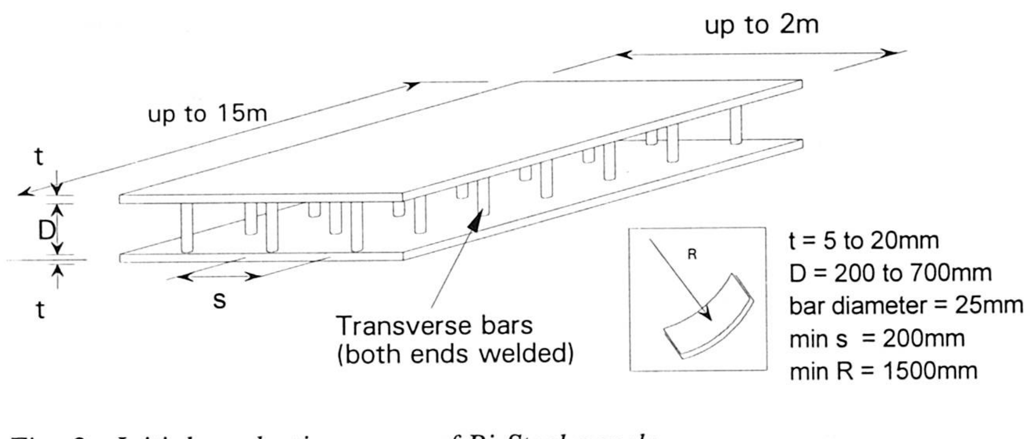

Fig. 2 Initial production range of Bi-Steel panels

In use, Bi-Steel panels would be welded together to form the shell of a structure. The panels would then be filled with concrete. It is the composite action of the steel and concrete which gives Bi-Steel its strength. Unlike concrete or steel construction, this composite action is fully utilised.

2.2 Basics of designing in Bi-Steel

The most useful way of understanding how Bi-Steel works is to regard it as a truss type structure. Figure 3 shows a section through a panel which is subject to simple bending. Using the truss analogy, the top steel plate and concrete act as a compressive top chord, the transverse bars act as tension ties, the concrete acts as diagonal compressive struts and the bottom steel plate acts as the bottom tensile chord. For the system to work requires that the relevant forces can be transferred at the 'joints', i.e., where the transverse bars are welded to the plates.

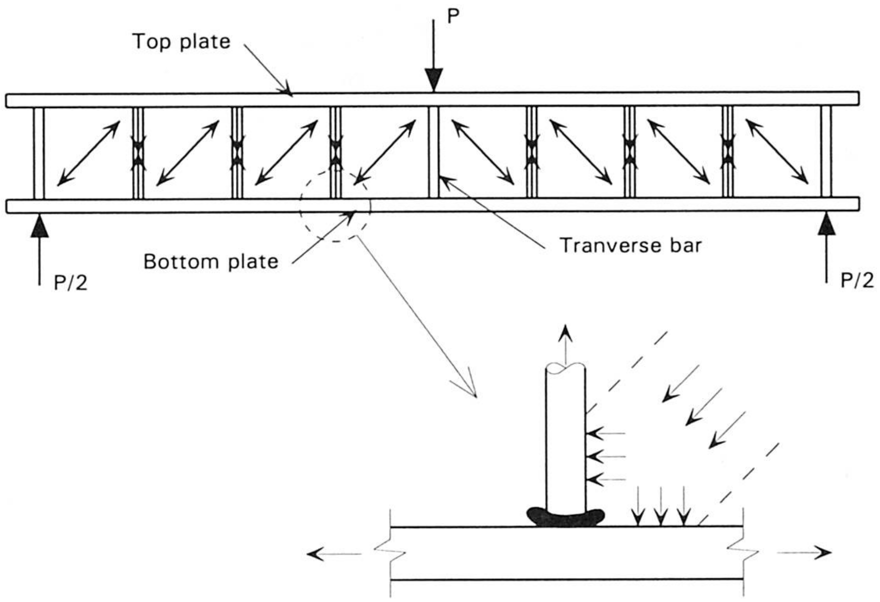

Fig.3 Diagram showing how Bi-Steel may be visualised as carrying load

The possible failure modes of Bi-Steel can be related to each of the elements in the truss analogy:

- *Compressive failure of top chord.* The top steel plate can carry a significant proportion of the compressive load. If this buckles, then there is a sudden loss of load carrying capacity. In practice the transverse bars are sufficiently close together that the compressive plate can reach yield stress before the onset of buckling.
- *Failure of transverse bar in tension.* This may occur by the bar yielding or by the weld connection to the plate failing. Yielding of the bar is a ductile failure mode. Usually the yielding leads to another failure mode being triggered (e.g., compression plate buckling). Weld failure leads to rapid load shedding.
- *Concrete compressive strut failure.* This tends to be gradual. Note that the concrete is confined and has no where to fail to unless a plate buckles.
- *Yielding of bottom plate.* This is a ductile type failure. As the plate yields, large amounts of energy can be absorbed by the structure.
- *Bar to plate joint failure.* This joint is under complex loading. The concrete is both pushing sideways onto the bar and down on the plate causing local bending. The bar is also in strong tension. The plate may be close to compressive or tensile yield. If joint

failure is by fracture, then a sudden failure occurs. It is therefore essential to achieve adequate joint toughness to ensure failure is ductile.

The Bi-Steel design guide teaches a comprehensive understanding of the above. The design method presented is based on providing adequate bar connectors in order to ensure that first failure is yielding of the steel plates. Special rules are presented to ensure that in compressive elements the steel plate does not buckle before yield stress is reached.

3 Benefits of Bi-Steel in immersed tunnel construction

3.1 Water exclusion

A primary objective of any immersed tunnel is to keep out water. Bi-Steel has two continuous steel barriers. Depending on the method of installation and element sealing technique selected, this double barrier may be maintained along the entire length of the tunnel.

3.2 Ductility

Bi-Steel has been tested in out-of-plane bending and has exhibited considerable ductility. Similar ductility may be anticipated for in-plane behaviour. An immersed or floating tunnel made from Bi-Steel will thus be highly tolerant to ground movement and accidental impact. This tolerance is enhanced by the orthotropic behaviour of a Bi-Steel panel - loads can be distributed in all directions rather than preferentially in one. A further observation arising from tests is that, when Bi-Steel is subject to large rotations, the steel plates deform rather than rupture. Thus water tightness is maintained.

3.3 Tunnel cross-section

Steel tunnels are generally round or octagonal in cross-section. Concrete tunnels tend to be rectangular in section. Because Bi-Steel is available as semi-rigid curved panels, there is much greater flexibility in the cross-section of tunnel that may be economically constructed. Figure 4 shows a number of options.

Figure 4(a) shows a rectangular cross-section. Bi-Steel is used in the walls and roof. However, the relatively thin Bi-Steel panels do not have enough mass to give the tunnel on bottom stability. This is therefore achieved using a thick concrete base. Extra benefit can be obtained from the backfill by adding small Bi-Steel wings.

Figure 4(b) shows a variant on (a) but using curved Bi-Steel panels. This reduces the thickness of panels. The voids around the traffic envelope may be used for fans, services, signals etc. Again, due to the low mass of the Bi-Steel, a massive concrete base could be used.

Figure 4(c) shows a tunnel cross section that may be used for a floating tunnel. The shape derives from two different diameter cylindrical elements. In Bi-Steel such a cross-section may be constructed as easily as a round section. Advantages relative to a round section are:

- an ability to better fit the traffic envelope
- less resistance to loads resulting from water currents. This is on account of the lower vertical height and more streamlined cross section
- greater vertical damping due to increased width
- less enclosed volume, and hence less need for internal ballast

The variations by using curved and flat Bi-Steel panels is quite extensive. What is significant is that there are options which are not readily available with the traditional materials.

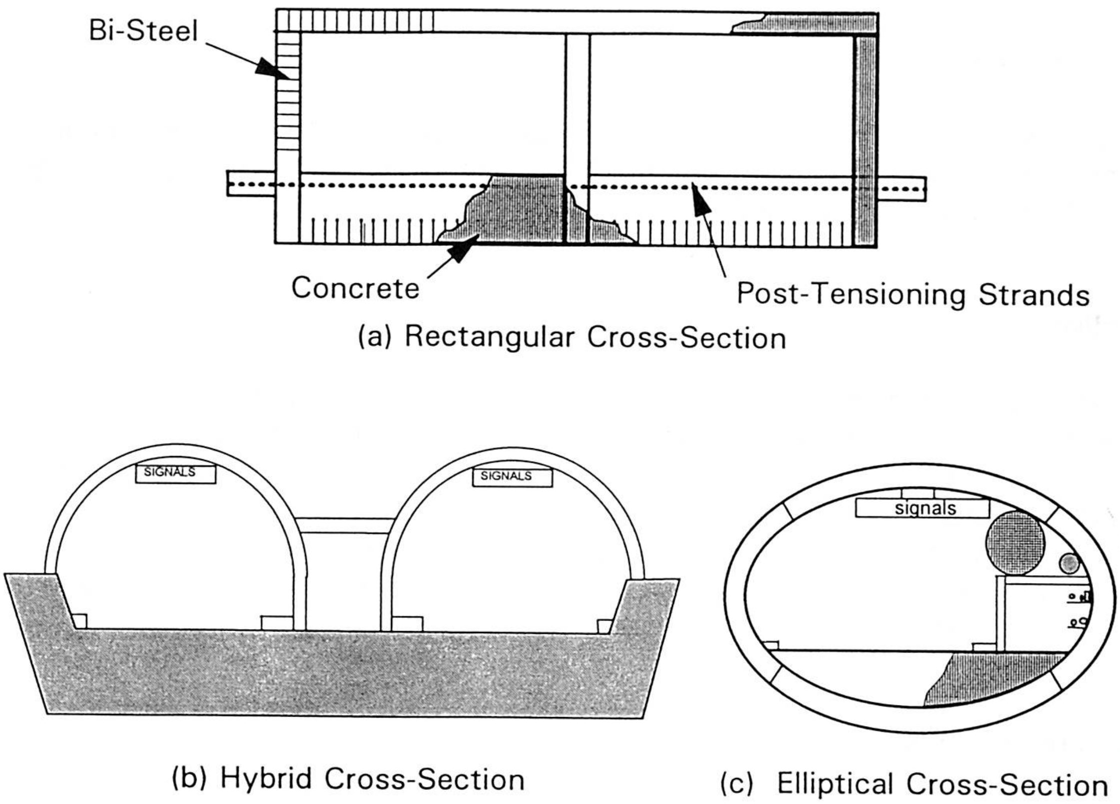

Fig. 4 Immersed tunnel cross-sections possible using Bi-Steel

3.4 Construction speed

Bi-Steel panels are factory produced to accurate tolerance. They may be delivered with surface coatings already applied. Where required, weld backing strips are fitted in the factory. In addition to assisting in the making of a good quality site weld, these also help the assembly of panels. A typical construction sequence is as follows:

- receive panels from factory. Store in a suitable location.
- using pre-fitted lifting lugs, crane panel into position. Note that unfilled panels are relatively lightweight - a 3.6 x 10 x 0.7 metre flat panel suitable for the roof of a two lane tunnel at 20m depth would weigh 8.5 tonnes empty, 69 tonnes when concrete filled.

- weld panels together. Semi-automatic welders running on pre-fitted tracks enable high quality welds to be made quickly and economically. Once one panel is positioned and part welded, adjacent panels may be fitted.
- on completion of welding, paint the weld zone (if required).
- fill panels with concrete. Mass concrete may be pumped in. Magnetic vibrators attached to the outside of the panel may be used to compact the plasticised concrete. Note that prior to placing the concrete the steel shell is already a substantial structure. Thus steel construction can proceed well ahead of concrete placement.

The above sequence can be carried out with surprising rapidity. It is estimated that a 90m x 10m tunnel element roof comprising 25 no. 3.6m x 10m panels could be assembled, welded, concreted and paint systems made good in 10 shifts. The labour on site required to complete this would be considerably less than for an all steel or concrete equivalent.

3.5 Construction flexibility

Concrete structures require large graving docks in order to be able to float the deep draft tunnel elements. US practice with steel tunnels has shown that shallower drafts enables tunnel elements to be built in conventional shipyards. Bi-Steel tunnels can be similarly built in shipyards, and then floated to deeper water prior to concrete filling.

Within a shipyard, Bi-Steel tunnel elements can be built vertically. This simplifies assembly and welding (no overhead welding). Due to their relatively light weight, the elements can be lowered down to horizontal and moved to position as required.

Building much larger elements in a vertical orientation is possible in deep water locations such as fjords. The general concept is shown in figure 5. Elements would be welded together and concreted off the side of a suitably fitted out flat barge. The completed section would be lowered into the water as construction continued. By suitable ballast control and mooring, tunnel elements of considerable length could be constructed. Once an element is completed, it would be upended and towed to site.

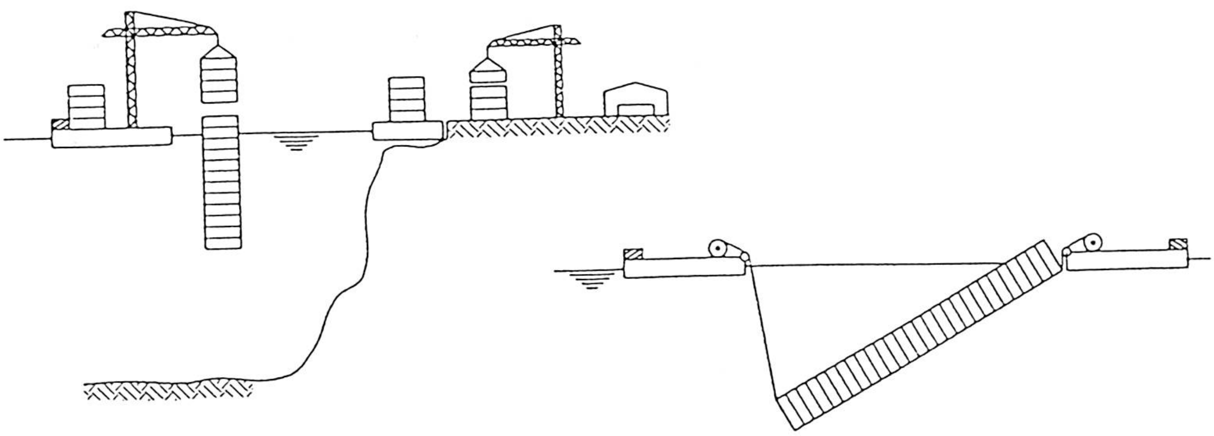

Fig. 5 Construction of tunnel elements in deep water

Where water depth is inadequate, a variation on constructing in a vertical orientation would be to construct on a slip way. As the tunnel elements are completed, so the tunnel is lowered into the water. In order to minimise loading on the slip way, the tunnel sections may be concreted as they enter the water. The nature of the construction sequence with Bi-Steel makes such a 'launched' element possible, saving both on graving dock and upending costs.

The ultimate extension of the above concept is to build the immersed tunnel as a continuous element. This is illustrated in figure 6. In this particular example the tunnel is part of a circular arc enabling all joints to be rigid. First step is to construct the approach roads which double as slip ways. Tunnels elements are then assembled on the slip way. A winch on the opposite bank pulls the tunnel across. In order to avoid stiction to the soil, provision for water jetting would be provided. Once the tunnel is completely across the channel, the external of the tunnel would be sealed off at the water bond. Advantages of this method are a lack of underwater joins (the tunnel is a continuous, double skin construction), reduced marine operations (dredging would still be required), speed (3m a day is considered attainable) and an ability to carry out a level of outfitting whilst the tunnel is being constructed.

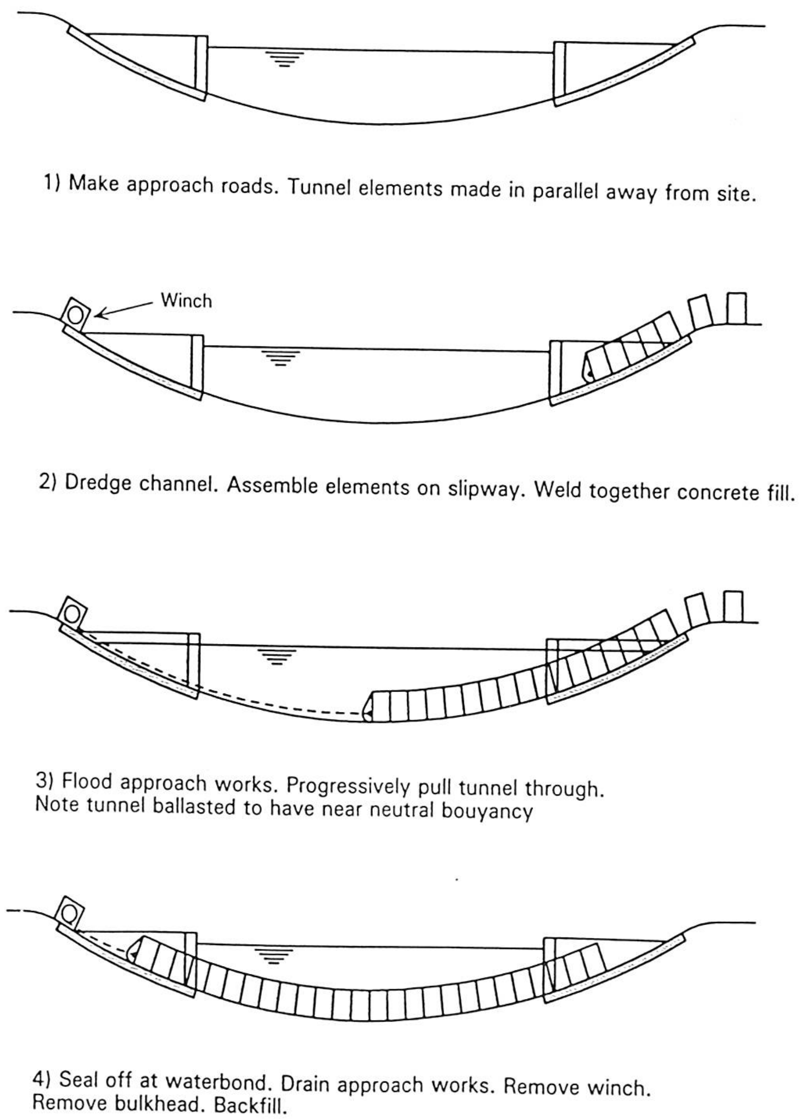

Fig. 6 Example of a launched tunnel using slipway construction

4 CONCLUSION

Immersed tube tunnels are not new, having been around for nearly 90 years. During this time nearly all tunnels have been built from concrete or steel. Steel solutions have made use of the concrete associated with them, but have not needed to mobilise the full potential of the composite action. Whilst some composite tunnels have been considered and tried, they have not become widely accepted. A reason for this is issues associated with construction.

British Steel Bi-Steel is a new, unique and patented construction system. It has been developed specifically with the objective of enabling large, composite structures to be easily constructed. However, for structures such as immersed tube tunnels, the material has a number of other benefits. The objective of this paper has been to introduce engineers and contractors to Bi-Steel. It is hoped that the ideas it contains will have stimulated some to consider ways in which Bi-Steel may be advantageously applied - it is the view of British Steel that Bi-Steel offers opportunities for considerable cost reductions if appropriately applied.

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