Construction Technologies for Wide Span Tunnels

A Comparison of Methods

By P. Lunardi

The construction of wide span tunnels involves far from ordinary design and production problems. This is mainly due to the considerable mass of the ground affected by excavation and the consequent difficulty in controlling instability of all types.

The problems appear to be particularly difficult to solve when the tunnel is located in an urban environment and especially so when the shear strength of the ground is very poor and the overburden is minimal. In the past attempts were made to deal with the statics problems posed by excavation in this type of situation by employing intense ground improvement around the tunnel before actual excavation. If this method did not provide sufficient guarantees of stability during excavation, and if cut-and-cover excavation was not feasible, then the only answer was to simply give up.

Today considerable progress has been made in several fields of engineering, including that of underground construction. The research and experimentation that has been undertaken in recent years by designers and constructors throughout the industrialised world has lead to the development and testing of new construction technologies capable of overcoming the difficulties posed by this type of construction.

One of these, the Cellular Arch technique, has aroused interest all over the world. It is an innovative construction system, invented by the author, that was employed with considerable success in the construction of the Venezia station on the Milan Urban Main Line Railway Link. The tunnel has a span of 30 m and was constructed using bored tunnel techniques in the centre of the city in loose ground, under the water table, with an overburden of only four metres beneath the foundations of ancient buildings (2, 3, 4, 10, 14, 16).

One particular characteristic of the technology saw the dreams of many designers come true; the tunnel was actually lined before excavation began. The system has been patented in Italy and abroad and following normal patent procedures, prior claims, which in this case arrived from various people, were examined before the patent was granted. All these claims were duly rejected confirming the innovative nature of the techniques introduced by Cellular Arch technology. As a consequence of this and of the great interest aroused by the construction method, it was felt that a comparative examination of Cellular Arch technology and similar technologies with which it has been compared might prove useful. Such an examination would highlight the differences between the various technologies and a knowledge of these is of essential importance when selecting which technology to employ in a given context for a particular construction.

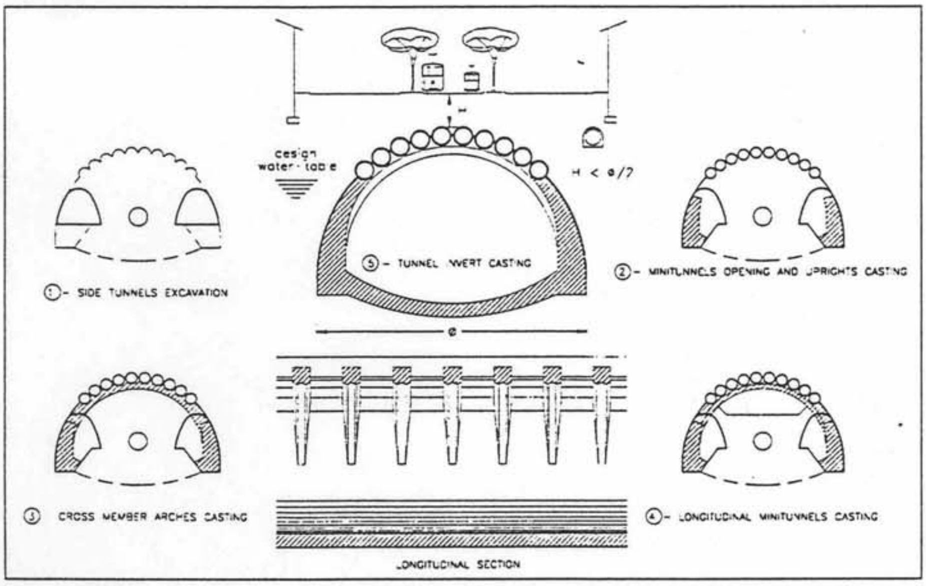

Figure 1 Cellular Arch – construction stages.

The Cellular Arch

The „Cellular Arch" is an innovative construction technique conceived of and developed to overcome, once and for all, all the difficulties encountered in the bored tunnel construction of wide span underground cavities in urban centres, in difficult ground with shallow overburdens and even below the water table, while keeping costs genuinely competitive with respect to traditional techniques.

The Cellular Arch is a composite structure (Figure 1), similar to a grid-like trellis with a semicircular cross section. The longitudinal members consist of r.c. tubes connected by cross members consisting of a series of arch-shaped ribs also in r.c. What makes the method particularly technically advantageous compared to other methods is the way that the passage is made from the initial condition of equilibrium of the undisturbed ground before construction begins and the final condition of equilibrium of the completed tunnel. It is effected in such a way as to prevent the ground from decompressing and producing surface subsidence. Excavation is in fact carried out after the very rigid load bearing structure has been fully constructed and is capable of exerting indispensable confinement action on the ground without undergoing any appreciable deformation.

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Cellular Arch construction is carried out in several stages; the first two are carried out simultaneously (see Figure 1):
- the opening of the minitunnels around the perimeter of the crown of the future tunnel by driving r.c. tubes into the ground from a launch pit located on the route of the tunnel;
- independent excavation beneath of two small tunnels for the uprights of the final tunnel;
- casting of the uprights of the future load bearing structure inside these two small tunnels;
- excavation, from the minitunnels, of the „cross member" shafts, which are to contain the forms for casting the connecting arches in r. c.;
- reinforcement and casting of the cross member arches and the longitudinal minitunnels;
- excavation of the ground inside the final cavity under the protection of the entire load bearing arch structure, which is already in place and functioning;
- excavation and casting of the tunnel invert.

This innovative construction method can be used to create underground cavities with a span of up to 60 m at shallow depths (i.e. with an overburden of only a few metres) in any type of ground and with genuinely competitive costs (8). In addition, with respect to previously employed methods it has the advantage of not causing any disturbance to surface activity and buildings. It is particularly suitable for locating the infrastructures of urban environments underground, e.g.: railway stations and depots, goods depots, parking complexes, shopping centres, libraries, museums, archives, sports and recreation centres, industrial plant, power stations, sewage treatment plant, military installations and bomb shelters.

As already mentioned, the „Cellular Arch" technique has already been employed with success for the construction of the Venezia station on the Milan Urban Link Line. With the current state of technology, it would be difficult to replace it with any other technology for the construction of large underground spaces, especially in loose ground under the water table and with very shallow overburdens above the roof of a tunnel. in fact there is no substitute for it in an urban environment. Employment of the method in Milan (Figure 2) also highlighted another point in favour of the technique: the extremely high degree of safety that is ensured during all stages of construction.

Construction times were also faster than with traditional construction systems since the two main construction stages, the driving of the minitunnels for the crown and the construction of the uprights, could be carried out simultaneously from completely separate construction sites which were nevertheless one above the other in the same section of tunnel.

Final tunnel costs showed themselves to be definitely very competitive compared to traditional methods employed under the same geological and environmental conditions. The latter resort to massive ground improvement ahead of the tunnel using cement injections, while the heavier costs for the microtunnels and arches of the Cellular Arch method are considerably offset by the savings on reduced ground improvement operations over the roof of the tunnel.

Comparative Analysis

Figures 3, 4, 5, 6 and 7 illustrate the construction methods of inventors who claimed priority for their patents over that of

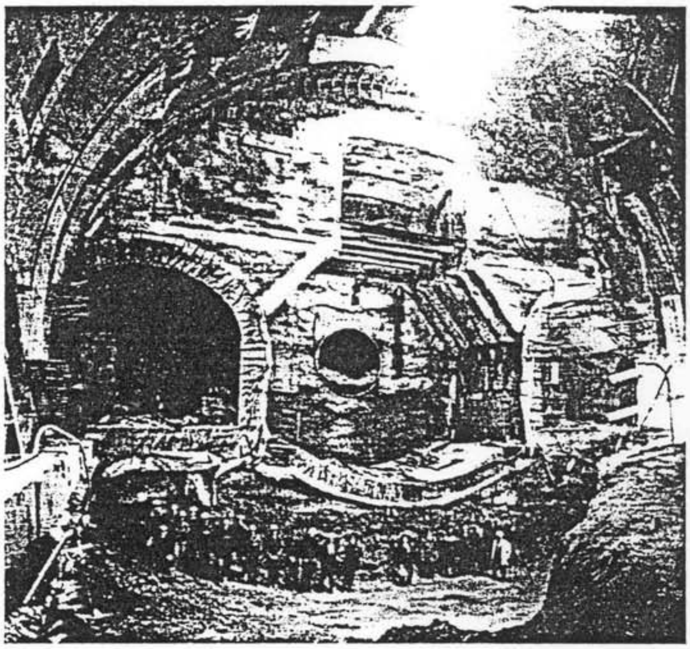

Figure 2 View of the Venezia Station (o.d.= 30 m, ground = Sand and gravel under watertable, overburden=4 m) on the Milan Urban Railway Link Line during construction using the Cellular Arch Method.

the Cellular Arch. These methods are reviewed below, one by one, giving a brief description, with consideration being given to how each method differs from the Cellular Arch method and why its patent claims were rejected.

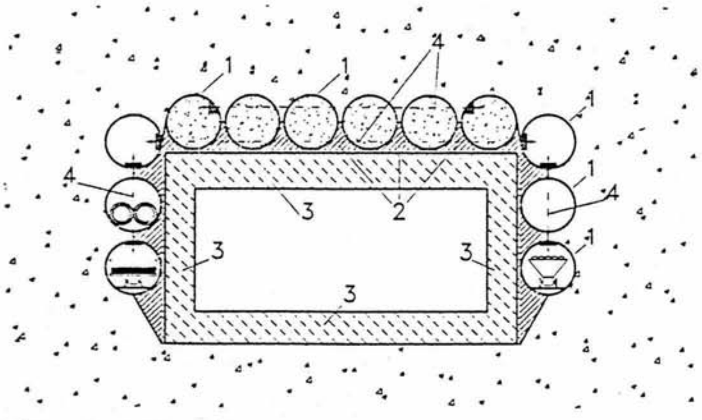

Figure 3 „Anchored Tubes Method".

„Anchored Tubes Method"

The first construction scheme considered here, is illustrated schematically in figure 3. The system was designed above all for the construction of tunnels in crumbly and loose ground (18).

The objective is achieved by driving reinforcing tubes longitudinally into the ground (Figure 3, detail 1) around the perimeter of the future tunnel. Once the earth has been removed from the tubes they are anchored together transversally under tension (Figure 3, detail 4) and excavation of the tunnel then begins. During this stage, some of the tubes are used for ventilation, cable ducts, earth removal, etc. As tunnel advance proceeds ribbing is placed to support the tubes if no transverse connection between them is provided, ensuring that the load is distributed laterally while the lining is cast (Figure 3, detail 3). After each stage of tunnel advance, the gaps between the tubes are filled with shotcrete (Figure 3, detail 2). If necessary, the strength of the tubes in the crown can be increased by reinforcing them and filling them with concrete too. A traditional lining completes the construction.

It is clear from the above that no comparison with the Cellular Arch technique can be made both with regard to the construction method and also to its potential application. What one immediately notices is that with this system the longitudinal tubes rest on the outside of the final load bearing structure like long forepoles: once the internal lining is in place they no longer have any further static function and in fact some of them may be used as cable or ventilation ducts and so on. Furthermore, as opposed to the Cellular Arch

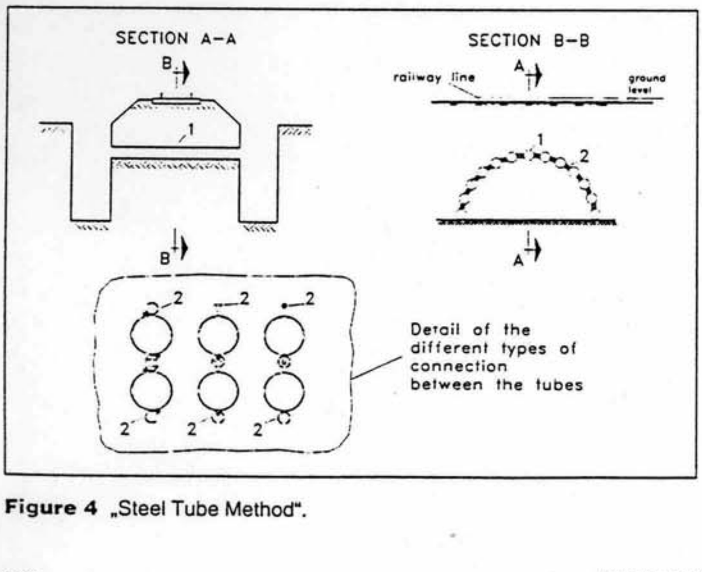

Figure 4 „Steel Tube Method".

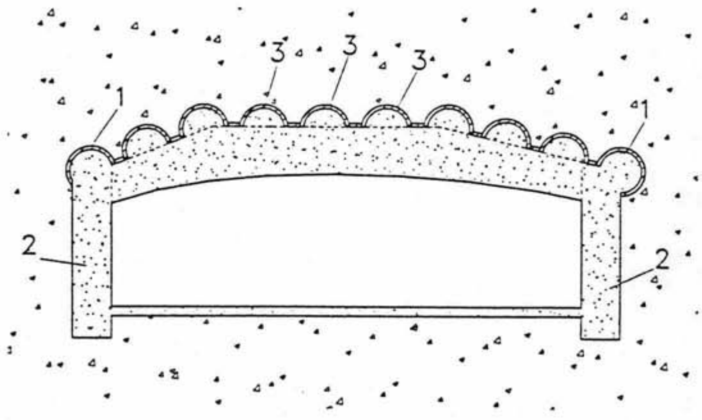

Figure 5 „Trenched Tubes Method".

method, the load bearing structure is constructed after excavation and not before. This all has a strong limiting effect on the range of application of this method for the construction of wide span tunnels in urban settings, a field in which the Cellular Arch method demonstrates all its potential.

„Steel Tube Method"

The construction method illustrated in figure 4 also involves actual tunnel advance under the protection of longitudinal tubes inserted into the ground before advance begins (19).

A number of steel tubes (Figure 4, detail 1) are driven horizontally into the ground from an access shaft at the height of the crown of the future tunnel. The tubes are fitted with joints (Figure 4, detail 2) and are connected cross-wise right from the beginning to form a single rigid structure. Once driven into the ground they are emptied, reinforced and filled with concrete, after which the tunnel is excavated using traditional methods under the protection of the tubular structure that is already in position.

Again, however, the technique used is the already well-known forepoling technique achieved by using large tubes driven into the ground. The only function of these forepoles is to prevent the round from falling in at the face and around the excavation and their ability to reduce radial deformation around the tunnel depends on the extent to which they are held in position by ribs placed during tunnel advance.

The joints connecting the tubes laterally have no strength capable of resisting bending stresses and consequently without the support of the ribs, the structure would be completely unstable. Once the lining of the tunnel is in place, the tubes no longer serve any statics function and remain in the ground completely inert.

Quite clearly then, given the transitory nature of the statics function of the tubes, no comparison can be made between this method and the Cellular Arch method in which the load bearing structure of the finished tunnel is constructed before excavation begins. It should also be added that while the Cellular Arch structure does not compromise the stability of the tunnel under construction at any time by resting on ground that might cave in, the method examined here involves resting the roof tubes on the core of ground ahead of the face and as a consequence stability in the core becomes an absolutely critical factor.

„Trenched Tubes Method"

The method illustrated in figure 5 was designed above all for the construction of tunnels with vertical side walls (20).

An access shaft is sunk and two small horizontal tunnels are driven parallel to each other (Figure 5, detail 1) by driving two tubes into the ground and them emptying them of earth. Then trenches are dug along the bottom of the small tunnels and the vertical r.c. side walls are cast in them (Figure 5, detail 2). The crown of the tunnel consists of a series of parallel tubes (Figure 5, detail 3) that are driven into the ground and connected together using special steel plates. After the earth has been emptied from the tubes, the bottom halves are removed so that a small transverse tunnel can be dug. This is then filled with concrete, as is the remaining upper half of the tubes.

There are two substantial differences between this method and the Cellular Arch method.

- The uprights are constructed by excavating downwards from two small side tunnels in the same way as the underpinning for a building is constructed (i.e. from the surface downwards) and the walls are vertical. With the Cellular Arch method, the side walls are built inside two large side tunnels in which it is possible to build from the bottom upwards and the walls are not exactly vertical but arched.
- The final load bearing structure of the very low roof is continuous and is constructed after excavation. This requires at least one construction stage where intermediate ribbing is used. After the roof of the tunnel has been built, the lower half of the tubes are demolished and the upper half is filled with concrete. They do not really form part of the true load bearing structure of the completed tunnel but remain above it in the ground and do not fulfil any statics function. Their only purpose is to provide transitory and temporary support.

The load bearing structure in the Cellular Arch method, on the other hand, consists of a solid structure of longitudinal tubes and transverse arches and forms a true arch right down to the foot of the side walls with very clear advantages for the statics of the structure. It is also completed before the tunnel is excavated and consequently no temporary ribbing is required during excavation work.

Basically, although the method described here does employ similar techniques to those used in the Cellular Arch method, it does not achieve the specific objective of the Cellular Arch technique (the construction of a full arch structure before excavation begins).

„Belgian Method"

Figure 6 illustrates a construction system involving the opening of a small horizontal tunnel (Figure 6, detail 1) driven from an access shaft. The tunnel is cylindrical in shape and large enough for workers to enter; all subsequent construction is carried out from it. It is created by driving a series of tubes with good strength properties into the ground and the tubes constitute the lining of the tunnel. When this tunnel is complete the invert is opened and a vertical trench is dug, reinforced and filled with concrete (Figure 6, detail 2) to form the first side wall of the completed tunnel (21).

A series of horizontal tubes are then piped jacked parallel to each other (Figure 6, detail 3) from the tunnel into the ground at right angles to the side wall. The earth is removed from these tubes and they are filled with concrete to form the roof of the completed tunnel. The tubes are connected to each other using traditional type joints so as to make the whole structure rigid. A second small horizontal tunnel (Figure 6, detail 4) is then excavated and lined parallel to the first. The tubes forming the roof are long enough to provide protection for the excavation of the second tunnel. The second side wall of the completed tunnel (Figure 6, detail 5) is then constructed in the same way as the first and finally the two small horizontal tunnels are also filled with concrete.

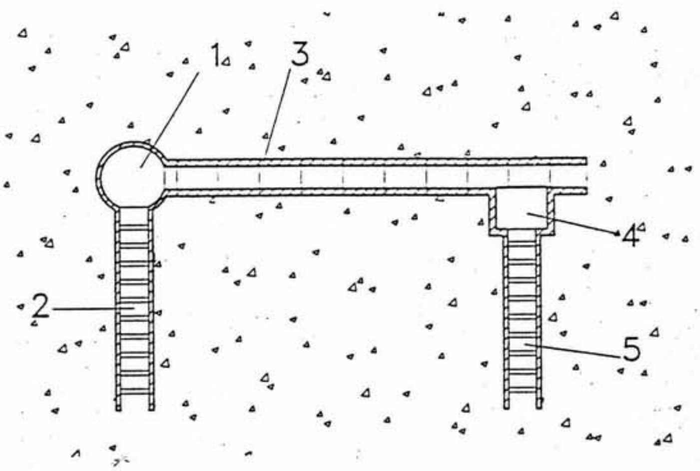

Figure 6 „Belgian Method".

As an alternative, the two longitudinal tunnels for the construction of the side walls can be driven simultaneously and the tubes for the roof can be jacked across from one or both of the longitudinal tunnels. This construction method was used for the construction of the Antwerp underground railway and consequently is known as the „Belgian method".

As we have seen, it is based on driving tubes with good strength properties into the ground at right angles to the path of the tunnel and these alone constitute the load bearing structure of the (flat) roof of the cavity. With the Cellular Arch method, however, the tubes are driven along the path of the future tunnel and the load bearing structure consists of a grid composed of longitudinal tubes (the cells) and transverse arches in the shape of an arch. With the excellent statics properties of this arch structure, bored tunnel construction is possible at very shallow depths with spans up to 60 metres, while the method described in this patent, which in any case uses entirely different types of materials, no tunnels with a span of more than 15 m have ever been built under such conditions.

„Tube Pile Plank Method"

The last construction system considered in this article is illustrated schematically in figure 7. It is a system that was designed for the underground construction of elongated reinforced concrete structures having a uniform cross section (22).

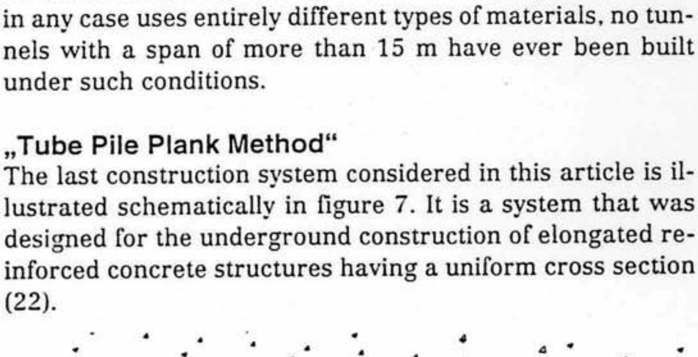

Figure 7 „Tube Pile Plank Method".

The structure consists of a series of tubular elements of permanent shuttering, connected by structural parts defined by external pile planks and internal permanent shuttering tangential to the tubular elements. The construction method is as follows:

➲ insertion of the tubular elements (Figure 7, detail 1) (diameter 140 to 400 mm) and the pile planks (Figure 7, detail 2) from an access shaft around the perimeter of the future structure;

➲ the tubes are then emptied of the earth they became filled with during pipe jacking and then reinforced and filled with concrete;

➲ the earth inside the space defined by the tubular elements and the pile planks is then removed;

➲ the full tunnel is then excavated with the progressive laying of the ribs (Figure 7, detail 3) and props (Figure 7, detail 4), and the insertion of shuttering (Figure 7, detail 5) between the ribs and the tubular elements on the underside of the final load bearing structure;

➲ the hollow space between the shuttering and the pile planks on the outside is then reinforced and filled with concrete.

The load bearing structure is complete at this point and the construction is finished with an internal metal lining (Figure 7, detail 6) and the laying of the floor of the tunnel (Figure 7, detail 7).

There are two important differences between this method and the Cellular arch method:

➲ the load bearing structure, or part of it, is constructed during excavation of the tunnel, while with the Cellular Arch method it is completely finished before excavating;

➲ the longitudinal tubular elements driven into the ground are explicitly specified as of small diameter and joined by pile planks.

This obviously leads undoubtedly to greater surface subsidence than the almost zero subsidence encountered using the Cellular Arch method. Another obvious consequence is that the method in question can only be used for the construction of small tunnels and not for large cavities as is the case with the Cellular Arch method.

Conclusions

Five construction methods designed for use in ground with poor geomechanical properties or for situations in which surface subsidence must be kept to a minimum have been compared with the Cellular Arch method. The following conclusions can be drawn from this comparison:

➲ the Cellular Arch method and the Belgian method are the only ones which involve the entire construction of the load bearing structure before excavation begins;

➲ the Cellular Arch method is the only method that can be used for bored tunnel construction of tunnels with very shallow overburdens and spans of more that 15 to 20 metres in any type of ground;

➲ as compared to the Belgian method the Cellular Arch method has the advantage of not imposing any rigid limits on the geometry of the cross section of the tunnel.

➲ there is no freedom of choice in the geometry of the cross section with Belgian method and „trenched tubes method"

Finally, when account is also taken of the costs, which are comparable to the costs involved using more traditional methods, the Cellular Arch method can be proposed as the standard method for bored tunnel construction with very shallow overburdens, wide spans (up to 60 m.), in loose soil and under the water table if necessary, without producing any appreciable surface subsidence. It would appear to be particularly suitable for siting urban infrastructures underground such as: railway stations and depots, goods depots, parking complexes, shopping centres, libraries, museums, archives, sports and recreation centres, industrial plant, power stations, sewage treatment plant, military installations and bomb shelters, etc.

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