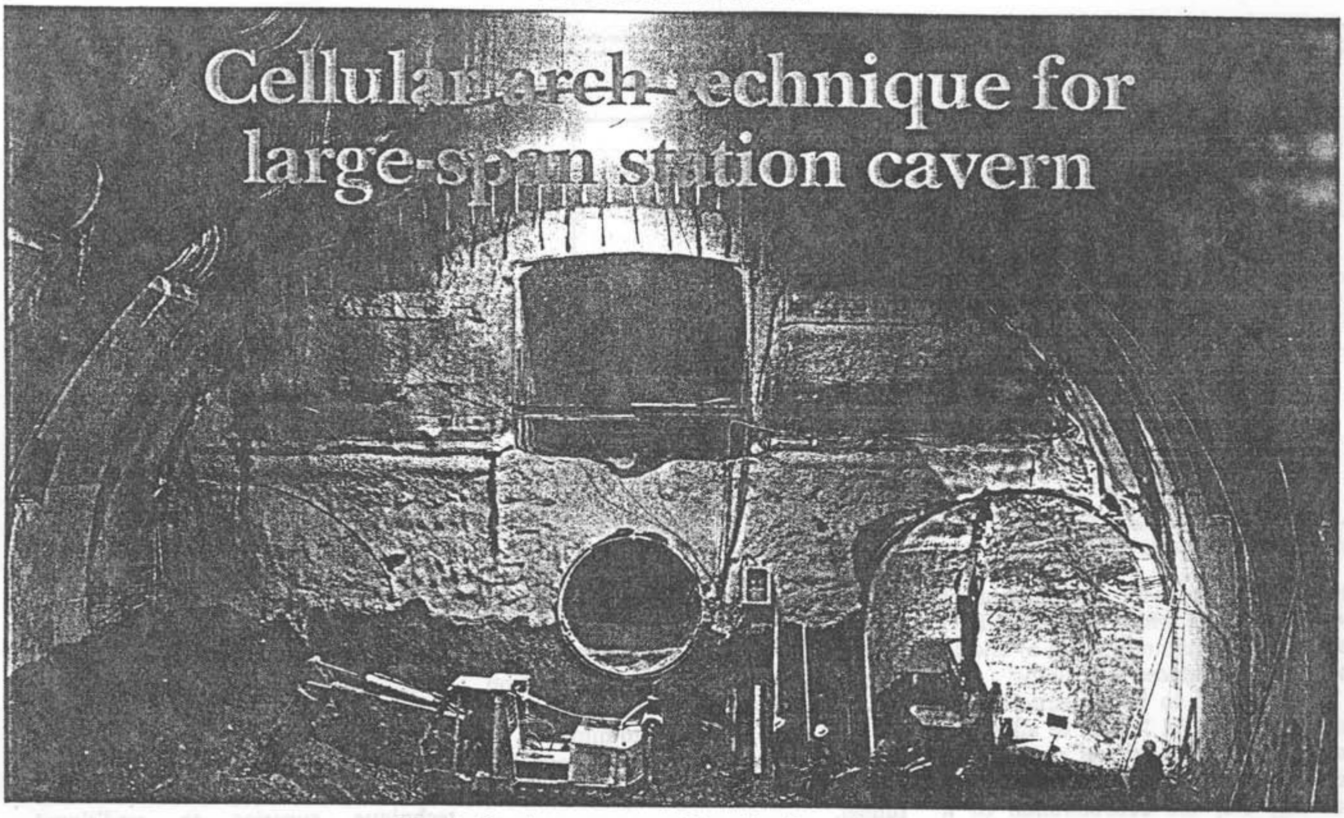
Cellular arch technique for large-span station cavern



Venezia Station: progress achieved by November 1990.

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Venezia Station on the Milan Rail Link is being constructed using a novel technique to cope with drawbacks such as unconsolidated ground and the presence of old foundations.

Currently under construction, the Milan Rail Link will connect the rail lines within the city to create a comprehensive regional, metropolitan and urban transport system. The project is being undertaken by the Metropolitana Milanese (Milan Underground Company). It was commissioned by the Comune di Milano and Regione Lombardia and comprises the construction of six stations, Lancetti, Garibaldi, Republica, Venezia, Dateo and Vittoria, in the urban section of the Link. Of these, Venezia Station, which forms an intersection with Line 1 of the Underground in the commercial centre of the city, is in an advanced stage of construction.

Economic, environmental and architectural considerations have dictated that all the station structures be incorporated in one large tunnel under a single roof. The tunnel, with a clear span of 22.8m and a length of 250m, is equipped with two lateral platforms and a mezzanine level. The latter is about 10m wide and is suspended from the vault. Its function is to collect incoming and outgoing passengers and to intersect with Line 1 of the Underground and the surface transportation system (Fig 1).

A novel construction technique has been developed to cope with the many restrictive factors of this project. These include: the unusual dimensions of the tunnel; the shallow overburden; the presence of foundations of old multi-storey buildings; the unconsolidated nature of the ground; the presence of groundwater; and the need to restrict ground deformations to a few millimetres. This technique is the 'cellular arch' technique.

Planning aspects

The construction of underground excavations of dimensions larger than 15m normally involves unusual planning and construction problems. This is mainly due to the considerable volume of ground affected by the excavation and, taking into account the size of the excavations involved, to the difficulty in controlling any kind of instability during the construction process.

It is therefore necessary to have a detailed knowledge of the nature of the ground in order to predict the deformation response to the excavation in the planning stage. Programming in the design stage must determine the sequence of excavation and the stabilising operations needed to ensure the stability of the tunnel both in the short and long term, in particular, the means whereby the redistributed stresses resulting from the arch effect can be controlled by the selection of appropriate excavation and stabilising methods in differing ground conditions.

A tunnel will be more stable the greater the arch effect mobilised near the walls of the excavation; it is also necessary for the stresses in the ground to be restricted so that the ground behaves elastically.

Three different situations can be envisaged:

a) The arch effect is mobilised at the profile of the excavation: if the resistance and the deformability of the ground are sufficient to result in an elastic response to the opening of the tunnel, stability will be guaranteed by the mobilisation of the arch effect near the tunnel;

b) The arch effect is mobilised away from the excavation profile: if the ground reacts plastically to the induced stresses, a plastic zone develops and spreads around the cavity until a state of equilibrium is reached with the resistance of the ground. The arch effect which thus tends to be produced away from the profile of the excavation can be redirected towards the tunnel or at least restricted by suitable stabilising operations on the annulus of soil surrounding the tunnel.

c) The arch effect fails to be mobilised

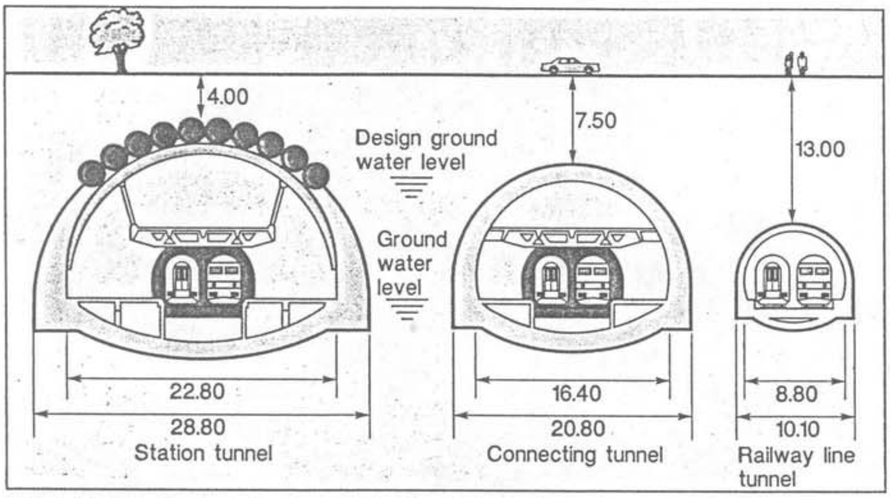


Fig 1. The three types of cross-section for the tunnel.

This is the case with incompetent or loose ground in which the arch effect does not form naturally as in a) and b) and must be produced artificially.

If the tunnel to be constructed has sufficient cover ($H > d/2$) to allow the employment of traditional stabilisation techniques (injection at low pressure, jet grouting, etc) the consolidation of a ground layer of suitable thickness can result in a satisfactory stress distribution around the tunnel and, as a result, the artificial mobilisation of the arch effect near the tunnel roof.

If, on the other hand, the cover is so reduced ($H < d/2$) as to limit the grouting pressures and so hinder stabiisation, it becomes imperative to adopt different construction methods.

Excluding cut-and-cover techniques which are not always feasible, especially in urban areas, the only system available up to now for direct underground excavation of large tunnels has been the 'Antwerp technique' (Fig 2) adopted for the first time in the 1970s for the construction of underground rail tunnels in Antwerp. This comprises the horizontal driving of a series of pipes into the ground by the pipe jacking method.

Subsequently, the pipes are reinforced and filled with concrete, while the surrounding ground is treated in order to obtain a monolithic slab under which the excavation work begins. Up to now, tunnels with maximum span not exceeding 18m have been constructed in loose ground using this system. Above this value the pipes, which behave as beams supported at their extremities, deform excessively and the settlements at the surface exceed the levels generally imposed in urban areas.

At present, the only alternative to the Antwerp method which appears feasible seems to be that of constructing a prefabricated compression arch (of a consistency superior to that of the consolidated ground) within the ground, before starting the excavation of the actual tunnel.

From these considerations the idea of the 'cellular arch' was developed. It is a new construction system, invented and perfected by the author, which allows the direct underground and full section excavation of tunnels with dimensions ($d > 20m$) until now unthinkable in competent and loose soil where the overburden is less than the radius of the tunnel.

Cellular arch

The 'cellular arch' is a composite structure of semicircular section similar to a framed structure, in which the longitudinal elements (cells) are represented by pipes in reinforced concrete rendered functional by a series of large transverse ribs (arches).

From a construction point of view it is interesting to emphasise that the structure arises from the co-ordinated assembly of a number of existing technologies all well understood and tested.

In fact, the cellular arch system represents an evolution of the 'Antwerp system' already described: instead of using the pipes to form a slab, it consists of driving them horizontally into the ground along the axis of the future tunnel and making the structure rigid with transverse connections placed at suitable intervals, which constitute the principal supporting structure. Thus, before starting the excavation of the tunnel, a semi-cylindrical framework of reinforced concrete is formed, capable of supporting the loads at the contours of the tunnel and of artifically generating the arch effect which is indispensable for the stability of the tunnel both in the short and long term.

The construction of the cellular arch occurs in nine main phases:

a) From a service drift, driven along the axis of the final tunnel, systematic pre-consolidation operations are carried out in the ground surrounding the future side drifts and if necessary along the arch of the crown. It should be noted that the pre-consolidation of the area around the crown of the tunnel is undertaken to impart some cohesion to the ground and may not be required in all types of material;

b) Excavation of the side drifts;

c) In a completely independent construction site from that of the side drifts below, the thrust pits are prepared for the driving (by pipe jacking) of a series of reinforced concrete pipes into the ground along the crown profile of the future tunnel;

d) Excavation through the microtunnels of the crown;

e) Excavation, through the microtunnels, of the 'formwork' (whose walls consist of the ground itself) for the casting of the connecting arches in reinforced concrete. The extraction of the material occurs through the side drifts;

f) Casting of the arch foundations of the final tunnel;

g) Placing reinforcement and concreting of the longitudinal microtunnels of the crown and transverse connecting arches;

h) Excavation of the ground inside the final tunnel under the protection of the cellular arch;

i) Concreting of the invert.

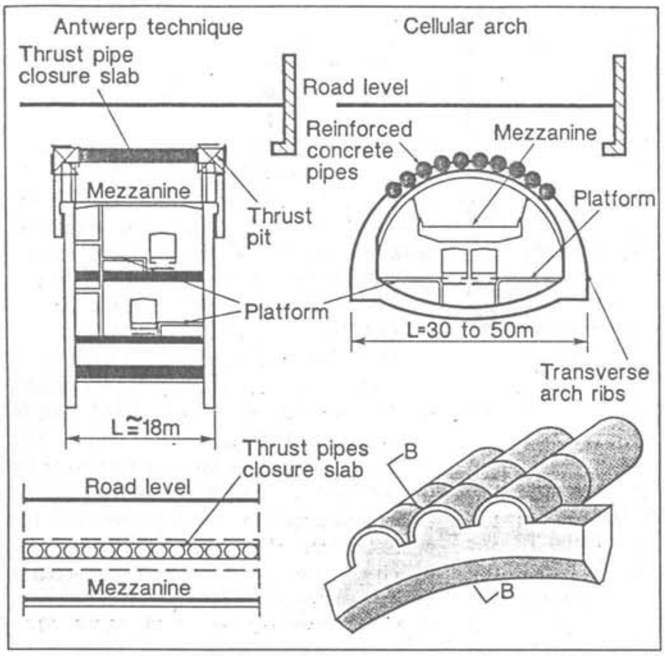
The characteristic that makes this technique superior to traditional methods, and perhaps really without alternative, is the way in which the transition is made from the initial equilibrium of the undisturbed ground to the final equilibrium of the finished tunnel.

The traditional systems of advance are based on the three-dimensional effect of the face, which offers an important contribution to the short-term equilibrium of the tunnel. If the tunnel face proves to be deformable in relation to the nature of the ground and the forces induced by the excavation, the subsequent deformations generated in the ground mass before the arrival of the tunnel face itself must be accepted by the planner or otherwise it will be necessary to resort to heavy and expensive pre-consolidation operations during the tunnelling process.

The cellular arch, by dispensing with the static contribution of the tunnel face, permits minimisation and often elimination of these deformations and therefore allows the direct underground excavation of tunnels of large dimensions without causing major surface settlements. Limitations of 'deforming phenomena' in certain types of material can also bring significant advantages with regard to the loads on the lining.

In tunnels constructed by traditional methods, especially when the ground is variable and of poor quality, the progressive decompression of the ground around the tunnel generally results in plastic behaviour which inevitably causes deformations and thus significant deferred pressures on the lining material.

With the cellular arch the ground is always constrained at a relatively low value of σ_3, but this is sufficient to maintain the elasticity of the surround-



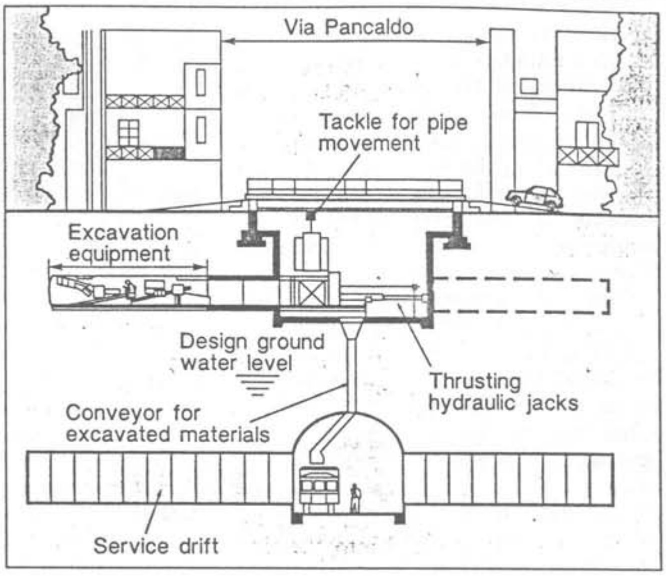


Fig 2 (left). Two techniques for large caverns; and cellular pipes (bottom right). Fig 3 (above). Thrust pit sections.

ing ground, minimising the value of these pressures and, therefore, disturbing the pre-existing equilibrium as little as possible.

Venezia Station

The diameter of the excavation is about 29m, the cover is minimal, underground services and existing structures provide endless obstacles, the ground is incompetent and saturated; with these disadvantages it is obvious that problems relating to the stability of the projected tunnel were not easily resolved.

The impossibility of excavating the tunnel by traditional methods, that is, excavation by sections with preconsolidation operations of the ground around the tunnel in several stages, was immediately proven by the numerical simulation, which indicated the formation of large failure zones during the excavation of the crown, and unacceptable deformations.

The cause can be attributed to the fact that it is impossible to achieve an adequate thickness of consolidated ground in the crown zone because of the reduced cover and consequent containment of the ground, and the excessive deformability of the pre-lining.

The finite element analysis carried out for the tunnel where the cellular arch system was used demonstrated the validity of the project inasmuch as, in all the 14 calculation phases corresponding to the various operational stages, there was no evidence of the development of plastic zones within the ground, and surface settlements did not exceed a few millimetres.

Encouraged by this result, before proceeding with the application of the system for the construction of the tunnel itself, it was considered appropriate to complete the study by carrying out a test at full scale, i.e. the driving of three pipes in ground consolidated to different degrees and their connection by arch segments before partially demolishing them. At the same time as the pipe driving test, control measurements of the induced deformation of the ground as well as topographical surveys of the surface were carried out.

The pleasing results of these experiments led to the decision to proceed with the detailed design of the project and the commencement of work.

The cellular arch system essentially comprises three operative phases:

a) Building the microtunnels;
b) Building the arch foundations;
c) Building the arches.

Excavation of the microtunnels and building the arch foundations can be executed at the same time.

Thrust pit

The thrust pit was excavated and equipped for driving the pipes after the installation of three temporary prefabricated steel bridges to maintain road and tramway traffic (Fig 3). Then, an underground service gallery was driven along the axis of the future station, from which light preconsolidation of the ground was carried out in the layer corresponding to the area of the pipes and the arches.

The spun reinforced concrete pipes which were driven into the ground for the formation of the microtunnels have an o.d. of 2100mm and an i.d. of 1800mm. Reinforcement consisted of a double electro-welded cage with 24 longitudinal steel reinforcements 6mm bars and 8mm spirals at 90mm centres.

The pipes were driven into the ground with a thrusting machine consisting of an 8m-long metallic shield divided into three sections. The first 1.3m-long section was movable and provided with a cutting edge, allowing the operator to control vertical and horizontal movement.

The shield is provided with a computer-controlled front drilling head about 30mm smaller than the o.d. of the shield in order to avoid the formation of cavities around the pipes. The excavated material was transported on a conveyor belt to muck cars on rail, to be dumped through a shaft into the lower tunnel.

The thrusting equipment includes two hydraulic jacks, a thrust distributing frame and a 60MPa hydraulic pump.

In ten months of work, a total of 2150m of pipes was driven into the ground with an average production of 8m/day.

For each microtunnel, strict measurements have been constantly carried out to control possible failures and vertical and horizontal deviations of the ground. The average results show that there are no surface failures and that vertical deviations are about 30mm, while horizontal deviations are about 25mm.

During the pipe thrusting phase, arch foundations to support the arches are built simultaneously. Two 11m-high and 7m-wide tunnels were excavated to build the foundations.

Excavation was carried out in two phases: the first down to groundwater level, where preconsolidation grouting under the future foundations and invert was carried out. Subsequently, excavation below the groundwater to foundation level could be carried out in impermeable ground.

Before proceeding to the building of the formwork, the tunnel floor and walls were waterproofed. Then, in turn, the three phases of placing formwork, fixing the steel reinforcement and concreting were undertaken.

At present, casting of the arch foundations is almost complete, with an average production of 2m/day of the finished foundation.

Constructing the arches is the most difficult phase of the cellular arch technique, particularly so because of the complex triangular shape allotted to the section for architectural reasons and because of the preparation of the equipment for the suspended mezzanine floor to be inserted into the pipes.

The construction of the arch was carried out in the following sequence:

□ cutting the lower half of the pipe by means of a special disc cutter. The pipe is cut in three elements which are then eliminated during the excavation of the ground for the preparation of the arch site;

□ excavation of the ground from the lower to the upper level, with dumping of the excavated material into the side drifts below;

□ levelling the ground excavation of the arch and casting the lean concrete base course;

□ introduction of the special arch formwork starting from the side drifts;

□ placing the steel reinforcement and positioning the special elements for the suspension of the mezzanine;

□ concreting (concrete strength 35MPa).

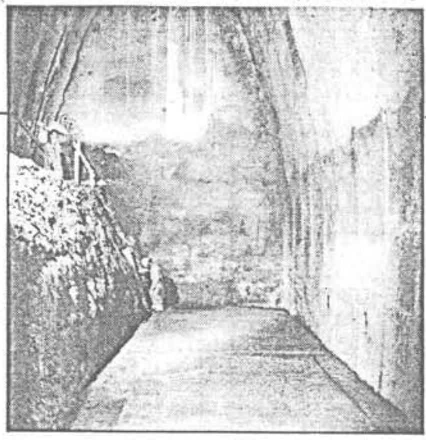
The preconsolidation of the ground played an important role in the construction of Venezia Station.

For preconsolidating the layer of ground used for the insertion of the concrete pipes forming the cellular arch of the vault, Rodio studied and applied a special concrete grout mixture known as Mistra-S which possesses suitable geological characteristics. The use of this mixture, highly penetrable and particularly stable with regard to pressure-filtration phenomena, avoided the formation of fractures as well as areas with high concentration of the mixture, whose mechanical resistance would have been uncertain and therefore interfere with the pipes being jacked.

The preconsolidation of the ground around the side drifts and below the invert was, instead, achieved by grouting with highly penetrable concrete mixtures containing a silicon dioxide non-polluting mixture (Silacsol).

Grouting was carried out with a 'controlled volume' system: each valve injects a predetermined quantity of mixture calculated according to the volume assigned to the valve itself, the porosity of the ground, and the surrounding conditions (groundwater, dimensions of the consolidation area). Predetermined quantities of the mixture were injected under pressure (usually 15-20 bar) i.e. below that at which the ground fractures and heaves and the mixture tends to escape outside the consolidation area.

In order to avoid the risk of ground heave with consequent damage to the structures above, an information system (the PAGURO method), specifically developed by Rodio, was applied to control and monitor in real time the major grouting parameters.



Invert laid before final lining cast.

Controls and measurements

The Technical Specifications of the Metropolitana Milanese for the construction of the work included the following requirements:

a) Compared with the initial undeformed situation, absolute movements must be restricted to 5mm in the street area and to within 2.5mm under buildings,

b) For the electric power line of 200 000V which runs along Viale Regina Giovanna at 1m below street level, maximum movements must be restricted to 2.5mm.

For control of the movements of the buildings, a network of automatic stations was located at various levels, while a line of angular displacement sensors was placed along the electric power line: both sets of control equipment were connected to a central station for the recording and display of the data, as well as to an alarm system, should the prescribed limits be exceeded.

The Venezia Station tunnel will be composed of 37 arches, or 36 sections with 6m of longitudinal extension, which can be grouped into 12 major categories. These differ according to dimensions of the openings and the entrances, to the internal constraints, for the different static schemes of the mezzanine, etc, all of which have required detailed planning.

Some solutions are of particular interest from the structural point of view:

Pipes are regarded as elements simply supported by the adjoining arches. This view has remarkably simplified their construction, as it was not necessary to reinforce the supports and interfere with the reinforcement of the arches.

Suspension system of the mezzanine: The mezzanine is suspended from the arches by means of 75mm high-yield steel tendons hinged at their extremities. The top hinge is screwed to a support fixed to the arch by four bolts which transfer the load to a distribution plate at the extrados. The bolts are mounted inside the reinforcement cage of the arch and inserted in a frame of steel sections to limit placing errors. The maximum suspension load is 120 + 130t, but the whole system was planned with large factors of safety in view of eventual misalignments between the bolts and the tendons and to obtain suitable safety margins in the event of fire.

The waterproofing and drainage of the water was a particularly significant phase of the project from the technical and architectural point of view, as the building system did not allow the laying of the usual waterproof covering on the extrados of the structure in the section occupied by the actual cellular arch.

While the structure was entirely waterproofed with a continuous PVC mantle to the top of the foundations, in the crown a drainage system was planned by means of PVC channels placed against the ground between the pipes and installed from the inside, and of transversal pipes let into the casting of the arches which convey the water into the tunnel's drainage network.

Publication of the DM 11/01/1988 (ministerial decree of Jan 11 '88) titled 'Rules for fire prevention in metros' attracted the attention of the Venezia Station planners, who have examined more closely the safety aspects of the station.

In particular, the dimensions of the exits from the platforms and mezzanine were planned with large safety margins and the project included the installation of an automatic sprinkler system above the permanent way with the dual purpose of cooling the environment and contributing to the containment, if not directly to the extinction, of the fire.

A special ventilation system protects passengers against smoke. Absorption of smoke is coupled with a system of air emission towards the fire along the passengers' evacuation pathways: this system clearly gives priority to safeguarding the passengers rather than containing the flames.

Smoke is extracted by concrete pipelines which run along the tracks below the platforms and is discharged to independent vertical shafts. Activation of the smoke extraction is monitored by a computerised autodiagnostic control system which is also programmed for preventive maintenance.

The cellular arch method allows the direct underground and full section construction of tunnels of large dimensions even with low cover and in difficult ground. For this reason its application seems well suited to urban environments and wherever it is necessary to minimise the disturbance of pre-existing structures. Venezia Station is a striking confirmation of the method's validity.

It is considered possible to achieve still greater tunnel openings of more than 60m as the method can be adapted to large dimensions with extreme flexibility by varying the dimensions of the arches and cells (pipes) and the spacing between these arches. □