Ground improvement by means of jet-grouting

P. LUNARDI*

University of Parma, Parma, Italy

After a description of jet-grouting technology some typical examples are given of its applications to a number of civil engineering problems. The following aspects are examined:

(*a*) suitability for different types of ground;
(*b*) design criteria;
(*c*) monitoring during construction;
(*d*) recent technological developments;
(*e*) jet-grouting techniques in civil and environmental engineering works;
(*f*) some case histories.

Keywords: Jet grouting; state-of-the-art review; plant & equipment; tunnelling; slope stability; foundations

Après avoir décrit la technologie du jet-grouting, l'article présente des exemples typiques d'application pour la solution d'un grand nombre de problèmes d'ingénierie civile. Il examine tout particulièrement:

(*a*) les possibilités d'application dans les différents types de terrain;
(*b*) les critères de conception et de dimensionnement;
(*c*) les contrôles en cours de chantier;
(*d*) les innovations les plus récentes;
(*e*) les possibilités d'application du système dans les ouvrages d'ingénierie civile et environnementale;
(*f*) quelques unes des applications réalisées.

Introduction

The transformation of cohesionless *sand* into *sandstone* occurs in nature over very long periods of time during diagenesis. It is caused by the very strong pressures of lithostatic loads or tectonic forces. Now, however, it can actually be produced by a number of artificial means on-site including the 'jet-grouting' technique.

Jet-grouting owes its origins to experiences acquired some decades ago in the oil drilling industry when unblocking strings of drill rods locked at great depths.

Applied for the first time in the civil engineering field by Cementation Co. in Pakistan, in about 1950, and subsequently used by the Japanese, it was introduced into Italy about ten years ago and systematically used in various civil engineering works with increasing success, thanks to the development of adequate equipment (pumps, automatic drilling rigs, etc.) and suitable structural designs. Jet-grouting, therefore, is still a fairly young technology open to further development. This article describes the current state of the art and also examines the following:

(*a*) suitability for different types of ground;
(*b*) design criteria;
(*c*) controls during construction;
(*d*) recent technological developments;
(*e*) jet-grouting techniques in civil and environmental engineering works;
(*f*) some case histories.

The jet-grouting technique

Operational methods and equipment

The 'jet-grouting' technology primarily consists of injecting controlled quantities of cement grout through small diameter bore holes (7 to 10 cm diameter) to treat controlled volumes of ground.

The treatment can be performed using three different methods. The first two were developed in Italy and the third is of Japanese origin. They are as follows:

(*a*) injections of grout only (monofluid system);
(*b*) injections of air and grout (bifluid system);
(*c*) injections of air, water and grout (trifluid system).

In *monofluid* jet-grouting, ground disruption is achieved by the action of cement grout, which also has the function of cementation.

In *bifluid* jet-grouting the disruptive action is entrusted to a high speed jet of grout guided by a ring of compressed air at about 8–12 bar pressure, which limits dispersion and, consequently, increases the penetrating power.

In *trifluid* jet-grouting disruption is essentially performed by an air-guided jet of water (air pressure about 5 bar; water pressure of about 400 bar), which breaks down and partially washes out the soil, which is subsequently replaced by grout injected at a pressure of about 50 bar.

Operating conditions and requirements on site, in terms of available space, construction stages and, most importantly, the type of soil to be treated, determine the choice of the most appropriate jet-grouting method to be used.

Figure 1 shows the equipment required to perform jet-grouting treatments:

Cement bins (1)
Batching plant (2)

---

* Address for correspondence: Rocksoil S.p.A., Piazza San Marco 1, I-20121 Milan, Italy.

(GI 003) Paper received 19 June 1995; last revised 3 October 1995; accepted 3 November 1995

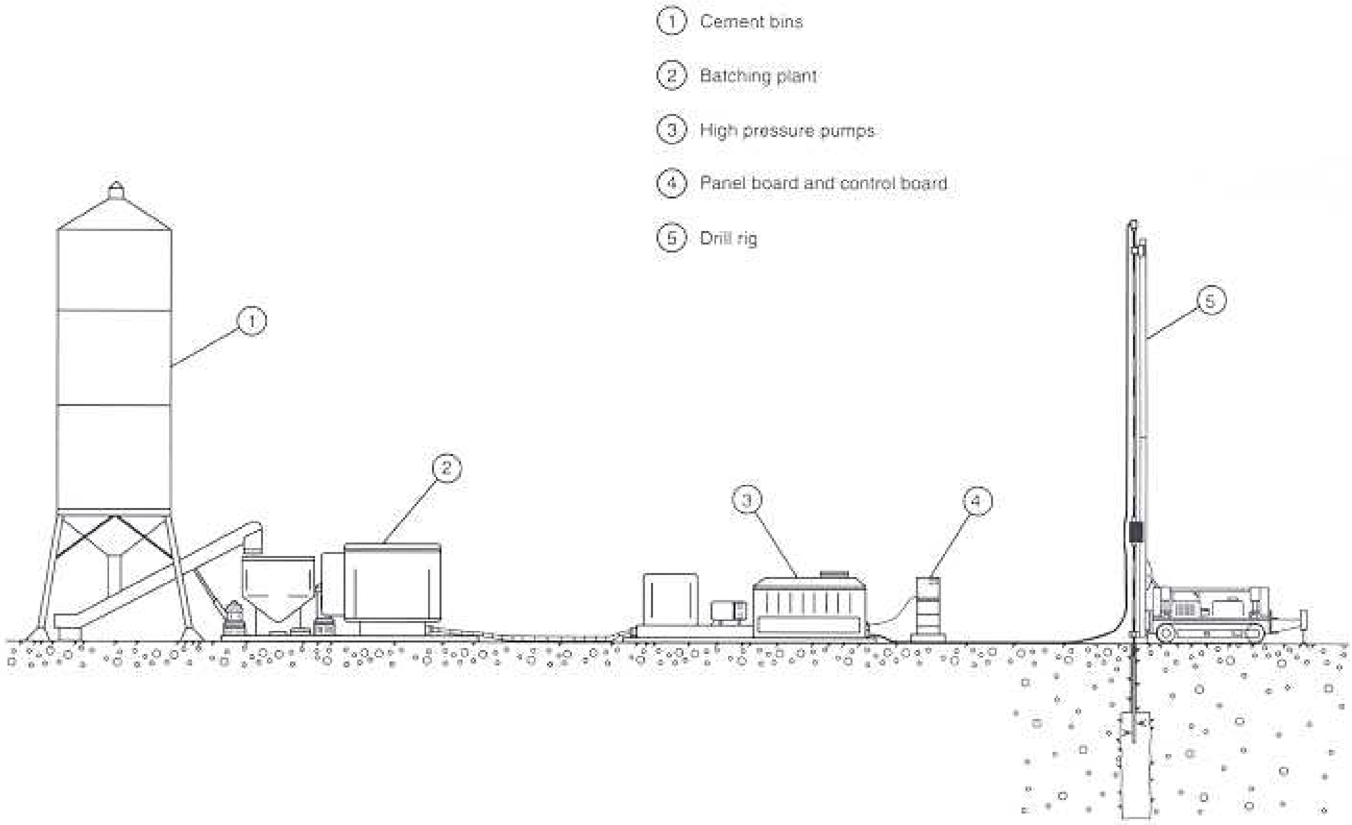


Fig. 1. Equipment required to perform jet-grouting treatment

400 to 500 hp high pressure pump (3), with compressors, for Bifluid and trifluid treatments
Panel board and control board (4)
Drilling rig (5) (Fig. 2)

The string of drill rods (1 in Fig. 2) on the rig has joints that will withstand high pressure; at the bottom end it is connected to the injection chamber and to the bit, usually a tricone. In the monofluid system, the upper rod is connected to the high pressure grout pump by a swivel-joint and a flexible pipe (2). Standard rod strings of 60, 76 and 90 mm o.d. are used. Equipment used to perform bifluid and trifluid jet-grouting are provided with a swivel for separate grout/air and grout/air/water supply, respectively, fed by appropriate pumps and compressors. The rods used for bifluid jet-grouting (76 to 90 mm o.d.) have two coaxial ducts to allow separate flow of air and grout. The trifluid system requires triple-duct rods (76 to 90 mm o.d.) in order to allow air, water and grout to flow separately. The injection chamber is located just above the bit. For the monofluid system, it is a hollow steel cylinder, about 40 cm long, usually of the same outer diameter as the drilling rods (6 to 9 cm o.d.). The walls have one or more radial holes fitted with nozzles and there is a central neck on the inside at the bottom of the chamber, 2 cm in diameter, to allow the drilling fluid to reach the bit when drilling. This neck can be blocked by dropping a 2·5 cm diameter steel ball inside the rods thus forcing the grout to be injected through the side nozzles. Grout nozzles can be one to four in number, with inner diameters generally ranging from 1·5 to 3·0 mm; they are usually staggered 1 to 2 cm, from each other. Recently much larger diameter nozzles have been used. They obviously require high capacity pumps.

Drilling operations are usually performed by *rotation* or *rotary-percussive* action, with or without the use of drilling fluid. Rotary drilling, requiring light drill rigs is preferred in medium to fine-grained soils while in cohesionless coarse-grained soils and/or when large boulders are found, *rotary-percussive* drilling can be better in terms of performance, although heavier equipment is required. The same rig is generally used for drilling and high pressure grouting.

Once drilling has finished and the required depth reached, the neck at the bottom of the injection chamber is blocked so that grouting can commence. The pump starts operating at very high pressure (40–60 MPa) pushing the grout through the flexible pipe (2) into the rods (1), down to the injection chamber and finally, through the nozzles, radially into the ground.

The drill rod is extracted at a carefully controlled rate and rotated to provide the correct angular velocity to produce the cylindrical columns required. The fluid can be pumped into the ground at very high energy levels (in fact the jet penetrates the ground at a speed of 800 km/h or more).

Over the years some contractors have developed drilling rigs featuring increased power, flexibility and reliability, with the aim of obtaining more versatile equipment, reducing operating times and improving size, shape and final features of the treated ground.

Rotary and rotary-percussive drilling rigs have been developed to work in restricted spaces and also to perform horizontal jet-grouting, required for many ground improvement operations especially in underground constructions.

Figure 3 shows one of the first rigs, manufactured in Italy by Rodio S.p.A., specifically designed for near horizontal rotary-percussive drilling and jet-grouting. Hydraulic jacks allow the mast to rotate 180 degrees with adjustable inclination, up to 14 degrees (25%) with respect to the horizontal. The first horizontal jet-grouting work was carried out using the design of the author in the 'Campiolo' tunnel on the Udine–Tarvisio railway line of the Italian State Railways, using a rig of this type.

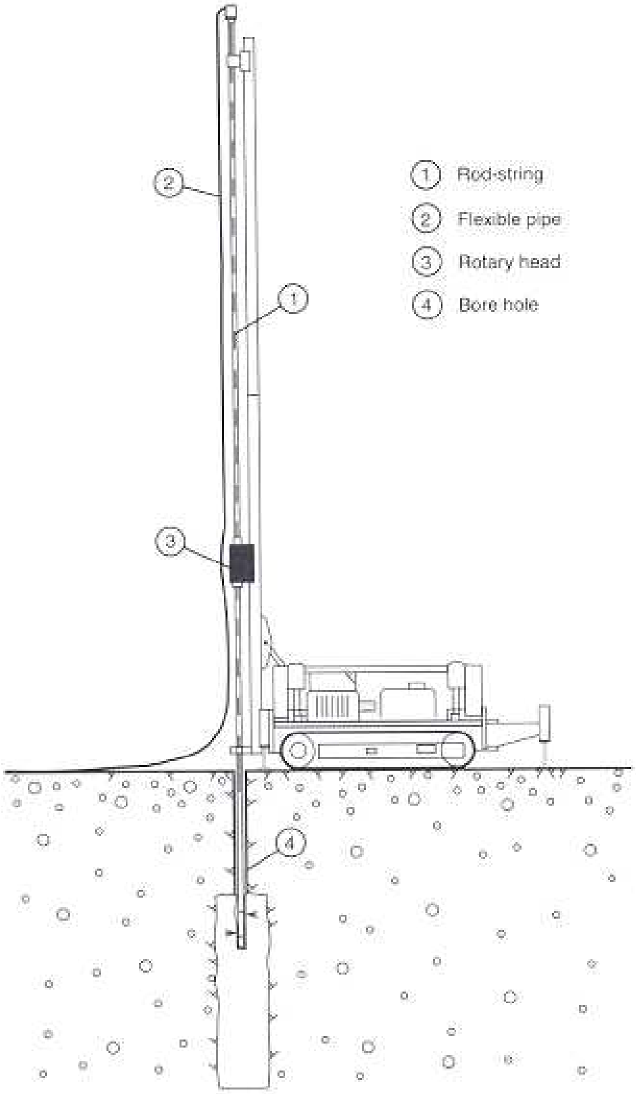


Fig. 2. Drill rig for jet-grouting

Working principles

The operations to be carried out for monofluid and bifluid jet-grouting, the most widely used systems, are performed in two stages (Fig. 4):

First stage: insertion of the drill-rods, equipped with the nozzle bearing chamber, down to the design treatment depth by drilling. To achieve good results this stage requires skill, as the treatment could be compromised by unwanted rod deviations.

Second stage: return or extraction stage. The drill-rod is extracted with rate of ascent and angular velocity carefully controlled while injecting grout through the nozzles; as mentioned above, with a bifluid system the grout jet is air guided to gain more penetrating power.

The following parameters are controlled to obtain volumes of improved soil of the desired shape and size: grout pressure, rate of ascent, angular velocity, numbers of nozzles, nozzle i.d. Treatment improves the mechanical properties of the soils to the point where permeability and strength is comparable to that of a concrete.

Operating parameters

The principal operating parameters are:

(*a*) injection pressure;
(*b*) number and diameter of nozzles;
(*c*) water/cement ratio of the grout;
(*d*) injection time.

The *injection pressure* is controlled by pressure gauges; the jet energy and consequently the radius of action depend on pressure. The upper pressure limit is essentially determined by the capacity of the pump used. Operational pressures of 40 to 60 MPa are generally employed.

The *number and diameter of nozzles* determine the injection capacity, the volume of grout injected into the ground per unit of time and, consequently, the rate of treatment. Of course, high flow rates require high-power pumps to maintain high pressure. Larger nozzle diameters make more efficient use of the power employed while a larger number of nozzles, with the total delivery rate held constant, decreases performance, due to a greater loss of head. It follows that if high-power injection pumps are not available it is preferable to limit the number of nozzles.

The *water/cement ratio of the grout* is the most important parameter with regard to the mechanical properties of the treated soil and the initial behaviour of the soil–grout mixture. A low water/cement ratio is extremely important where there is groundwater flow, as this could wash away

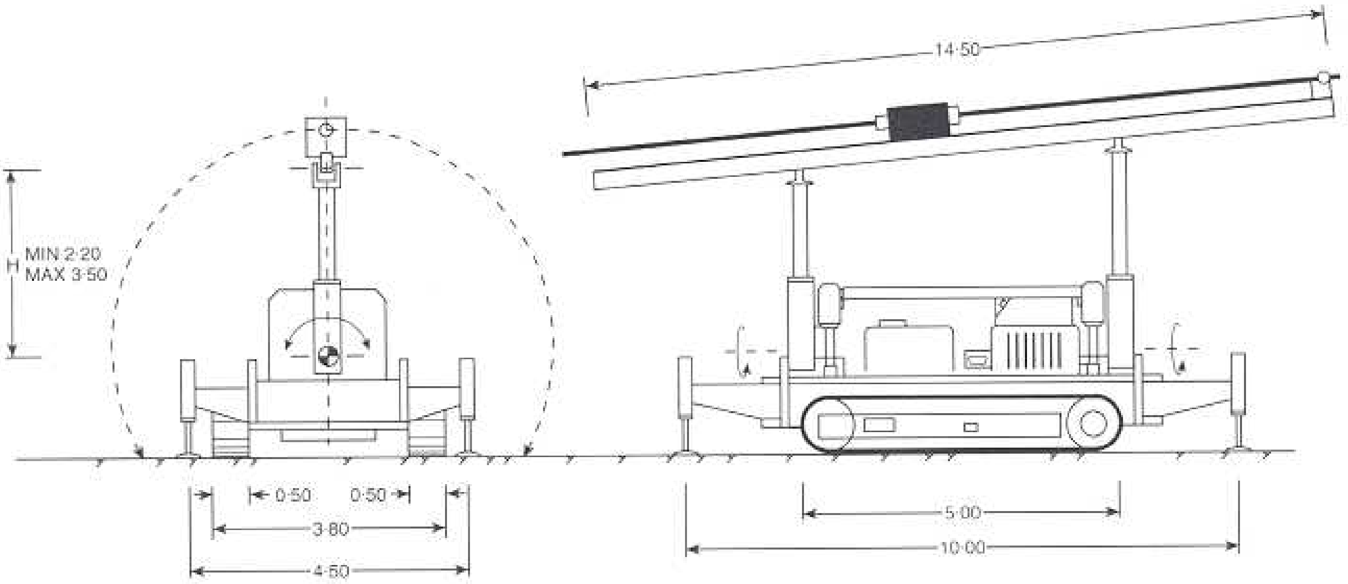


Fig. 3. Drill rig for near-horizontal jet-grouting (measurements in metres)

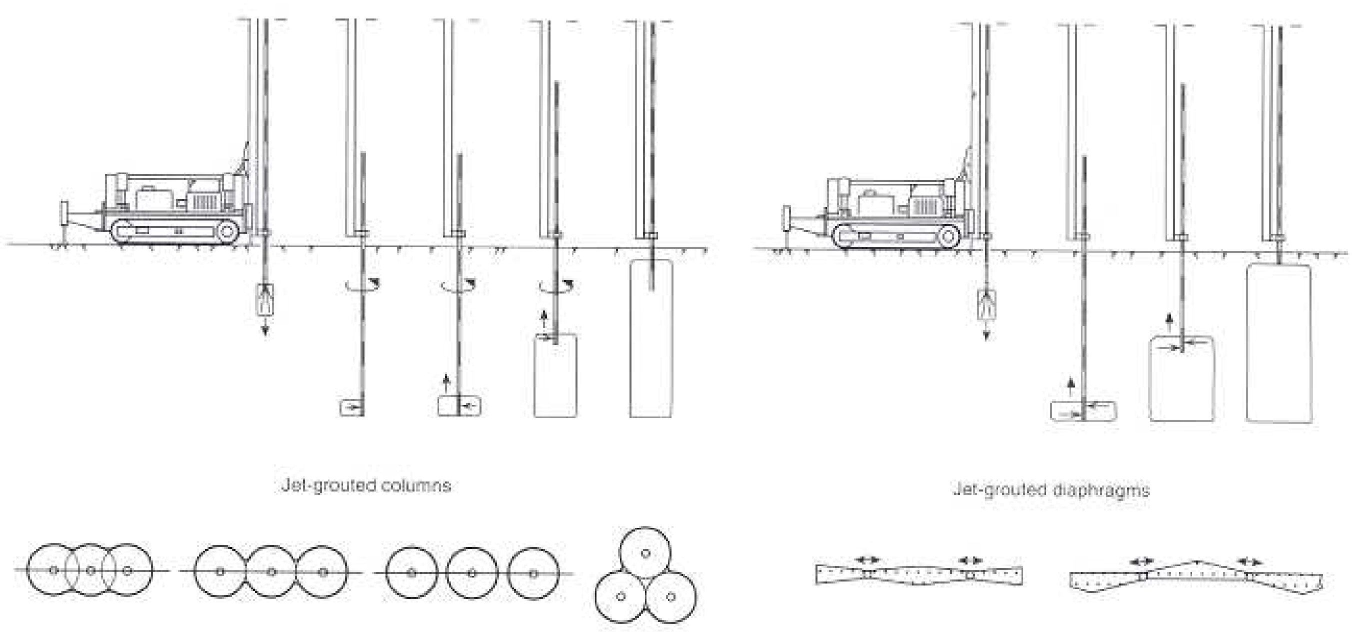


Fig. 4. Jet-grouting in operation

the cement shortly after injection. Laboratory and field tests have shown a relationship between compressive strength of treated soil and the water/cement ratio.

The *injection time* depends on the *ascent rate* and the *angular velocity* of the drill rod.

The *ascent rate* is controlled by a timer placed on the drill rig. Raising is usually performed in 4 cm steps, thus allowing the jet to act on the surrounding ground, for set time intervals. The diameter and the mechanical properties of the ground treated as well as of course the time required for treatment are all affected by the ascent rate. For any given soil type, delivery rate and pressure there is a minimum ascent rate below which operation is not feasible. It has in fact been discovered that, if the extraction speed is too slow, the jet, not having sufficient energy to enlarge the radius of action, starts to flow along the outer surface of the drill rod.

The *angular velocity* of the rods will depend on the ascent rate and the two must be regulated together to optimize the disrupting action of the jet. There is a lower limit for angular velocity, below which jet reflection occurs. This reduces efficiency unless special precautions are taken as shown by recent research (see section entitled 'Innovations').

Table 1 gives typical values for the principal operating parameters.

The columns produced

Using the monofluid system, columns of diameter varying from 0·40 to 1·40 m are currently obtained depending on the features of the ground and on the operating parameters used (see Figs 5 and 6).

The bifluid system increases the jet power and consequently its penetrating capacity. The diameter of the columns obtained using a bifluid system is 30–70% greater than that obtained with a monofluid system, while the mechanical strength is reduced by the effect of air entrained within the treated material.

The trifluid system, which for technical reasons cannot be used for horizontal work, produces columns with diameters larger than 2 m, but the higher cost, the lower operating flexibility and, above all, the risk of loosening the surrounding ground when soil is disrupted and washed out has limited its use.

Columns having a large diameter can also be obtained using the 'two-stage' system. Grout injection is preceded by very high pressure water injection (first stage), designed to produce preliminary breakdown of the ground. The subsequent grout injection (second stage) replaces water and the washed-out finer soil fractions. As it encounters less resistance from the already remoulded ground, the grout penetrates deeper. Moreover, the removal of the finest fractions gives better mechanical properties to the treated material.

Suitability of soils for jet-grouting treatment

From the experience we have acquired, we can confidently say that jet-grouting can be successfully performed in *any type of soil*, independently of grain size and permeability,

Table 1. Operating parameters for jet-grouting

System	Fluid	Pressure: bar	Nozzle No. & i.d.: mm	Ascent Rate V_a: cm/min	Angular speed: r.p.m.	w/c ratio	Discharge: l/min
Monofluid	Grout	400–550	1–2 × 2–5	15–100	5–15	1·0–1·5	70–600
Bifluid	Grout Air	400–550 10–12	1–2 × 2–5 –	10–30 10–30	4–8 –	1·0–1·5 –	70–600 4000–10 000
Trifluid	Grout Air Water	50–100 10–12 400–500	1–2 × 4–5 – 1–2 × 2–3	6–15 6–15 6–15	4–8 – –	1·2–1·5 – –	80–200 4000–10 000 40–100

Fig. 5. Soil columns obtained by jet-grouting treatment

with the exception of very hard cohesive soils whose strength cannot be overcome by the jet. This technology has the considerable advantage of being able to treat *stratified soils* (alternating sands, silts, clays, etc.) providing a uniform degree of cementation and waterproofing, independently of the nature of the original ground (see Fig. 7).

In *fine-grained* soils the outer surface of the columns obtained is normally well defined and fairly regular. In *coarse-grained* and heterogeneous grounds, on the other hand, this surface is irregular and there is the systematic appearance of 'root effect', i.e. grouting through 'claquage' of the ground outside the radius of action of the jet, occurring as a result of the escape of a small amount of grout along preferential paths into the surrounding ground (see Fig. 6).

The occurrence of still groundwater does not in any way compromise the results of the treatment. When seepage occurs special precautions, such as the addition of accelerators to the grout, give good results even at groundwater discharge velocities of the order of 0·1 cm/s.

The *compressive shear strength* of jet-grouted volumes is normally a function of the water/cement ratio of the injected grout and of the grade of the ground. It generally increases from clays to gravels (see Fig. 8). Maximum strengths in excess of 50 MPa have been reached in sands and gravels, while in fine-grained peaty soils it is hard to attain values 10 times lower. Generally speaking, with monofluid systems and grout composed of cement and water only, long-term shear strength in sandy and gravelly soils usually produces average values of 12 to 19 MPa.

In fine-grained soils, satisfactory strength values are obtained only by resorting to high cement/water ratios (at least 1·2–1·3): in such cases values of 2 to 14 MPa have been obtained.

Using the trifluid system it is possible to attain even greater strengths, due to the purity of the column obtained, while the bifluid system is slightly penalized in this respect by the possible occurrence of entrained air bubbles.

The *stiffness* of grounds treated with different jet-grouting techniques presents an even greater variation. In general the ratio E/R_f between the secant modulus E and the compressive strength R_f tends to increase with R_f, from a minimum of 200–300 in fine soils to about 1000 in gravels and sands (see Fig. 9).* With bifluid systems strengths are lower than with monofluid because of the effect of entrained air. In addition, for cohesive soils a larger volume of soil is affected by the same quantity of water/cement mix, using the same specific energy, due to the higher penetration of the air-guided jet.

The trifluid system shows an even greater variation in results: in grounds which interfere with the setting of the concrete, the qualitative mechanical outcome is positive only if the operation of cutting and removing the original ground is complete and the two principal operations of the system, namely cutting with air and water and replacement with grout, are kept separate. To favour the replacement of disrupted and washed-out material, it is vital that the grout always has a low water/cement ratio.

---

* E is the secant modulus, at a stress equal to $0{\cdot}4\,R_f$.

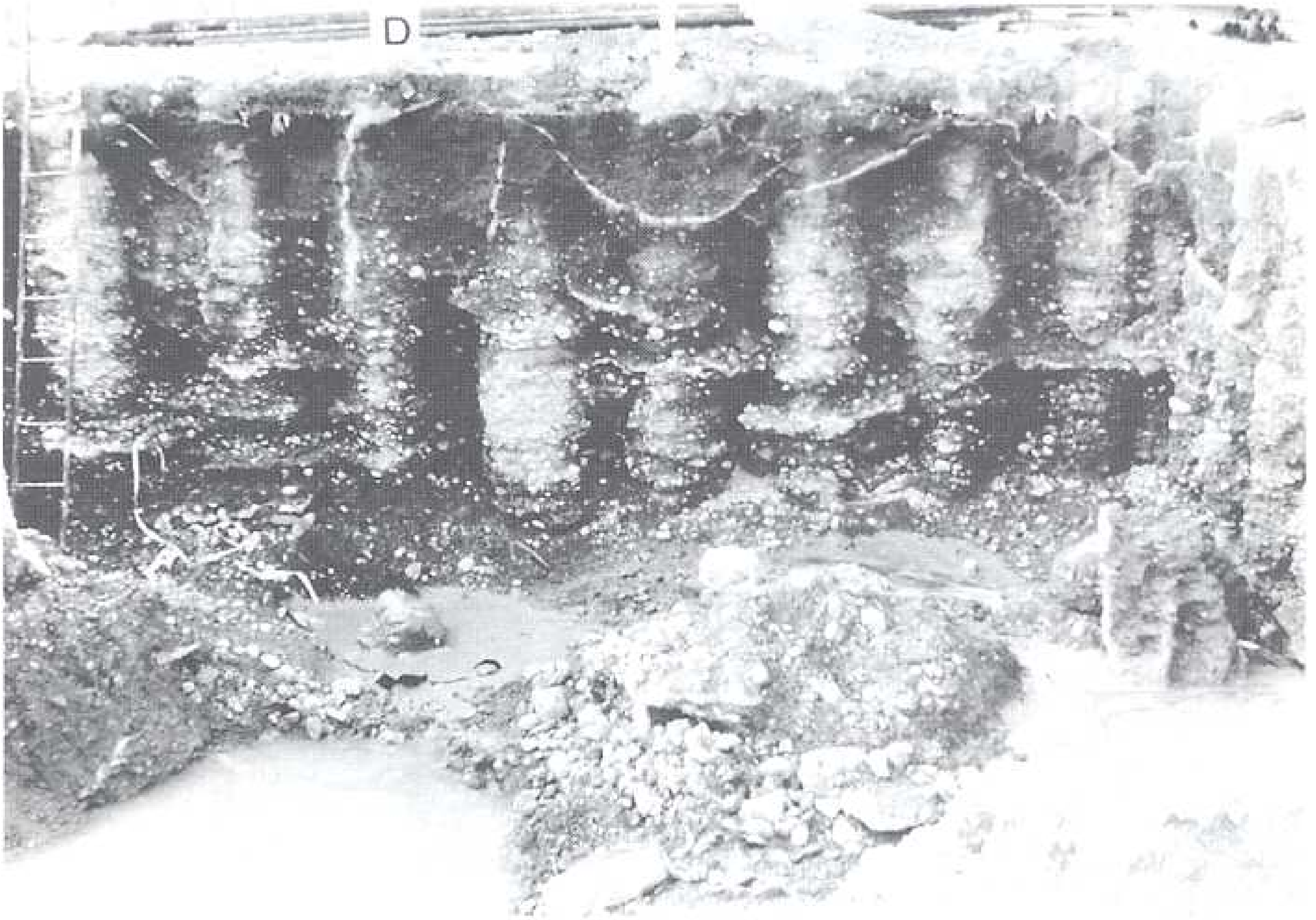


Fig. 6. Soil columns obtained by jet-grouting treatment

Fig. 7. Results obtained from jet-grouting treatment in stratified soil

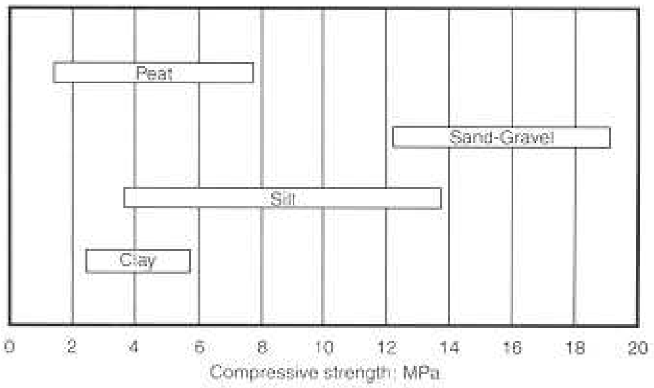


Fig. 8. Compressive strength of jet-grouted soils

Design criteria

The design of ground improvement using jet-grouting must involve the following stages:

(1) soil investigations and preliminary field tests
(2) choice of grout type and operating parameters
(3) deciding the pattern, shape and size of the grouted volumes
(4) identification of the most appropriate mathematical model to study the stress–strain behaviour
(5) choice of the monitoring systems.

Investigation and field testing

Preliminary investigations play a fundamental role because they determine whether jet-grouting is feasible and

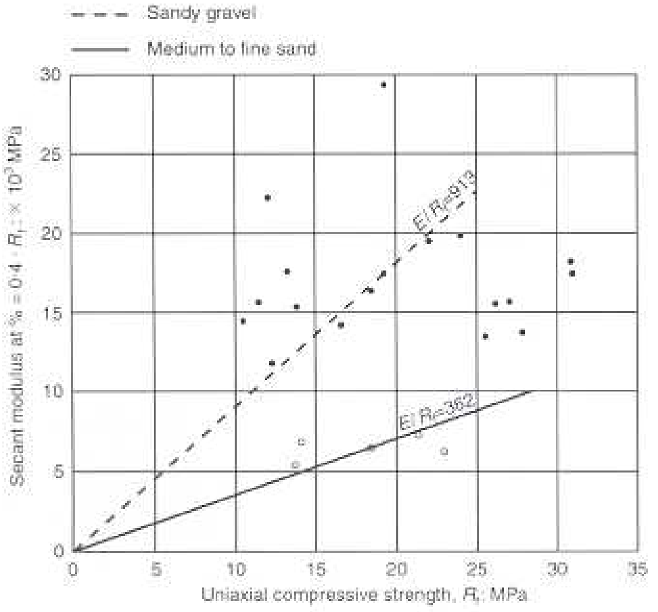


Fig. 9. Elastic properties of treated grounds

also the main parameters of the work. Preliminary investigations include:

(*a*) exploratory boreholes to determine ground conditions;
(*b*) static and/or dynamic penetration tests to evaluate the mechanical properties of the ground;
(*c*) laboratory permeability tests, particularly for cohesive soils;
(*d*) field injections tests on a site similar to actual working conditions.

The field injections test is certainly the main source of information for deciding on the grout composition and the operating parameters. This is also because current theory does not yet provide reliable support in this area.

A number of test columns or treated volumes of the same size and pattern as the actual design are drilled and injected on a suitable site, generally adjacent to that of the actual operation. The working parameters are varied for each test column, or each group of columns, in order to subsequently choose the most appropriate combinations based on the test results. Upon completion of the field injection tests, the following tests are performed.

(*a*) Sonic tests (downhole and crosshole). Vertical pipes are inserted into the ground and/or into jet-grouted volumes, at preset distances.

    In *downhole tests* a probe equipped with a sound transmitter and a sound receiver device which are set at an appropriate vertical distance from each other is lowered into the borehole. The sound waves emitted pass through the treated ground surrounding the hole before reaching the receiver. Amplitude, frequency and shape of the signal are profoundly modified by the characteristics of the material, which also affects the speed of the sound (Fig. 10). Diagrams like those shown in Fig. 11 are obtained.

    The *crosshole* technology measures the horizontal wave velocities between two points located in adjacent boreholes by inserting a sound transmitter and sound receiver(s) into them.

(*b*) Direct site inspection of treated volumes, by excavation, to visually check diameter, structural continuity and possible overlapping (see Fig. 12).

Fig. 10. Field injection test: three columns downhole tested (see Fig. 11)

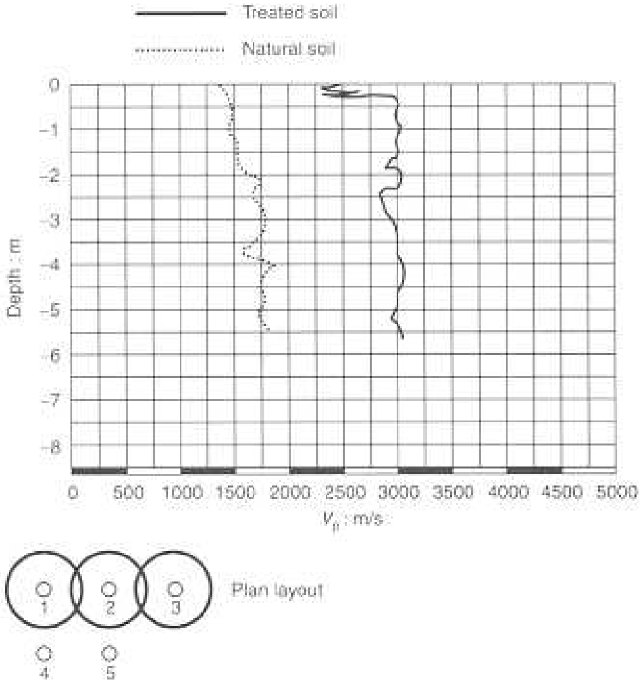


Fig. 11. Example of data acquired from downhole tests (see Fig. 10)

(*c*) Destructive tests on cores of treated ground, both vertically and transversely cored, so as to evaluate mechanical strength by laboratory tests (see Fig. 13).

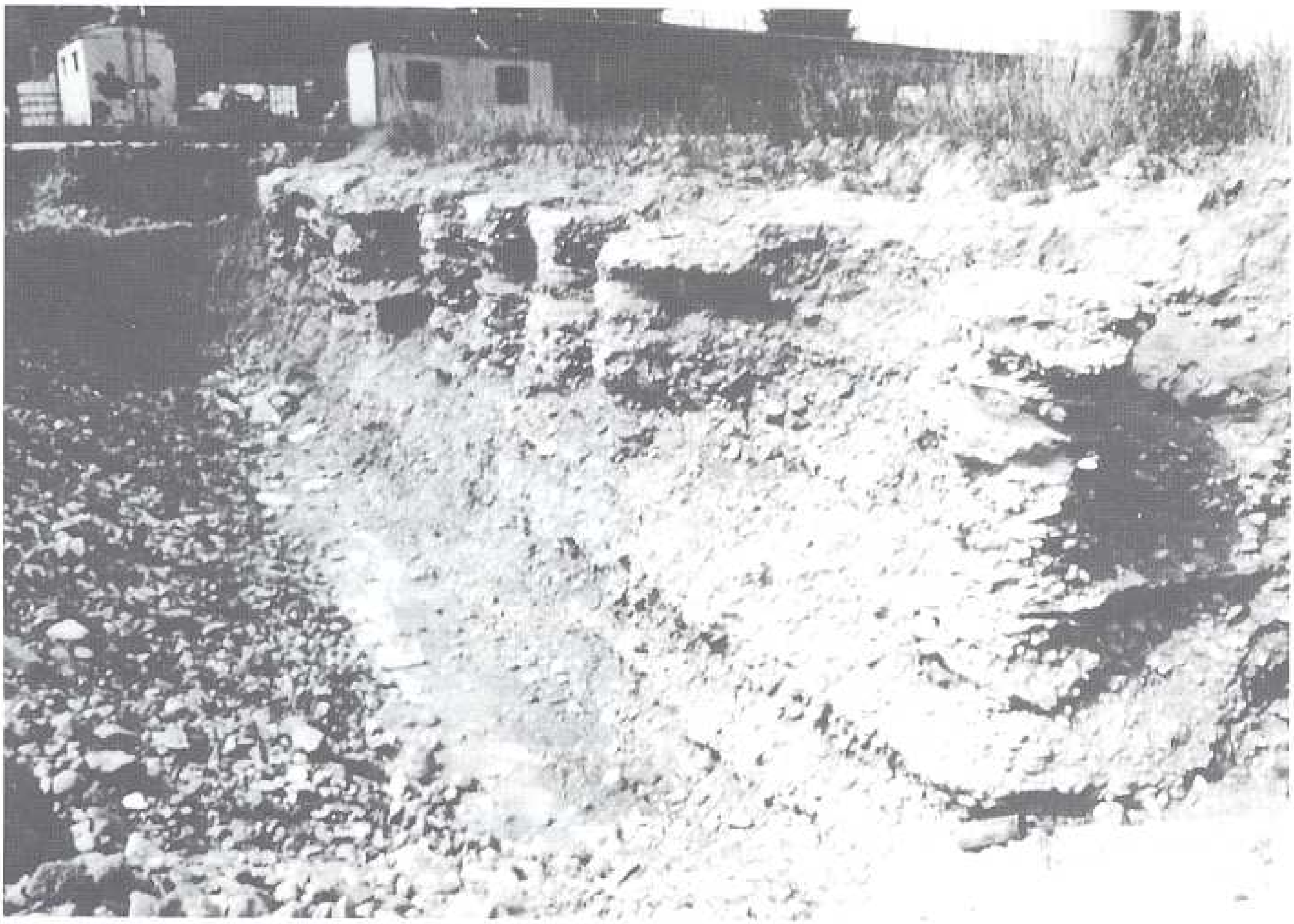


Fig. 12. Field injection test: direct site inspection of treated volumes

Jet-grouting design

When it comes to designing the pattern and dimensions of jet-grouting treatment, it is essential that designers have a good understanding of various fundamental concepts: i.e.

(*a*) volumes of ground treated by jet-grouting are *cemented ground* and not a structure, even if they have a shape which is reminiscent of that of piles;

(*b*) when giving a static function to treated ground, it must be remembered that the existence of volumes in the ground that are more rigid than those in the untreated adjacent ground may possibly be used to produce a system which channels stresses in a desired direction;

(*c*) the treated ground can take *compression* and *shear*, and consequently the application of other types of stresses (i.e. tension) should be avoided.

In this connection, it must be mentioned that it is possible to reinforce the jet-grouting, if necessary, but it is important to keep in mind that a real structure, like reinforced concrete, will never be obtained.

The insertion of bars and steel sections into improved ground can be achieved, before setting takes place, by gravity or using high frequency vibrators.

Calculation models

The types of problems connected with jet-grouted ground are clearly non-linear as the materials involved have typically a non-linear stress–strain behaviour. In addition to this, it is often necessary to analyse structures whose shape changes over time due to excavation or construction operations. Consequently it is easy to understand that, apart from the simplest cases, the analysis of such problems implies the use of the finite element method. This starts with analysis of the natural untreated conditions and develops through an appropriate sequence of stages realistically approximating the actual development of the work.

Monitoring

It is important to organize an efficient system for monitoring jet-grouting operations, namely, *monitoring during treatment* and *monitoring after treatment*. During treatment, special care should be taken to ascertain the reliability of the principal mechanical and electrical characteristics, which requires the continuous monitoring and recording of such operational parameters as water/cement ratio, pressure and delivery of grout, ascent rate and angular velocity of the drill rods.

Other monitoring is needed to:

(*a*) check that drilling is in the correct direction;

(*b*) detect possible surface lifting and/or settlement of adjacent ground (especially when the work is carried out near buildings or other structures);

(*c*) analyse the effluent material flowing to the surface during injection. The final features of the improvement can be estimated from qualitative and quantitative examination of this material.

Monitoring after treatment includes:

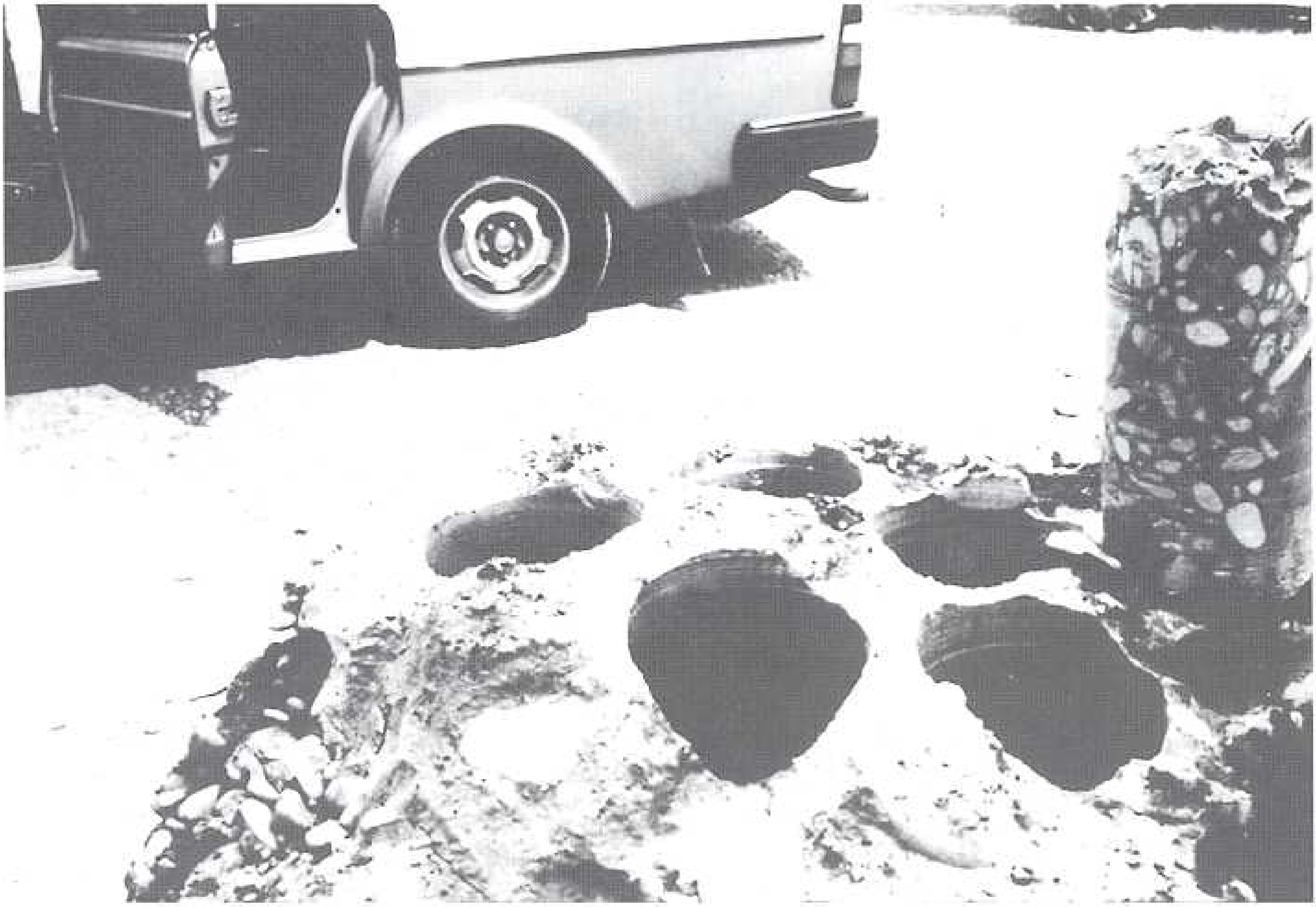


Fig. 13. Destructive tests on cores on treated ground

(*a*) load tests (in the case of foundation columns), extended to several columns;

(*b*) sonic tests to check the improvement of mechanical properties as well as the continuity and possible overlapping of contiguous columns.

Innovations

Over the years remarkable progress has been made in the use of jet-grouting technology. These advances have occurred both in the equipment, in operational techniques, in studies on grout, and in construction designs developed to extract the maximum advantage from the particular features of the system.

Technological progress

Research has mainly been directed to the mechanics of pumps, as well as to experimentation on high pressure circuits and on more efficient nozzle shapes. The first aim is to increase the disruptive power of the jet to give it a wider radius of action and to add sand to the grout to give stronger treated materials. Experimental field tests were performed on both soft clayey/silty soils and on gravel, adding well-graded limestone and/or silica sand aggregate, up to and above 1 mm in particle diameter, in amounts up to 100% of the weight of the cement to the mix.

Pumps of 2700 h.p. with a capacity of 1500 litres/min at 500 bar pressure and operating with monofluid jets were used to create columns of more than 2 m in diameter, composed of homogenous, compact mortar, even in layers of clay. These results were achieved with fast performance times and also a remarkable reduction in the quantity of effluents.

The second aim is to perform injection while drilling. In the first experiments carried out, the injection chambers were equipped with one to five nozzles fitted so as to direct the jets at an angle that would favour penetration of the drill. The result was 50% faster performance times, as compared to existing techniques.

The third and final aim is to reduce or eliminate the reflection effects which normally occur due to low rod ascent rates and low angular velocities. Very interesting results were obtained which allowed diaphragms of improved ground to be formed in place, from a single drill-hole (see Figs 14 and 15). One of the most exciting results was the wide radius of action of a single jet. This was 3 to 4 m which, with low angular velocities, produced columns of about 8 m in diameter.

Recently jet-grouting technology has also been successfully applied to the waterproofing of rocks where traditional low pressure injections are inefficient as the injected grout tends to escape through fractures and/or joints without filling them sufficiently. An interesting example (see next section) of the use of this technology is on the Brombach dam (Germany).

Jet-grouting in civil and environmental engineering works. A design outline

The jet-grouting ground improvement technique has been widely used in several fields of civil engineering, thanks to

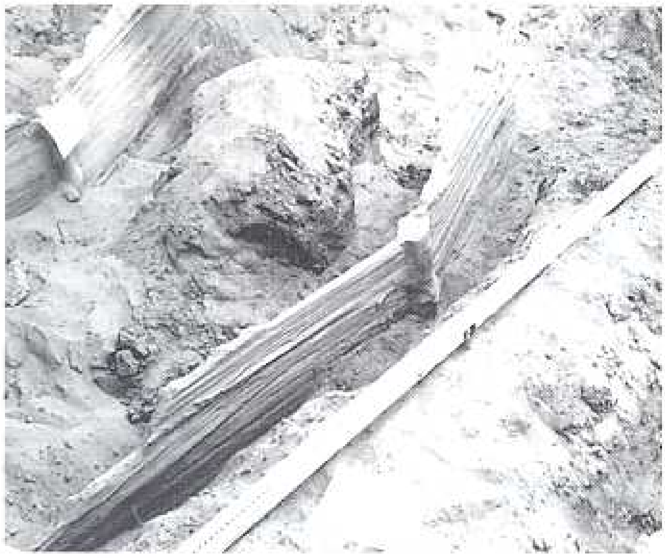


Fig. 14. Diaphragm of improved ground by jet-grouting from a single drill-hole

specific structural designs which can be applied to various operational situations.

Early uses concerned *earth retaining* and *foundation work*, perhaps because of the columnar shape of the treated volumes, which is reminiscent of piles. This was quickly followed by more sophisticated and ingenious uses for slope stabilization, hydraulic works and excavation of tunnels in loose ground. A few examples of actual applications helps to trace the development of design models.

Retaining structures

There have been considerable advances in the design of confinement for open pit and trench excavations (see Fig. 16). Early designs consisted of one row of columns of treated ground spaced at varying distances, located along the edge of the future excavation. Such a design was first used in Italy by the author in 1980 for the construction of the Sesto San Giovanni pit for the Milan underground railway (Fig. 6). A similar design was used in Lyons to protect cut and cover excavations of the 'Sans Souci' station on line D of the metropolitan railway. In this case the soil cohesion made it possible to increase the distance between the 70 cm diameter jet-grouted columns to approximately 2 metres (see Fig. 17).

Such designs, although effective for temporary confinement of excavations in coarse-grained or cohesive soils with moderately good geomechanical properties, are not sufficiently reliable for long-term protection. Consequently, in order to achieve this, more complex designs were developed, which consisted of several staggered rows of jet-grouted columns. This technique gave excellent results together with ease and speed of construction and as a result rapidly gained acceptance, often replacing traditional technologies. It is sufficient to recall the success it has enjoyed, together with horizontal jet-grouting technology, in the construction of tunnel portals in cohesionless or slightly cohesive soils (Fig. 18). The jet-grouted ground means that

Fig. 15. Diaphragms of improved ground by jet-grouting

tunnelling can be performed with a very low overburden, which in turn reduces the amount of surface excavation works thus minimizing the risk of slope instability. As shown in Figs 19 and 20 this method provides outstanding results from an environmental and landscape point of view as compared to traditional methods.

Finally Fig. 16 shows the 'truss' design used at Sarno (see Fig. 21) near Naples to support trench excavation along the FS railway line (1986). It has the advantage of making the ground confined between the rows of jet-grouted columns contribute to the stability of the entire system. This ground, in addition to being improved by claquage, is also under triaxial stress.

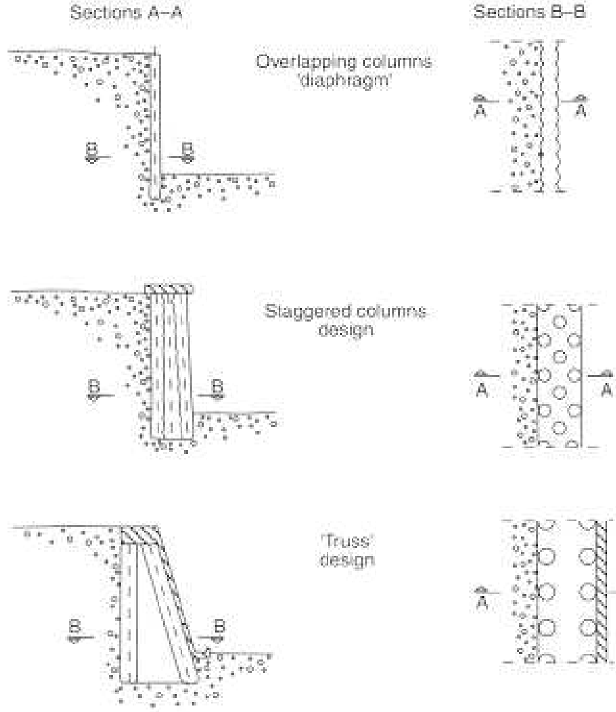


Fig. 16. Typical designs for retaining structures

Stabilization of slopes

Figure 22 shows some typical designs, *fan shaped*, *'buttresses'* (jet-grouted columns radially placed, in the plan view, around a circular arc) and last, but not least, *large diameter caissons*, which are often very efficient.

The first type of design was used for the first time at Gela in 1982, combined with near horizontal drains, to stop landslide caused by the erosion produced at the toe by groundwater seeping along the surface of an underlying impermeable layer. The combined action of drainage and jet-grouting provided an adequate safety factor to prevent

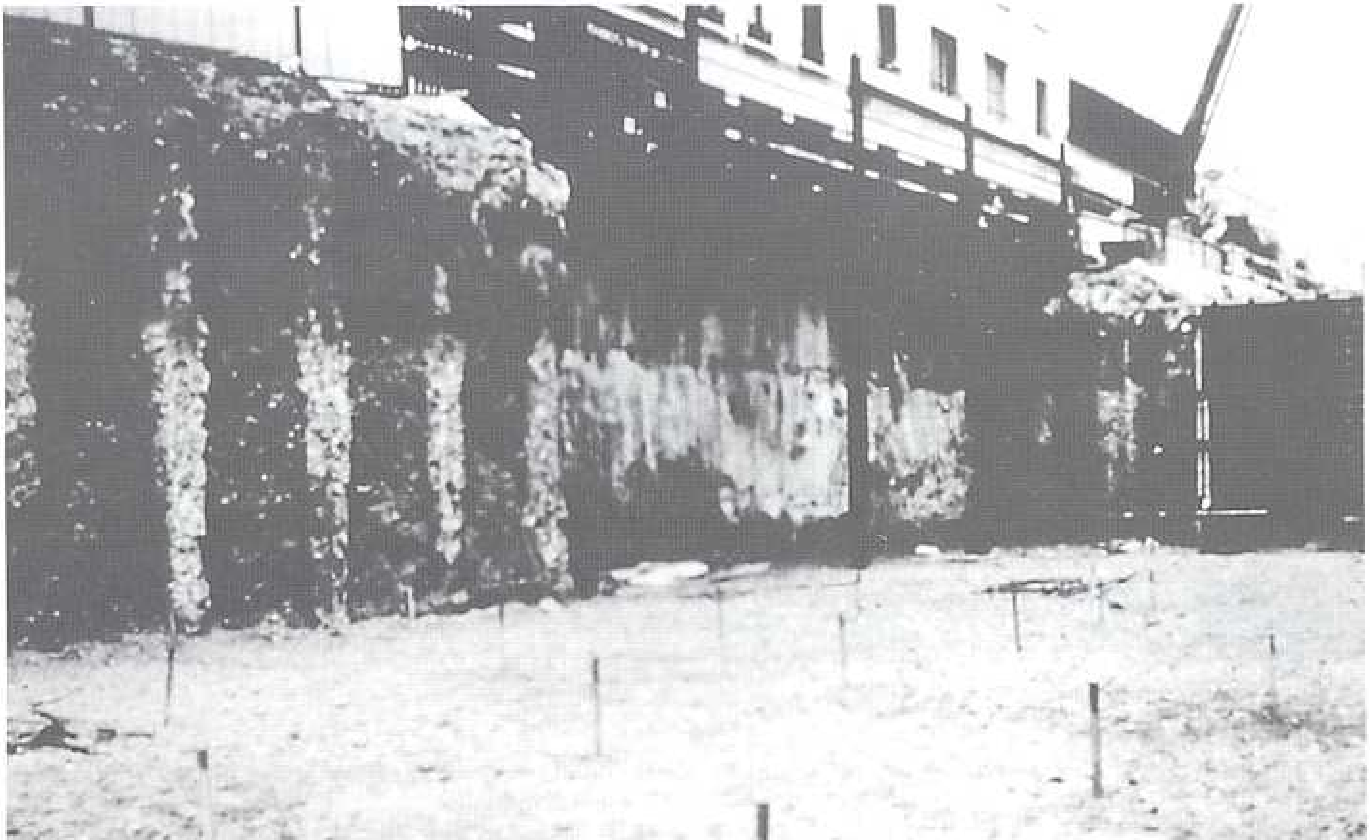


Fig. 17. Improved ground by jet-grouting for cut and cover excavations of the 'Sans Souci' station on line D of the metropolitan railway in Lyons (France)

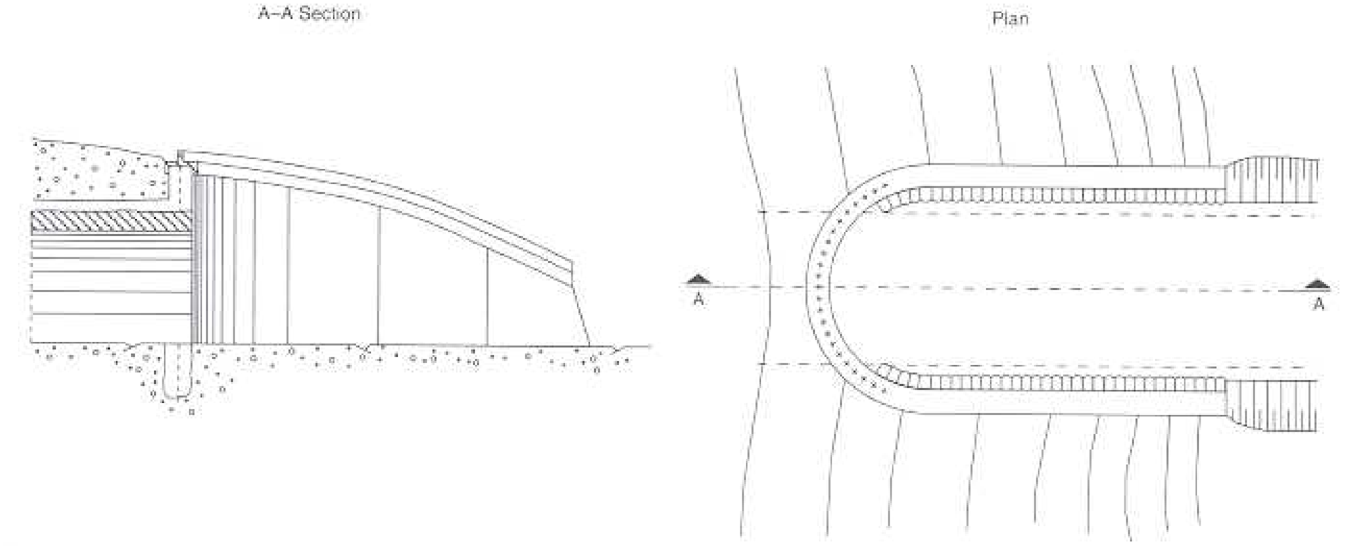


Fig. 18. Tunnel portal shell structure using jet-grouting

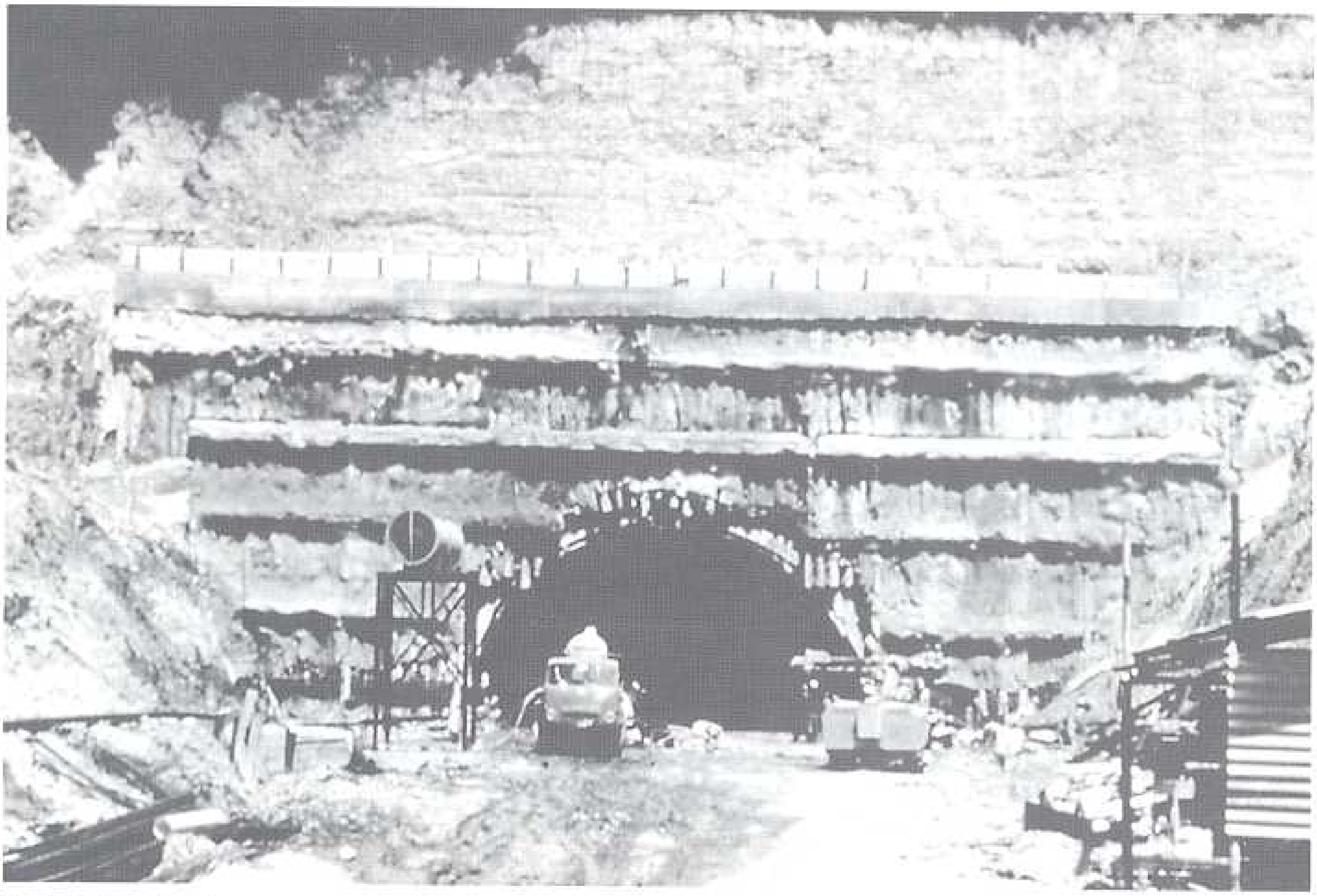


Fig. 19. Traditional portal structure

failure of the slope, which has several buildings located on the top.

The 'buttress' pattern was used in 1984 in Val Topina to stop the slide of a silty detritus layer, which occurred during the construction of a parking area beside the 'Flaminia' No. 3 state road.

Jet-grouting technology provided the following advantages:

(*a*) ground removal was not required, thus further decompression of the slope was prevented;

(*b*) it did not cause vibrations which might have triggered other landslides;

(*c*) it did not overload the slope thanks to the lightweight equipment needed to perform the job;

(*d*) it achieved complete claquage of the ground resulting in satisfactory stabilization.

Caissons have been recently used to stabilize the entrance way to the southern portal of the Mont Blanc motorway tunnel.

Fig. 20. Jet-grouting portal shell structure

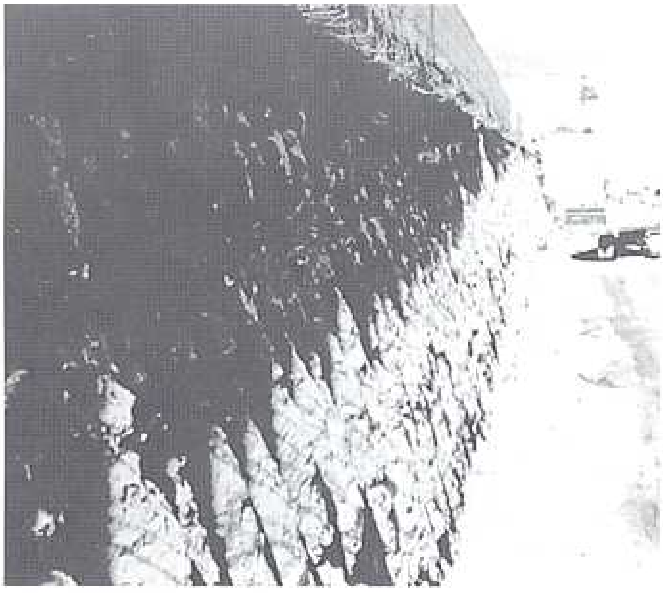


Fig. 21. Improved ground by jet-grouting for trench excavation near Naples (Italy)

Foundations and underpinning

Jet-grouting has found wide use in foundation and underpinning works. As far as foundations are concerned, two design methods are mainly used (Fig. 23).

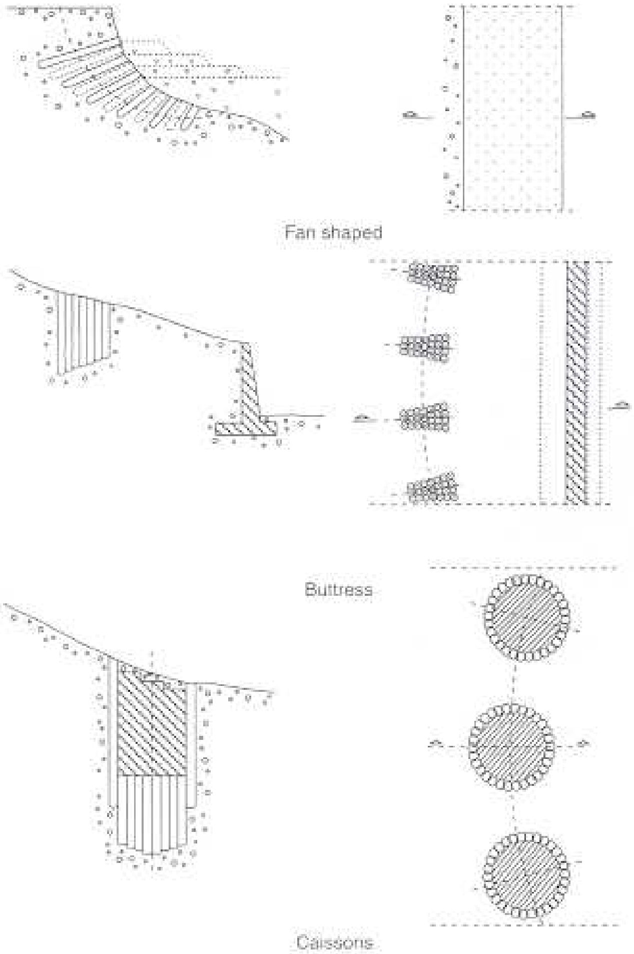


Fig. 22. Typical designs for stabilization of slopes

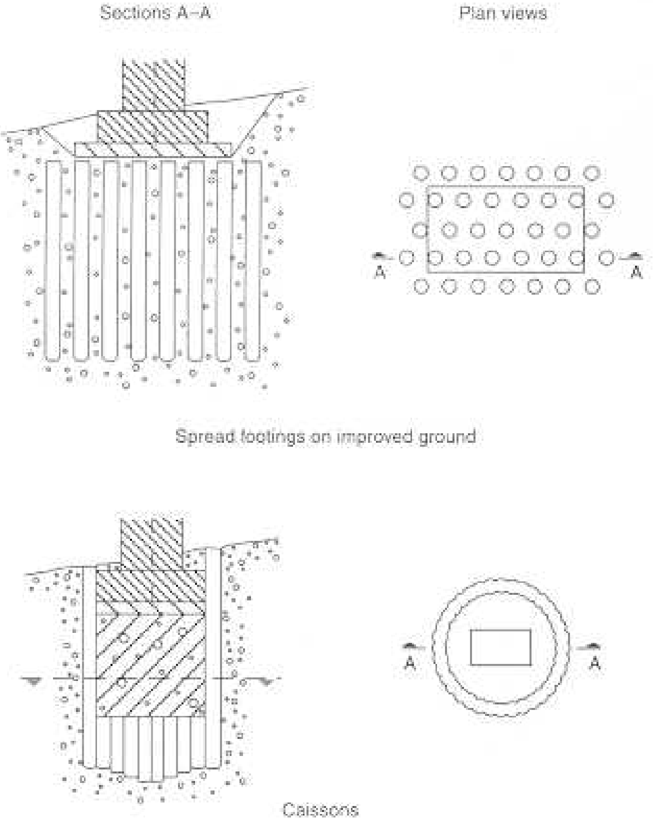


Fig. 23. Typical designs for foundation work

(1) Spread footings on improved ground: this design technique with its gradually increasing rigidity is particularly suitable in seismic areas. Foundations of this type have been used extensively for viaducts at Bardonecchia (see Fig. 24), along the Frejus highway, and in Val Topina.

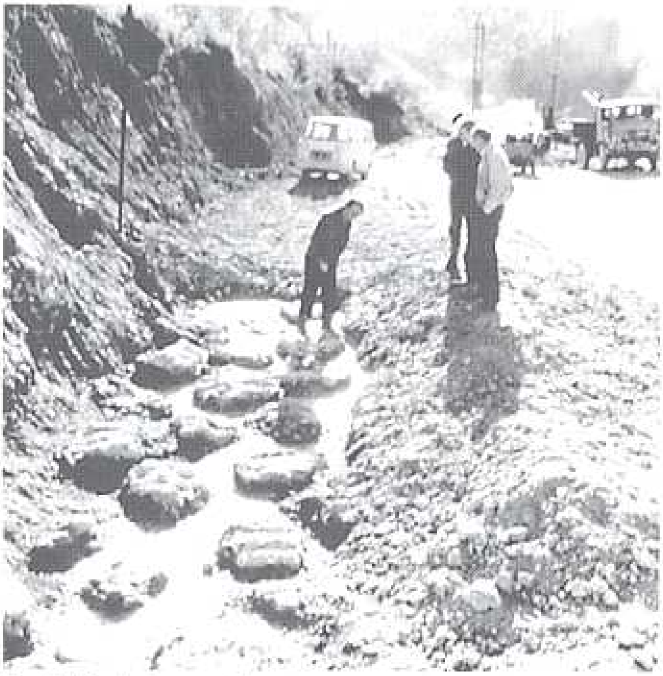


Fig. 24. Works for spread footings on improved ground at Bardonecchia (Frejus highway)

(2) Large diameter caissons: these are suitable for foundations on slopes needing stabilization or in river channels. Large diameter caisson construction is a very rapid and economical operation using jet-grouting and truly irreplaceable when working below groundwater level. It involves the construction of a continuous diaphragm of overlapping jet-grouted columns and a jet-grouted bottom plug. Inside, ground excavation is performed under dry conditions, down to the top of the bottom plug. The well is then usually filled with lean concrete up to the footing level.

Caissons under groundwater level were built using this system for the first time in Carnia (1983) for the foundations of a railway bridge over the Fella river along the Italian State Railway Udine–Tarvisio line (see Figs 25 and 26).

As far as underpinning is concerned, jet-grouting is rich in interesting case-histories. Figures 27 and 28 show the design used for the Banca del Monte in Parma (1982). In situations such as these in which it is necessary to work close to ancient stone buildings, dangerous uplift phenomena may occur if traditional injection techniques are used. With jet-grouting, however, if the radius of action of the jet is properly controlled and the operating parameters appropriately set, there is no problem even at a short distance from footings, despite the high grout pressures used.

Another use for foundations is shown in Fig. 29, a particular application which has found a powerful construction method in jet-grouting: the repair of foundations in river channels.

The repair operation on the foundations of the State Railway bridge over the Taro river, damaged in November

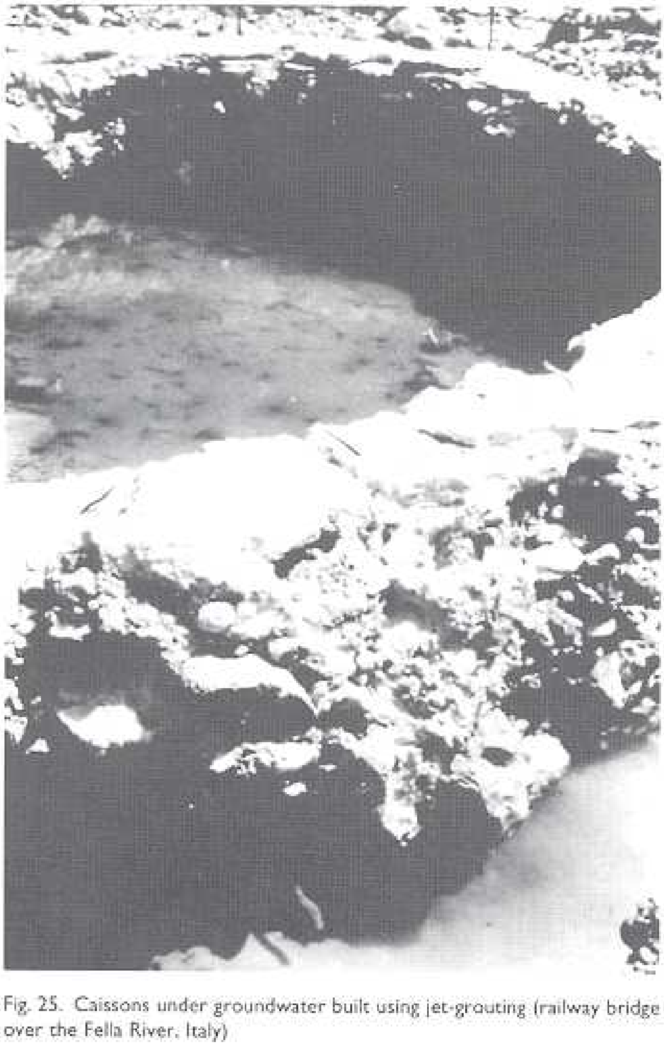


Fig. 25. Caissons under groundwater built using jet-grouting (railway bridge over the Fella River, Italy)

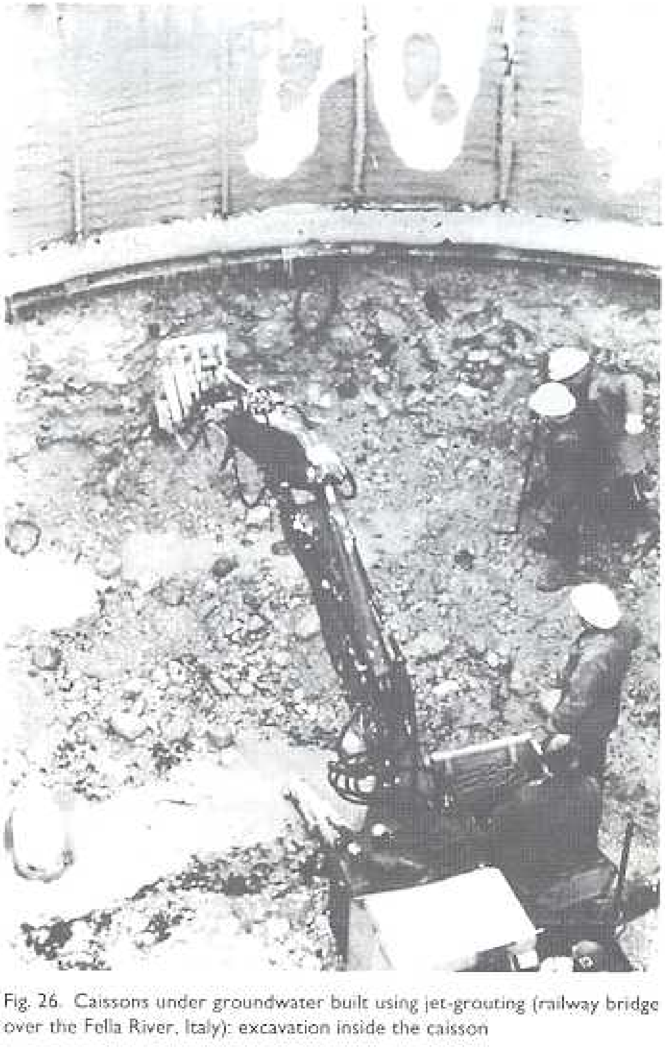


Fig. 26. Caissons under groundwater built using jet-grouting (railway bridge over the Fella River, Italy): excavation inside the caisson

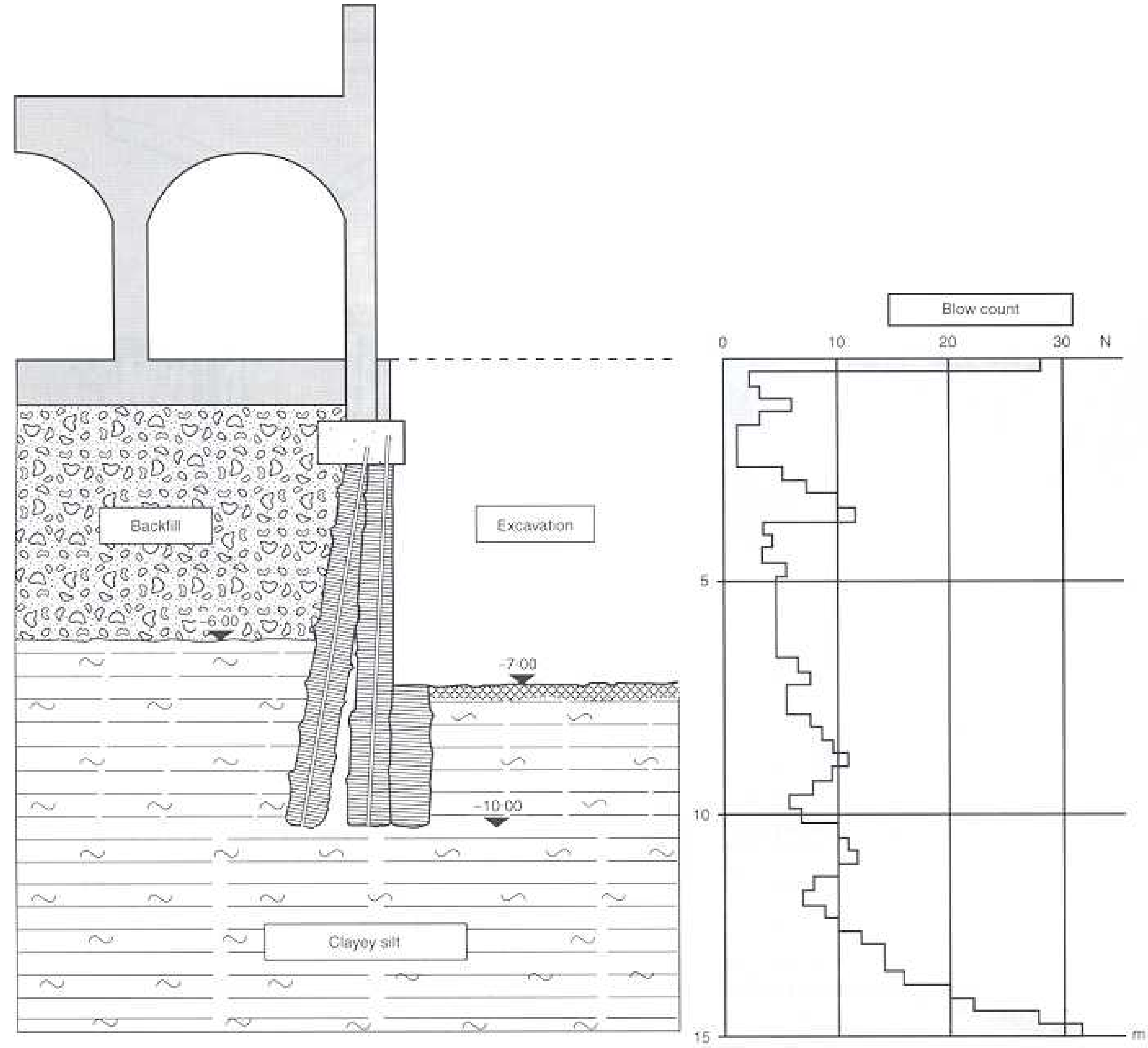


Fig. 27. Design used for underpinning work for the Banca del Monte in Parma (see Fig. 28)

1982 by exceptional flooding which caused the partial collapse of the bridge itself, is of importance here because of the time in which the repair had to be completed (Fig. 30). The designed ground improvement work was two-fold and consisted of (see Fig. 29):

(1) Creation of a continuous protective belt of jet-grouted columns around the foundations of each pier, of sufficient thickness and depth to guarantee its primary function of combating the undermining action of the water running in the river channel and sub-channel, and to strongly limit lateral decompression of the foundation ground so as to help conserve its load-bearing capacity.

(2) Ground improvement using traditional low pressure grouting, inside the protective belt, to reduce permeability and increase strength.

Tunnels

Jet-grouting has played a fundamental role in the progress that has been achieved over the last ten years in tunnel construction. Horizontal jet-grouting in particular made it possible to overcome all the difficulties connected with excavation in cohesionless soils. In this case also a statics design that is congruent with the features of the treated ground was fundamental, namely, a design in which the material is mainly subjected to compressive and shear stresses. This is the famous 'umbrella' treatment which, by penetrating beyond the face of a tunnel, develops arching in the ground ahead of the excavation.

The first full-scale application of this technique, which was developed by the author in 1983, was during the construction of the 'Campiolo' railway tunnel. Figure 31 shows the method employed. The continuity of the treated ground around the tunnel is very important. For this purpose, the excavation is performed in two stages. It is necessary to jet-grout a series of near vertical columns to transfer the stresses channelled by the arch of the treated-ground down into the ground before the excavation is lowered down to the invert. Experience has shown that making sure that there is good stress transfer from the arch of treated-ground to the untreated ground has an outstanding effect on convergence control. As a result the method

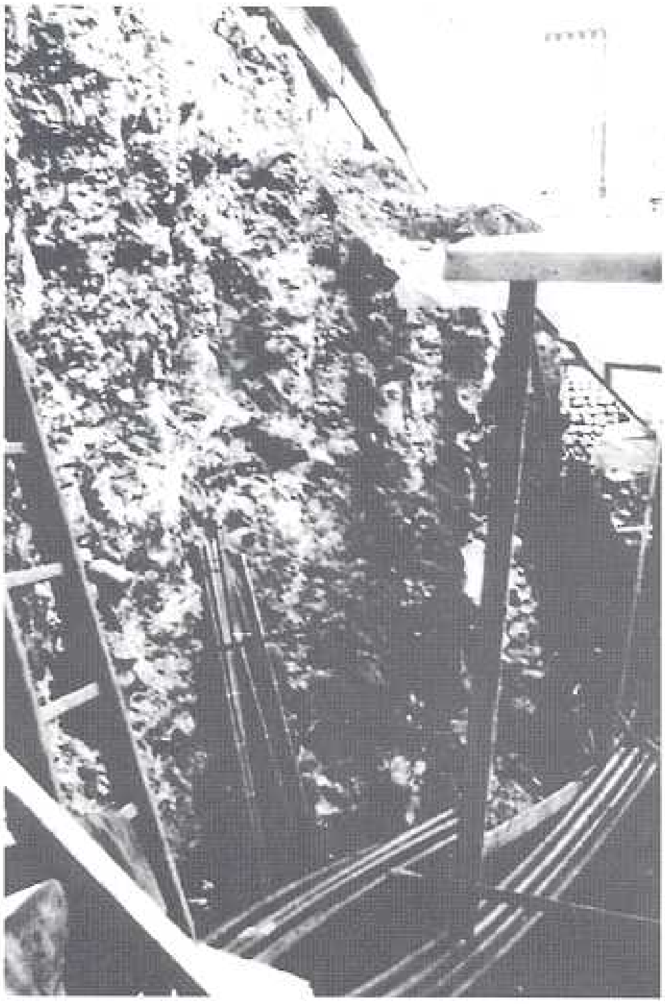


Fig. 28. Underpinning works for the Banca del Monte in Parma (Italy)

adopted for the 'Campiolo' tunnel was subsequently modified to intensify improvement of the lower half of the cross-section, under the ribs.

The use of horizontal coupled with vertical jet-grouting technology to create shell structures at portals has resulted in work being carried out with success under extremely difficult conditions, without causing appreciable deformation in the surrounding ground. An example is shown in Fig. 32. The underpass was built without interrupting rail traffic in Campinas (Brazil), although there was only a 2 metre overburden above the crown.

Figure 33 shows an application of jet-grouting carried out in Rome for the construction of a highway underpass. Jet-grouting was used to stabilize the face by horizontal treatment of the core of ground ahead of it.

Hydraulic work

As far as hydraulic work is concerned, jet-grouting has been mainly used in waterproofing dam foundations and in protecting levées (see Fig. 34). At Ravedis, for example, waterproofing of coarse alluvial deposits below the cofferdam was performed by building a diaphragm consisting of two rows of overlapping jet-grouted columns extending down to the impervious bedrock. The ground between the two rows of columns was then treated by low-pressure grouting.

Another interesting example of waterproofing dam foundations using jet-grouting was performed in Brombach (Germany). The interesting thing here is that, for the first time, it was done in rock, sandstone in this case. A bifluid jet-grouting system was used to make a series of angled intersecting cuts, more than a metre long, in the rock. They were filled with cement grout containing admixtures to reduce permeability (see Figs 35 and 36).

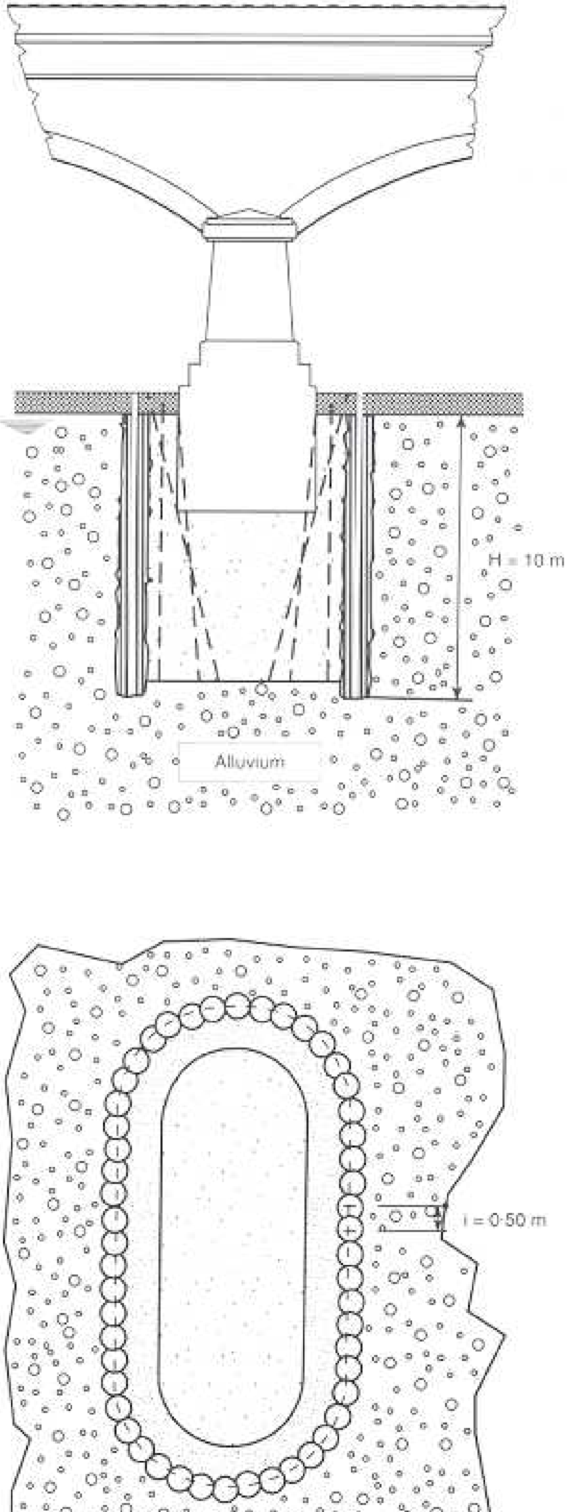


Fig. 29. Design used for repairing the foundations of the Taro River railway bridge

As far as dikes are concerned, it is interesting to look at a particular piece of work executed in 1987 to plug a 300 m stretch of dike destroyed by flooding on the Adda river, near Talamona. Makeshift repair under emergency condi-

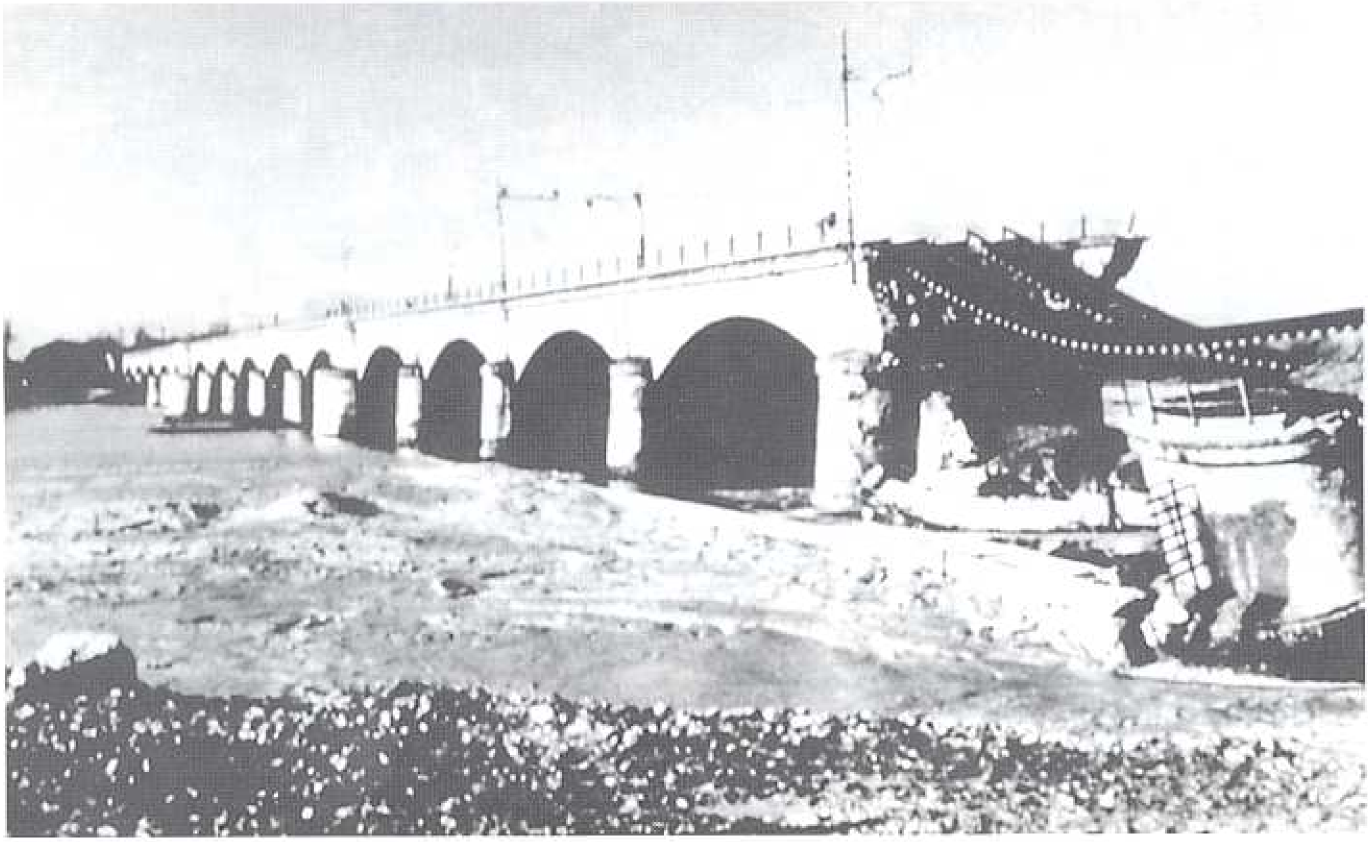
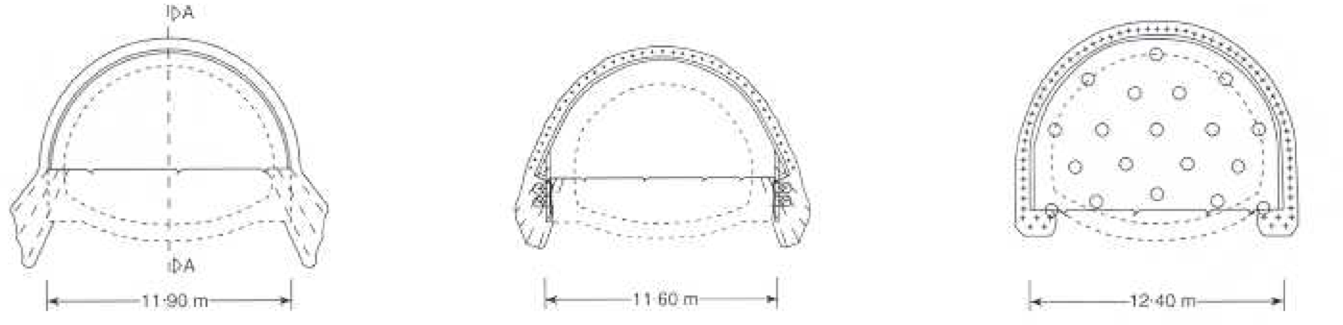


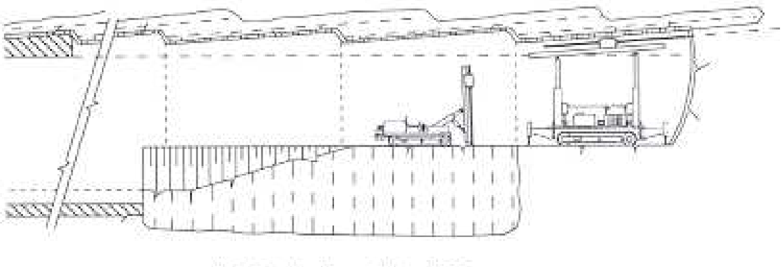
Fig. 30. Railway bridge over the Taro River (Italy) that collapsed due to the exceptional flooding in November 1982



'Campiolo' – 1983

'Costa Volpino' – 1989

'Cristoforo Colombo' – 1990



A–A Section 'Campiolo' – 1983

Fig. 31. Development of designs for 'umbrella' treatment in tunnelling

Fig. 32. Underpass built in sand without interrupting rail traffic in Campinas (Brazil) using near-horizontal jet-grouting techniques

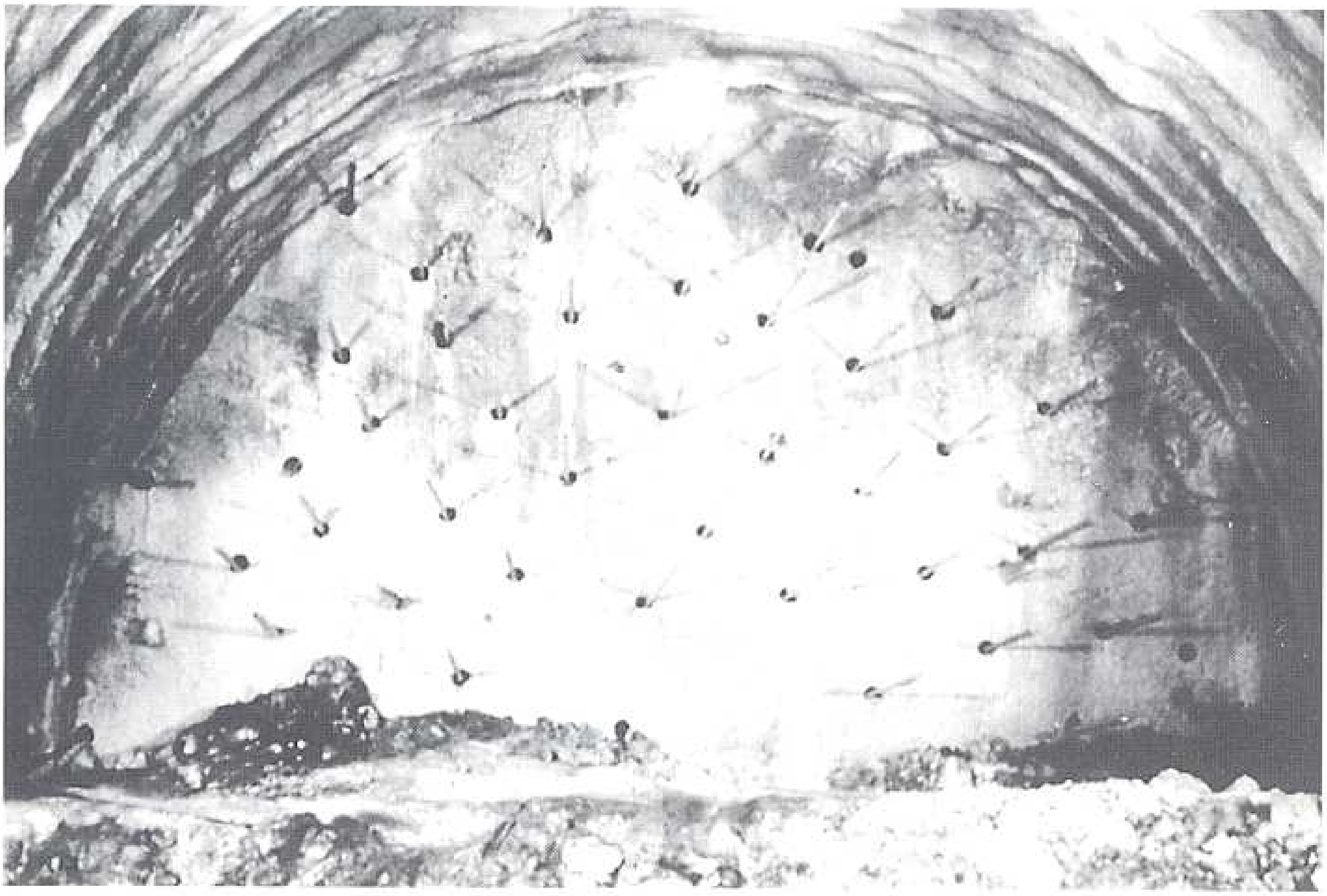


Fig. 33. Jet-grouting used to stabilize the face of a tunnel in Rome

tions had been done with large stone blocks which did not provide sufficient impermeability. It was quickly reconstituted using explosives and jet-grouting (see Figs 37 and 38): the first stage involved reducing the permeability of the embankment by crushing the boulders in it to reduce the voids ratio. This was done by blasting calibrated explosive charges placed inside the dike body; the second stage involved creating a diaphragm of jet-grouted columns in the crushed stone zone for permanent waterproofing of the dike.

Conclusions

Following a description of jet-grouting technology some typical examples have been given of its application to a number of civil engineering problems. It is certainly still a relatively young technique and consequently has not yet been fully developed.

Results obtained in this first decade of application have, however, been very encouraging and constitute the best incentive for continuing research and experimentation.

Acknowledgements

The author would like to express his thanks to Rocksoil S.p.A., Rodio S.p.A., Presspali S.p.A. of Milan and Fondazioni Speciali S.r.l. of Parma for their co-operation.

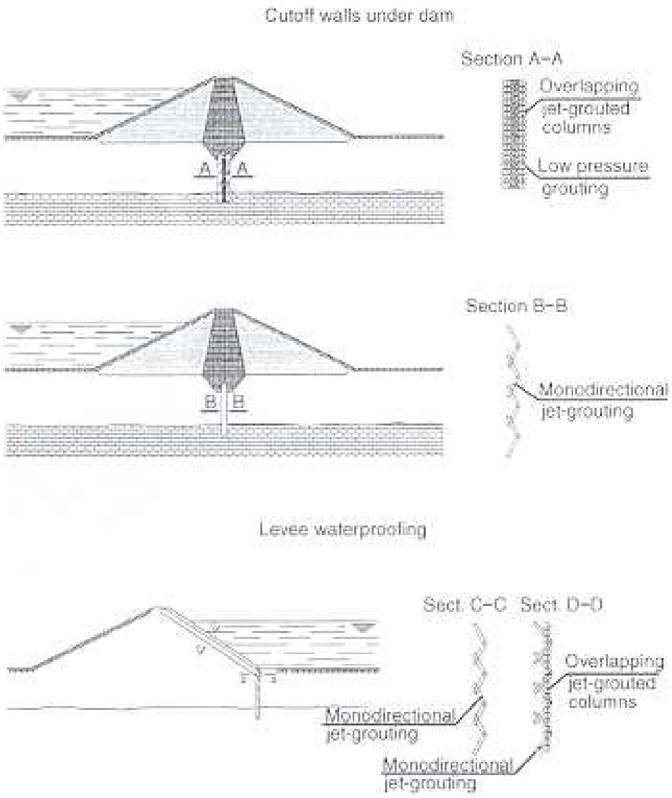


Fig. 34. Typical designs for hydraulic work

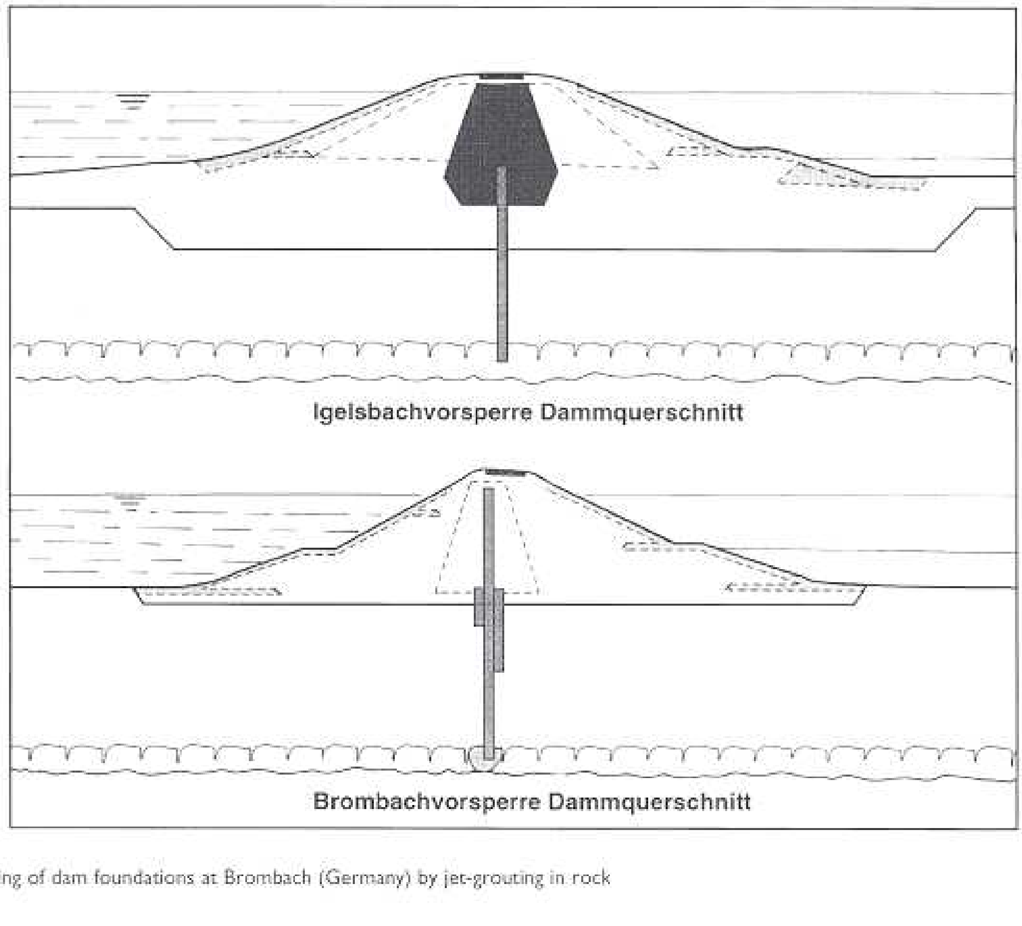


Fig. 35. Waterproofing of dam foundations at Brombach (Germany) by jet-grouting in rock

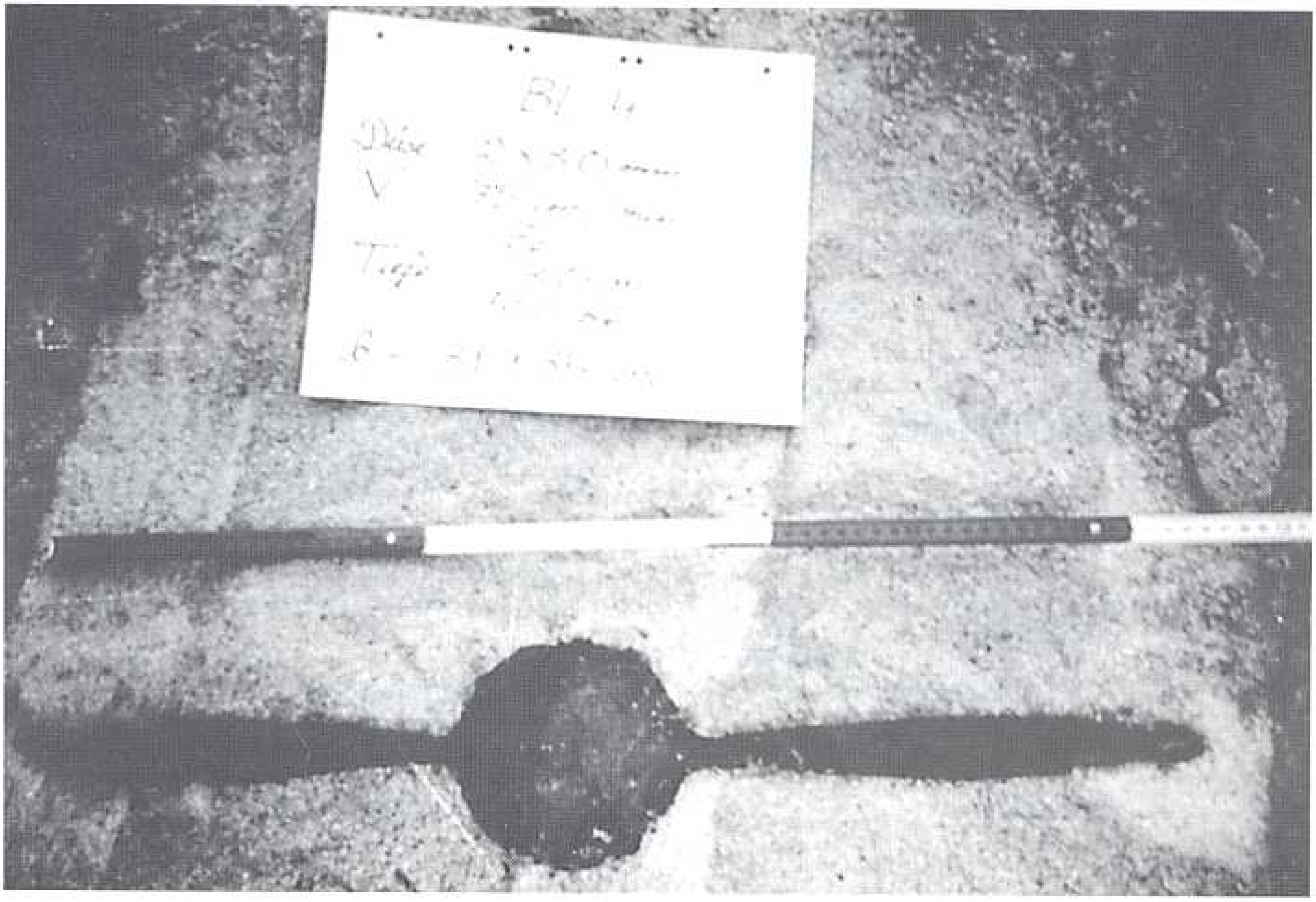


Fig. 36. Jet-grouting in rock: result of a test carried out at Brombach (Germany)

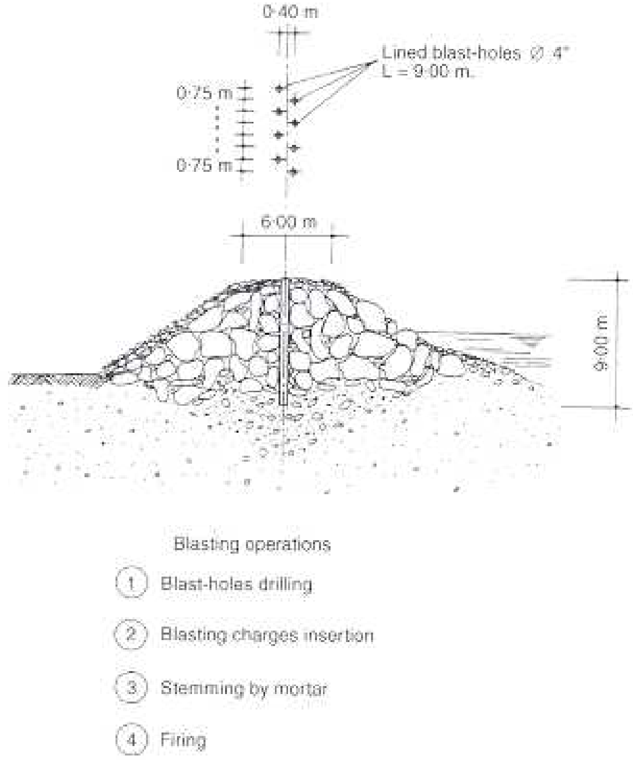


Fig. 37. Waterproofing work of a large stone block dike: blasting operations

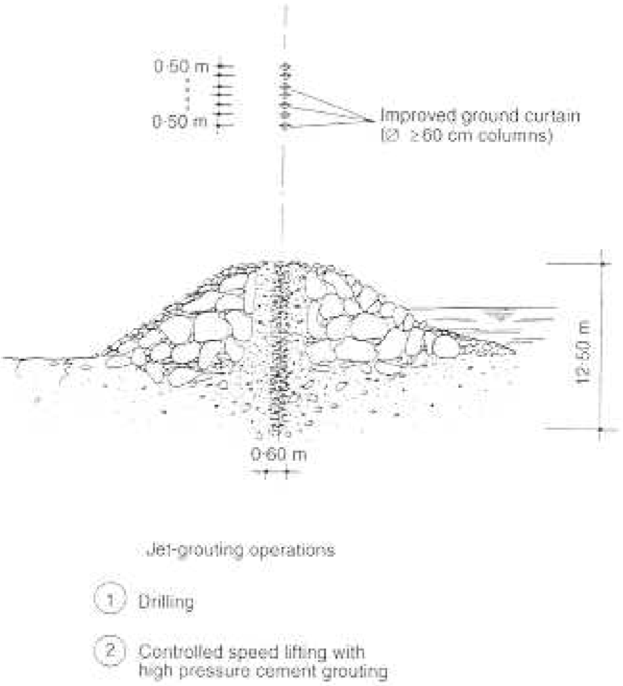


Fig 38. Waterproofing work of a large stone block dike: jet-grouting operations

Bibliography

Biagi G., Lunardi P. and Pellegrini V. (1991) L'applicazione del sistema jet-grouting nel progetto e nella costruzione delle gallerie dell'autostrada Livorno-Civitavecchia. *International Meeting on Soil and Rock Improvement in Underground Works*. Milan.

Bonasso R., Ricci P., Lunardi P. and Focaracci A. (1991) L'impiego del jet-grouting per lo scavo di una galleria urbana a debole profondità. *International Meeting on Soil and Rock Improvement in Underground Works*. Milan.

Camargo Guazzelli J. L. and Lunardi P. (1988) Tunel de Campinas: evolucion del diseno y problemas de operacion. *International Congress on Tunnels and Water*. Madrid.

Colombo A., Lunardi P., Pizzarotti E. M. and Tesserin G. D. (1991) Preconsolidamento del terreno mediante jet-grouting nel sottopasso della Tangenziale Est di Milano da parte della Linea 3 della metropolitana. *International Meeting on Soil and Rock Improvement in Underground Works*. Milan.

Focacci C., Lunardi P., Pizzarotti E. M. and Zambon F. (1991) Il preconsolidamento del terreno a mezzo di iniezioni jet-grouting per la galleria a tre binari "Tarvisio" della Linea F. S. Udine-Tarvisio. *International Meeting on Soil and Rock Improvement in Underground Works*. Milan.

Golinelli G., Lunardi P. and Perelli Cippo A. (1991) La prima applicazione del jet-grouting in orizzontale come precontenimento delle scavo di gallerie in terreni incoerenti. *International Meeting on Soil and Rock Improvement in Underground Works*. Milan.

Louis C. and Lunardi P. (1984) Consolidation des sols par la technique de jet-grouting. Etat des connaissances et experiences. *Colloque International Renforcement en Place des Sols des Roches*. Paris.

Lunardi P. (1982) Nouvelle méthode de construction des écrans d'étanchéité dans les barrages en remblai. *XIV International Congress on Large Dams*. Rio de Janeiro.

Lunardi P. (1983) La piena del fiume Taro del novembre 1982. Danni, ripristino provvisorio, ricostruzione definitiva del ponte ferroviario distrutto dalla piena. *II Convegno di Idraulica Padana*. Parma.

Lunardi P. (1991) L'impiego del jet-grouting per l'attacco di gallerie in terreni soffici. *International Meeting on Soil and Rock Improvement in Underground Works*. Milan.

Lunardi P., Bindi R. and Focaracci A. (1989) Nouvelles orientations pour le project et la construction des tunnels dans des terrains meubles. Etudes et experiences sur le preconfinement de la cavite et la preconsolidation du noyau au front. *Colloque International 'Tunnels et Micro-tunnels en Terrain Meuble'*. Paris.

Lunardi P. and Louis C. (1984) Méthodes de présoutènement et pré-étanchement pour les travaux en souterrain. *Journées d'Etudes Internationales*. Lyon.

Lunardi P., Mongilardi E. and Tornaghi R. (1986) Il preconsolidamento mediante jet-grouting nella realizzazione di opere in sotterraneo. *International Congress on 'Large Underground Openings'*. Florence.

Lunardi P. and Pizzarotti E. M. (1990) Soft ground tunnelling in the Milan Metro and Milan Railway Link. *Case histories, Soft Ground Tunnelling Course*. Institution of Civil Engineers, London.

Discussion contributions on this paper should reach the editor by 26 September 1997