THE VENEZIA STATION OF MILAN RAILWAY LINK CARRIED OUT BY THE CELLULAR ARCH METHOD: WATER PROOFING, FIRE PROOFING AND SAFETY, VENTILATION.

Adolfo Colombo
Metropolitana Milanese S.p.A.Strutture e Infrastrutture del Territorio, Italy
Pietro Lunardi
RockSoil S.p.A, Italy
Enrico M. Pizzarotti
RockSoil S.p.A., Italy

SUMMARY

The Cellular Arch is a new construction method which allows the building of large underground cavities in loose ground with a minimal overburden, and which is competitively inexpensive. It was first used in the construction of a railway station in Milan (Venezia Station, span=29m approx.). This work is characterized also by an important structure composed of a mezanine floor, suspended from the vault, necessary to enable travellers to move around. In the report the planning and executive aspects are described, related to the water proofing of the structure of the Cellular Arch, carried out from inside with the application of special technologies, to the fire proofing of the structure suspended from the vault, and to the ventilation system, planned to allow the maintenance of safety conditions in case of fire.

1. GENERAL

The possibility to exploit the underground for public or industrial uses is becoming an increasing reality. Especially in highly populated urban centres where overground space is limited and very expensive, underground construction is a solution to problems of congestion and pollution of the environment. Plans for underground construction are, however, often impeded by unfavourable conditions for the exploitation of underground space which is close to the surface, such as loose ground, possible interference with pre-existing underground structures, and with normal overground city life, especially traffic flow. The solutions to all these problems, at competitive cost compared to overground construction, are often impossible to apply with traditional construction methods. Infact if the excavation is carried out at a deeper level in order to minimise surface interference and/or the problem of loose soil, the costs increase, and the exploitation and safety conditions worsen. The alternative, which is to carry out excavation from the surface, reduces construction and working costs, but is usually unfeasable due to interference with surface structures and activity. Over the last few years an innovative and competitively inexpensive construction methodology has been developed to resolve these problems: the Cellular Arch methodology. The Companies represented by the authors have developed an agreement to supply all engineering activity as the method is used in successive applications. The Cellular Arch was succesfully used for the first time in the construction of the "Venezia Station" of the Milan

Railway Link. In the report some specific aspects of this experience will be discussed (see bibliography for a more in depth treatment of the techinical details of the excavation work).

2. THE CELLULAR ARCH

The Cellular Arch is a composite semi cylindrical ribbed structure(fig.1). The longitudinal elements consist of r.c. tubes fixed into the ground around a circular profile. The transverse or rib elements consist of arches in r.c. The characteristic which makes this method advantageous compared to others is the change from the initial undisturbed condition of the ground to the final condition of the completed tunnel without decompressions in the soil. Infact the excavation is only carried out once the rigid supporting structure has been built and can support the soil without deformation. The construction of the Cellular Arch occurs over various stages the principle ones being (fig.2):

- construcion of minitunnels on the perimeter by inserting r.c. tubes from a central service shaft
- excavation of lateral post tunnels from a site to be carried out contemporaneously to the last one
- casting of the posts of the tunnel
- excavation from the minitunnels of the tunnels which wil contain the moulds for the casting of the connecting arches
- reinforcement and casting of the longitudinal minitunnels and arches
- excavation of the tunnel beneath the final active supporting structure
- excavation and casting of the invert.

With this construction method it is possible to obtain large cavities close to the surface in difficult soil and with construction costs comparable to those of conventional construction methods, but without any disturbance to overground conditions. It is also possible to use this system for the creation of underground urban infrastructures such as stations, warehouses, libraries, shopping centres, museums, sport and recreation centres, theatres, power plants, sewage plants, car parks.

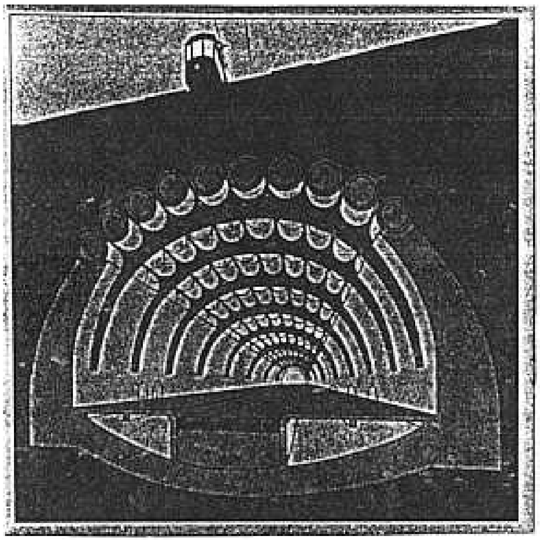


fig.1– The Cellular Arch

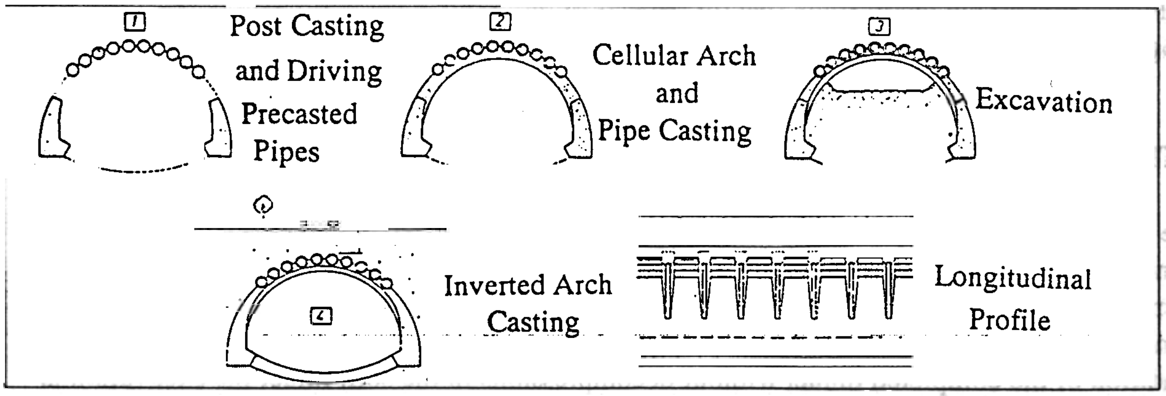


fig.2 – Cellular Arch: phases of construction.

3. VENEZIA STATION

The tunnel (internal diametre of 22.80 m with a total excavation width of approx. 29 m, an overall size of 440 m^2) was excavated with an overburden of only 4–5 m, in loose alluvial ground, in the town centre, near important underground and surface structures, under a main road (fig.3). The 215 m long tunnel required: the execution of 10 microtunnels, by inserting 2150 m of concrete tubes of 1800 mm in internal diametre, 15 cm in thickness and 2000 mm in length, carried out by a shield with a cutting head and thrust equipment operating from a thurust pit; 35 arches, 2x2 m inside, 6 m apart which were built tapering at the top for architechtural reasons. In total 100000 m^2 of soil was excavated, 40000 m^2 of concrete cast, and 3000 tonnes was used for the steel reinforcements. All this was carried out without interrupting the traffic flow above and with maximum surface settlements of 1.5 cm in the tunnel axis and 0.5 cm in the sides. The construction of the station took 5 years of which 4 were dedicated to the structure and the excavation. Particular technical problems arose during the construction, from the mezzanine platform suspended from the vault and its fire proofing, from the planning of a ventilation and evacuation system in case of fire and from the water proofing of the Cellular Arch vault.

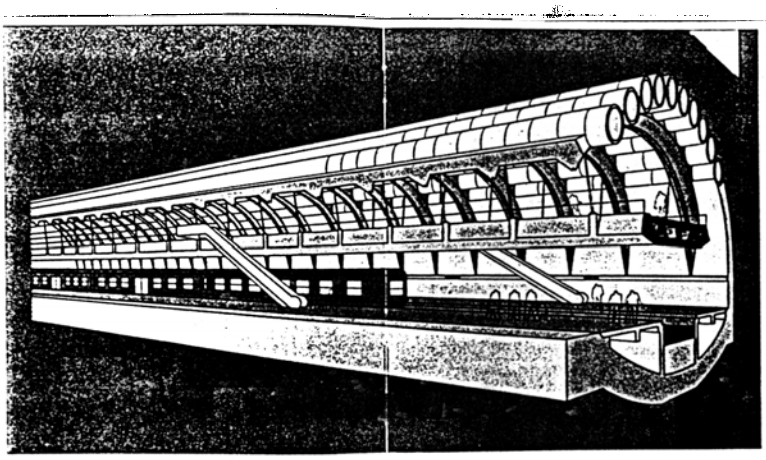
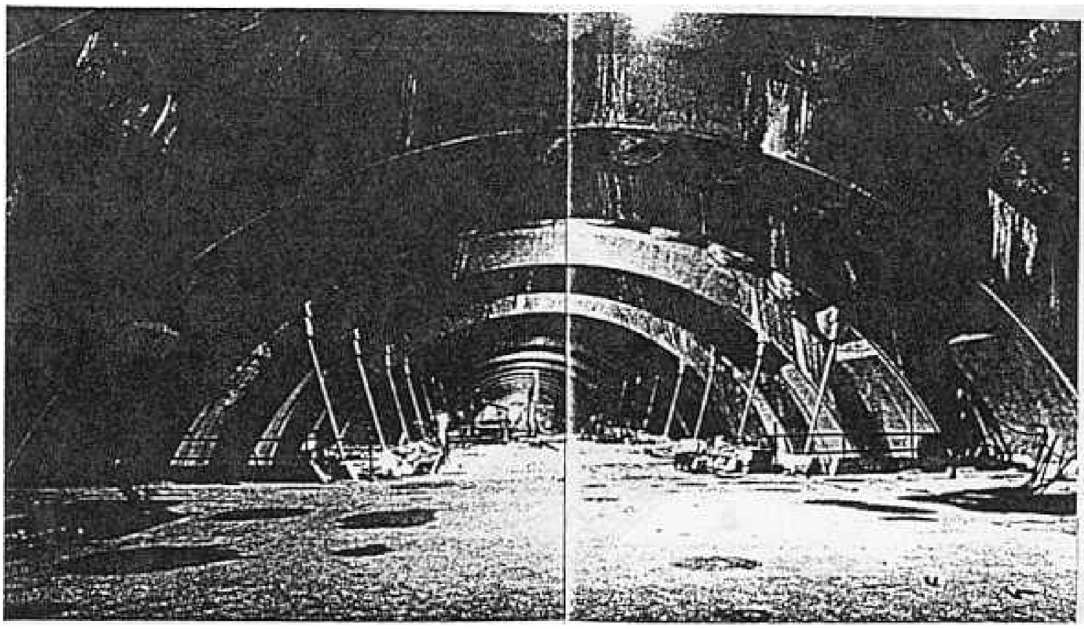


fig.3 – The Venezia Station of the Milan railway link

4. FIRE PROOFING OF THE SUSPENDED MEZZANINE

For functional and architechtural reasons, the mezzanine floor was suspended from the arches which consitute the vault, rather than resting the floor on pillars on the invert (fig.3 and photo 1 and 2).



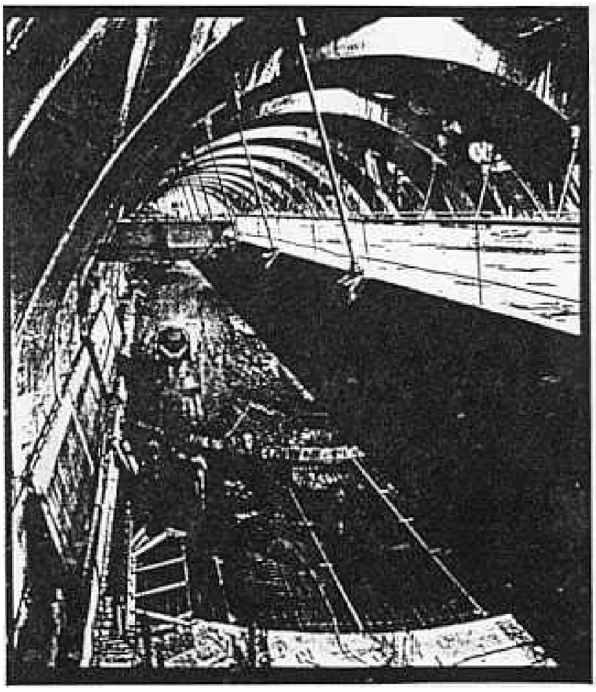


photo 1 and 2 – With the side beam highlighted in the photo 2

The suspension was acheived via a system composed of a steel connecting rod of high yield eld limit fixed at the extremites by steel hinges (fig.4). The maximum load is about 1300 KN in the case of one connecting rod breaking and distribution of loads over the remaining rods.

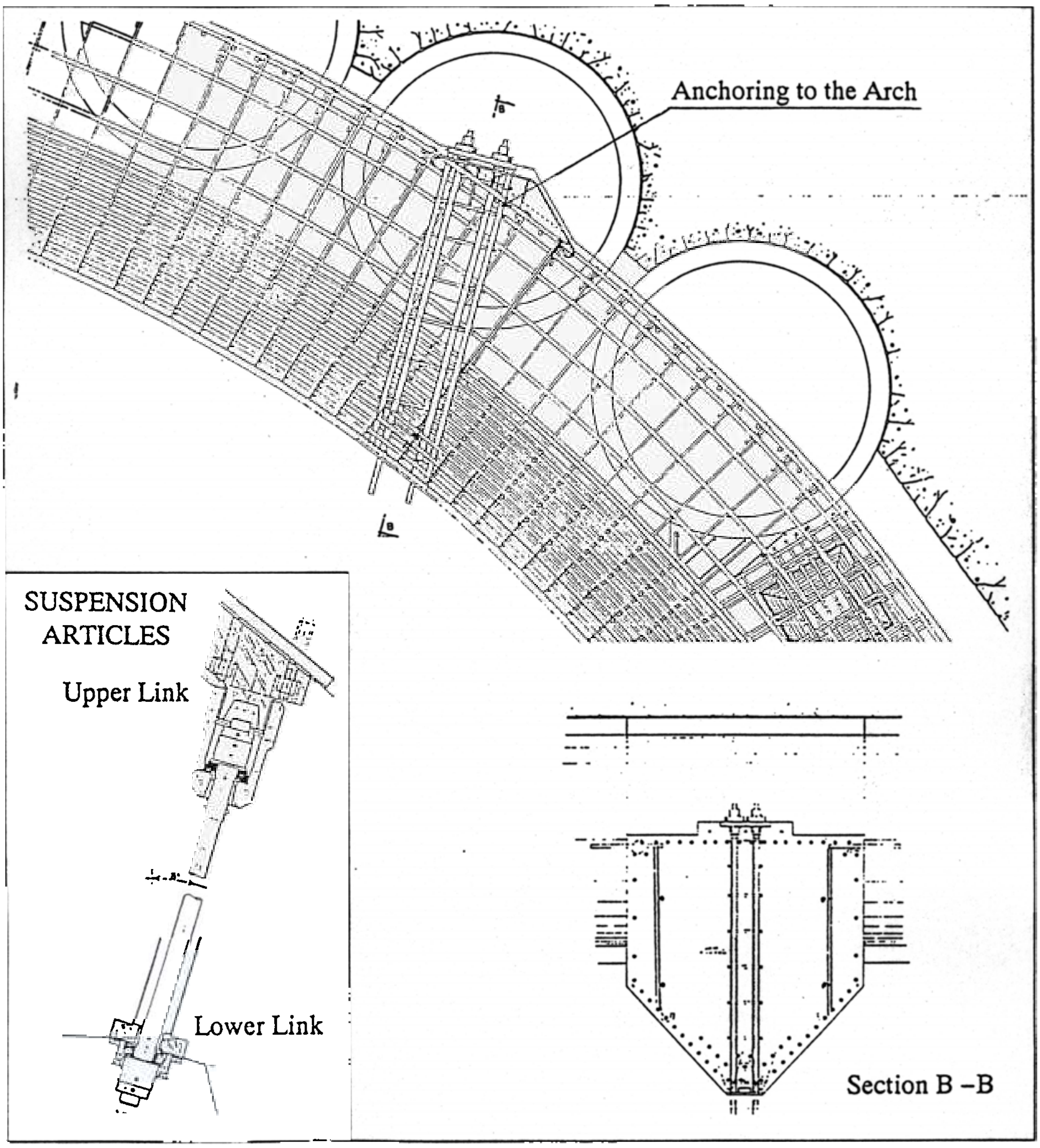


fig.4 – Details of mezzanine suspension

A system of compensating for broken suspension devices has been provided which consists of provisionally supporting the mezzanine on the platform with the help of steel pillars. The fire proofing of the suspension system will be carried out by enveloping the equipment with insulation materials in order to guarantee the structure a level of fire–safety REI120. The reaction of the supension equipment and structure was evaluated via a thermal analysis of the side beam, which is the elements most vulnerable to fire. As well as the effects of fire on concrete and steel, the lengthening effects of fire on the connecting rods (which provoke additional distortion to the side beams to which they are anchored) must be taken into account. From the analysis it was possible to calculate the appropriate thickness of the insulation materials for the supporting equipment. The calculation was done through an automatic code of finite elements (Mapptemp, Alphard Milano) through which it is possible to establish the distribution of the temperature inside a mass which is subjected to progressive heating (in this case the time/temperature curve from the ISO standard 834). The code of calculation takes into account the variation with temperature of density, of specific heat, and the thermal conductivity of concrete, and it imposes non linear boundary conditions for irradiation phenomena of the beams' external surface. Given the temperature distribution inside the beam, USL analyses were carried out following the CEB analysis methodology which anticipates a progressive reduction in the resistance characteristics in concrete and steel according to increase in local temperature. In the graph (fig.5) it is possible to see the bending resistance values as a function of fire exposure time divided by the bending resistance when cold M0 (20 C°) and the progress of bending action in the beam as a function of fire exposure time for two different insulation materials under examination and for one of them, as a function of thickness (50 mm, 70 mm, 90 mm). The latter was evaluated according to a response curve of the insulation materials to fire, therefore calculating the lengthening of the rods and therefore the bending actions in the most extreme case, corresponding to the sketch in the figure. The lengthening is taken as a settlement within the beam.

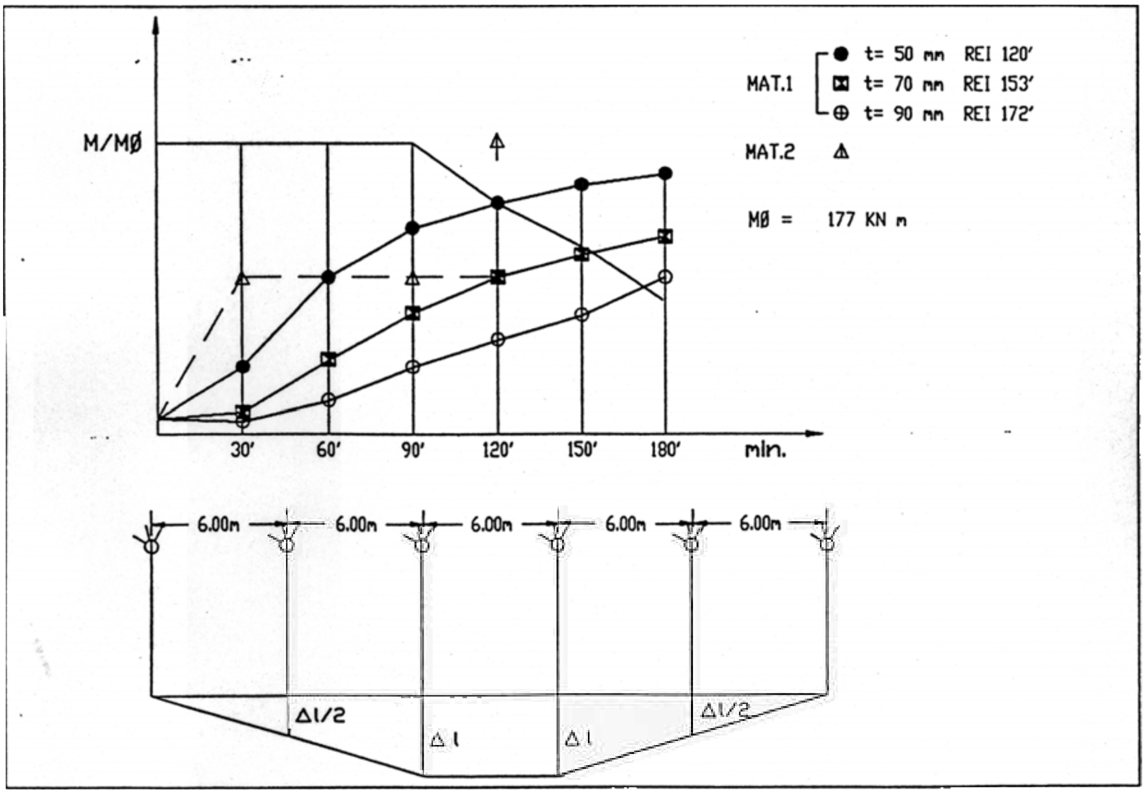


fig.5 – Side beam fire exposure analysis

5. SAFETY IN CASE OF FIRE AND TOXIC FUMES

Different criteria were adopted for entrances/exits, from platform to mezzanine and from mezzanine to the exterior, by considering the mezzanine a "protected area". The possible flow of passengers from the platform and mezzanine is nearly twice as much as necessary. The exits are distributed along the platform and the maximum distance to an exit from the platform is 45 m. The station will be equipped on the platform level, with an automatic sprinkler system placed along the rail lines, with the dual aim of cooling the atmosphere and smoke, and containing, if not extinguishing the fire.It will not be difficult to conform to the safety criteria as far as the electrical equipment is concerned. In order to solve the problem of protection from fumes, a special ventilation system has been planned which allows the evacuation of passengers within acceptable safety conditions (fig.6). Planning and design of ventilation plant was carried out by Prof. Evandro Sacchi, Milan Polythecnic. The size of Venezia station is much greater than the platform space of an average underground station (approximately 4÷5/1) so the dilution of toxic fumes is very high: the fumes are extracted as soon as the emergency system starts working. A toxic fumes extractor is one of the most important components of emergency equipment which is designed to cope with risks incurred by fire by:

- reducing the probability of catastrophe;
- safeguarding human life.

The presence of a fumes extractor alone meets the safety criteria to a reliable degree. The system planned consists not "only" in capturing and controlling flow of fire fumes but also of bringing in fresh air from outside. The fresh air is blown along the platform, then together with the diluted smoke expelled autside. "Only" in the sense that in planning the system, sprinkler barriers were deliberately avoided, concentrating on the efficiency of a system which is simple to set in motion in the incidence of fire.

The equipment is designed to "capture" the smoke, preventing it from invading the pedestrian area; thus the problem of toxic fumes and poor visibility is solved. The extraction of the fumes is connected with the extraction of air towards the fire along the passenger evacuation ways (flow of fresh air in contraflow to the direction of passengers leaving the station), the air coming from outside from the normal openings (stairs) and safety openings (air vents). This system is much safer for people than containing the flames, as, statistically, fire victims result more from exposure to fumes than to fire, with few exceptions. The flow of smoke diluted by the extracion of the ventilations has a direct effect on the heat of the fire, and the relationship between dilution and air should result in a flow temperature of not more than 150°C. Although the equipment working, according to plan, covers the whole pedestrian area of the station in terms of air exchange, it is, in case of fire occuring in any wagon near the platform, designed to extract air such an emergency.

In the ventilation plant, the smoke as well as the fresh air from outside are extracted by concrete pipes which go along the railways under the platforms, and sucked into independant vertical shafts per zone. Each platform has two zones. The four vertical shafts are each equipped with 2 extracting machines of equal strength (the eight ventilators are all identical) and finish in chambers in the "roof" of each shaft. The planned electroventilators are of two speeds, completely reversible, heat resistant, can function in inverted flow, according to the source of the fire. These are high-tech very reliable machines. The high speed of the ventilators is activated in case of fire emergency, the low speed during the normal ventilation of the station, to insure a constant, ade-

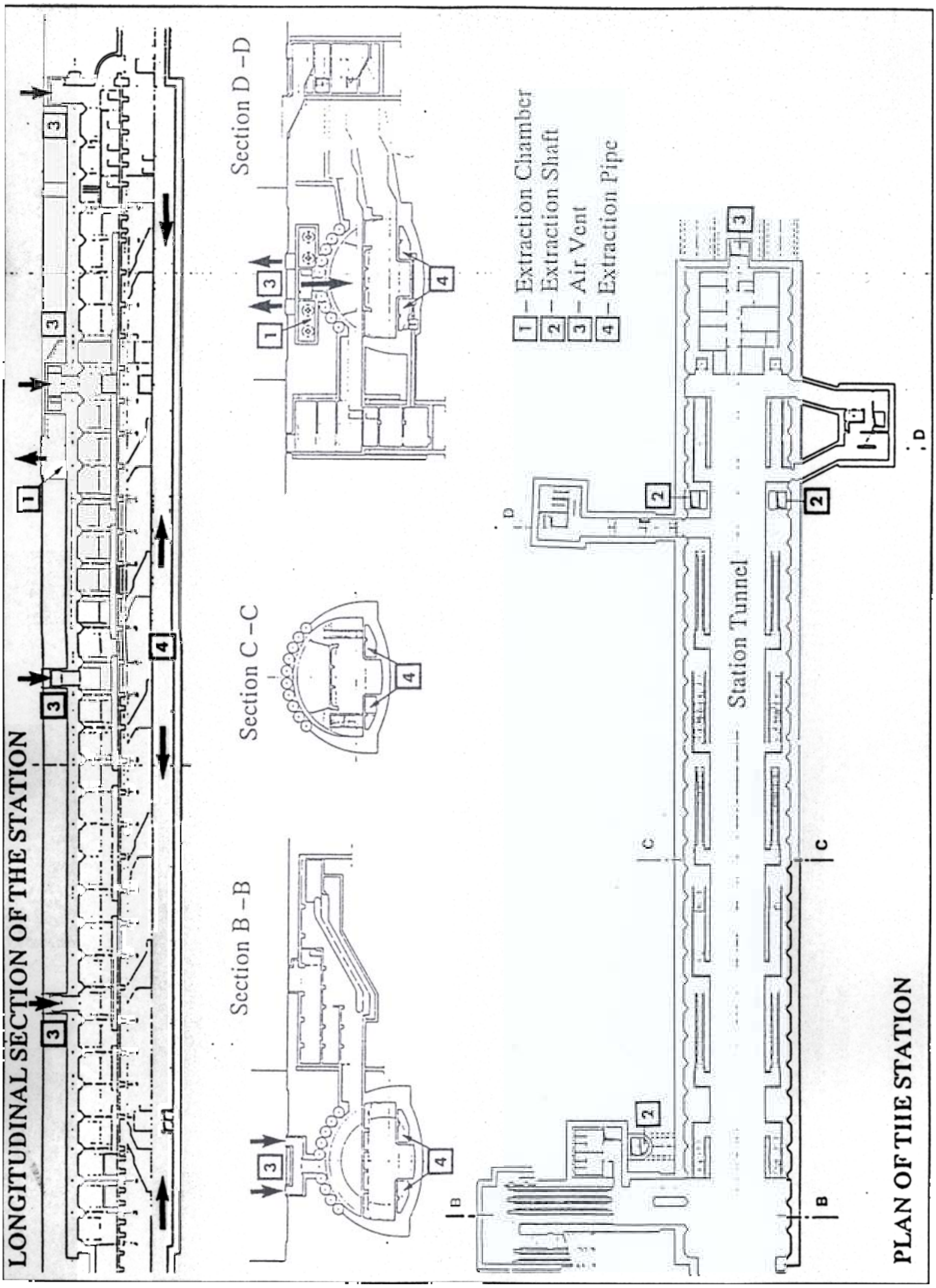


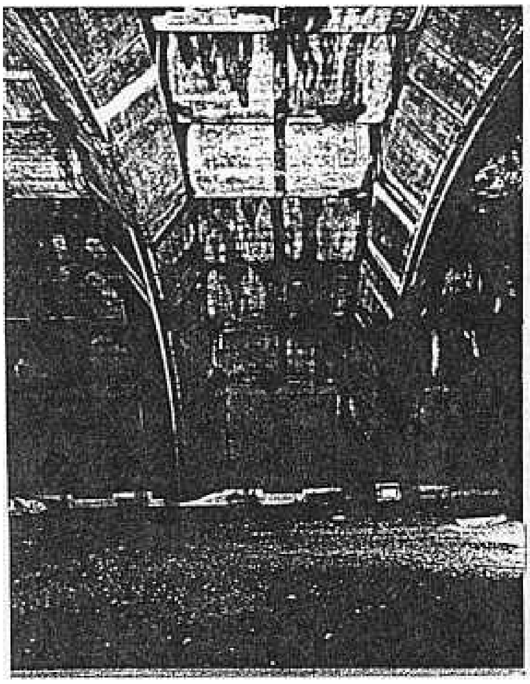
fig. 6 – Air flow scheme

guate exchange of air. The activation of extraction of fire fumes is carried out by a computerized control system which is capaple of self–diagnosis and is preventatively maintained. The computerized control system constituites one part of the supervisory system with which the station will be equipped under normal operating circumstances to great economic advantage. The intensity and temperature of a fire are difficult to predict with regards to train wagons contaning heterogenous materials. For this reason it was desirable to extract the fire smoke from as close to the bottom of the wagons as possible, in order to respct the flow of people on the platform. The extracation of diluted smoke will be more or less efficacious according to the strength and nature of the fire; in planning the safety equipment, a fire of such strength was hypothesized that a speed of air flow of 2 m/sec would be required to avoid the spread of smoke around atrium over the platforms. The level of dilution of the smoke should not be such as to cause damage to the extractions plant and the outer plant of the expulsion pipes next to the railway lines: with a dilution of smoke with air of a 1:15 ratio the temperature of the mixture, for this hypothesized fire, is less tham 50° C (because of inductive effects the temperature of the outer part of the tubes will be even lower).
The whole underground station, air flow coming through at an average speed of approx. 2 m/s would be equal to 180 m^2 x (2 m/s x 3600 s/h)= 1296000 m^3/h. Infact the already existing openings allow an extraction of diluted smoke egual to 1200000 m^3/h. The speed through the suction points along both sides of the platforms, 100 cm apart and 30 cm high, which gives a total of 250 points, is 4.44 m/sec.
The flow capacity along the length of the platforms is 0.67 m^3/s x m, which is much greater than that advised in literature (Kennedy et al. = 0.25 m^3/s x m. In our case, the total enviromental space being equal to 54000 m^3, we have 432000 m^3/h, which is decidedly less than the maximum flow that the electroventilators, at low power (600000 m^3/h) are capable of dealing with. The characteristics of the safety plant are:

- the stations safety power supply will be able to power at least one of the four machine rooms in case of emergency;
- the total extraction capacity is of 1200000 m^3/h, 300000 m^3/h for each of the four sections of electroventilators, each having a capacity of 150000 m^3/h;
- the ventilators (approx. 55/Kw of absorbed power, ensure during reversable functioning at least 70% of the nominal flow. They are equipped with automatic opening valves which operate as soon as the machine starts working;
- during the fuctioning of the ventilation of the station each machine ensures half the nominal flow, so 75 m^3/h activating only one machine on all four chambers/cabins; the ventilation of the platforms occurs with 6 changes of air per hour (the air is changed every 10 minutes). This forced ventilation can become necessary, as well as the natural ventilation, during peak travelling;
- in order to reduce the noise produced by the ventilators, the cabins are provided with silencers on the exit of the air flow. The size of these effectively quadruples the length of the ventilation cell;
- the equivalent section in the vertical shafts which connect the ventilation cabins to the horizontal collectors in the platforms, as well as the expulsion grills, is equal to 4.8 m^2;
- the extracted air mixed with smoke in the case of fire, is extracted as a result of the decompression which results from the ventilators, through pipes under the platform. These are connected to the train site via windows of 1000 x 300 mm at an interaxis of 2.00 m in the wall supporting the platform towards the rail.

6. WATERPROOFING AND DRAINING

A particularly important aspect of planning and construction is the waterproofing and draining of water from the soil surrounding the tunnel.
This particular method of construction does not allow the traditional installation of a layer of waterproofing behind the the Cellular Arch structure.
In the case of the Venezia Station the highest forseeable level for the water table touches the lowest tube.Up to that level the structure was completely water proofed by a continuous PVC cover.
The tunnel vault could be affected by the percolation of water from the surface, for which the concavities produced by the adjacent tubes could be a source of accumulation.
Consequently a collecting and draining network to deal with this water composed of tubes inserted within the casts of the arches which take the water to the main collecting network.
A water proofing system was devised for the internal surface of the structure, which is now completely visible (photo 3 and 4).



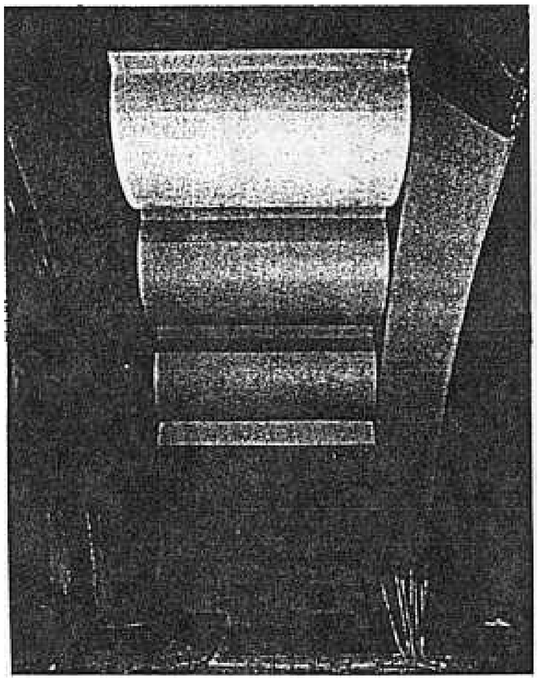


photo 3 and 4 – Cellular Arch structure before and after the water proofing system implementation

The planning of the draining and waterproofing system aimed to overcome the following problems and neet the following aims:
- maintain functioning under a pressure limit of 1 bar;
- guarantee functioning, in the presence of localized movements between the arch structures or between the tubes;
- use of materials exposed to the external environment of the station, which are at least 70% incombustible and autoextinguishing without producing toxic fumes in the remaining 30%;
- use of materials which will preserve functioning of the system even in contact with agressive water;
- permeability to steam;
- durability consistant with that of the rest of the structure without the necessity for constant maintenance and repairs;
- the internal surface after treatment should have the properties of a normal concrete or plaster wall which can be painted over;
- the surface should also be sound proof and be permeable to superficial condensation.

After careful experimentation a solution to guarantee the above conditions was found which consisted of a system of waterproof joints on plastic sheet fixed on the structure. The system was implemented in the following stages (fig.7):

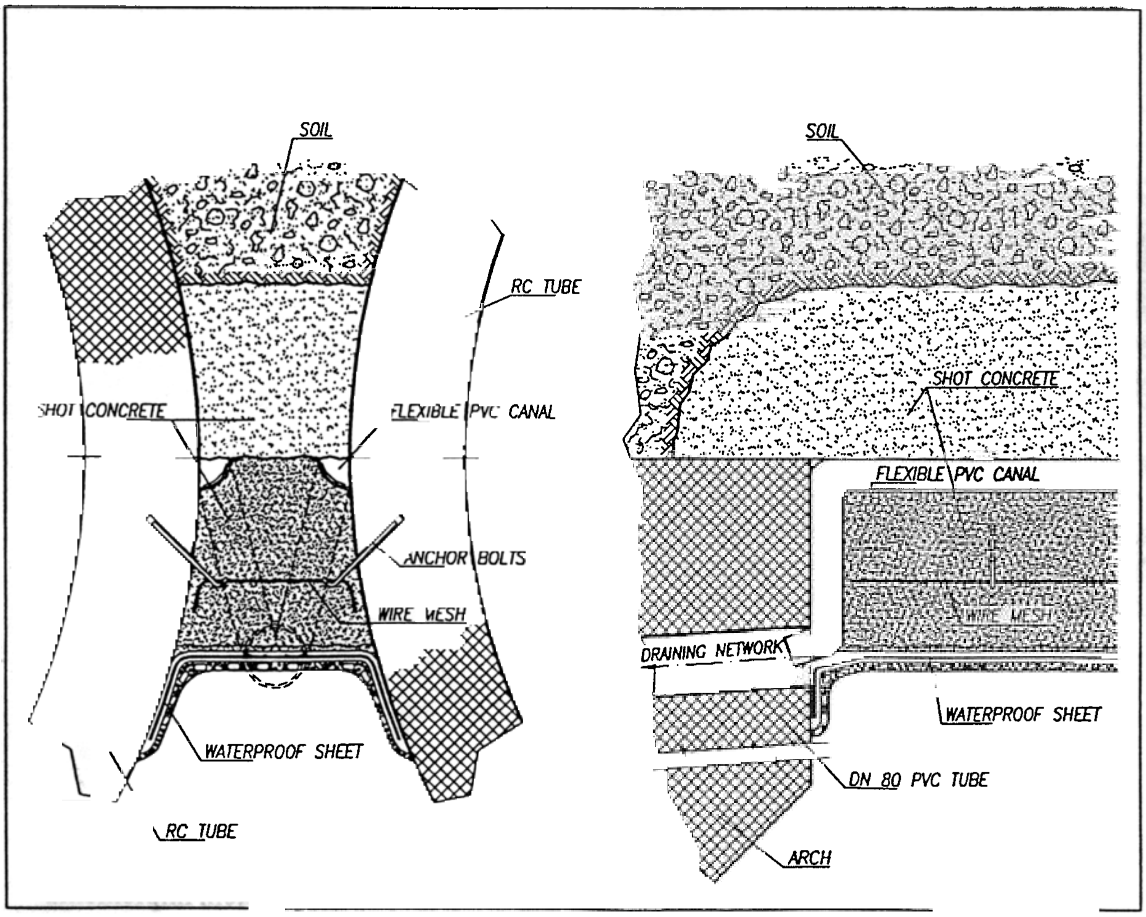


fig. 7

– cleaning of the surface via sand blasting, hydro–sand blasting and hydro blasting;
–placing of special shot–concrete in the spaces between the tubes after the placement of a wire mesh anchored onto the tubes, and of two flexible PVC tubes connected to tubes in the arches.
– gluing with resin a waterproof sheet under the "cork" layer described above. This operation was repeated on all the joints in the system (between one tube and another, between arches and tubes, between different day joints of the structure);
– the visible surfaces of the structure were therefore covered with plaster reinforced by a polyester mesh made of a cement mix of high elasticity, added by resin on the internal surface of the tubes.

This system produced excellent results both functionally and aesthetically.

REFERENCES

1. Colombo A., Lunardi P., Luongo E. "Innovative Technique for the Realisation of Large Diameter Tunnels in Loose Sand". International Congress "Progress and Innovation in Tunnelling", September 9–14 1989, Toronto. 1989.
2. Lunardi P., Pizzarotti E.M. "Soft Ground Tunnelling in the Milan Metro and Milan Railway Link. Case Histories". Soft Ground Tunnelling Course, July 10–12 1990, London. Institute of Civil Engineering, 1990.
3. Greeman A., "Costruction Today". July 1990, London. 1990.
4. Stussman H.B. "ENR – Engineering". August 16 1990, London. 1990.
5. Lunardi P. "Cellular Arch Technique for Large Span Station Cavern". Tunnels and Tunnelling, November 1991.
6. Greeman A., "Costruction Today". June 1992, London. 1992.
7. Lunardi P., Colombo A., Pizzarotti E.M. "Performance Observation During Construction of the Large Span Milan Metro (Venezia) Station". International Congress "Option for tunnelling", April 19–22 1993, Amsterdam. 1993.