MICROPILES:
a "multipurpose" technology in foundation engineering

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1 Introduction

The use of Micropiles in foundation engineering field has largely expanded due to different reasons,such as: the versatility of such technology, the possibility of using small equipment,the minimum disturbance caused to the soil and the existing structures.
In general micropiles are described as:
"Structural elements which can be used for deep and underpinning foundations, soil consolidation; supporting wall for deep excavation, tunnel construction".
In general micropiles diameters range between 100 and 300 mm, while the maximum length may be up to 30÷35 meters or more.
As a function of grouting procedure, Micropiles can be divided in:

a Gravity back-filling
b High pressure grouting

Gravity back-filling micropiles are performed by reproducing the large diameter bored piles technique; therefore their working bearing capacity is largely lower in respect of high pressure injected micropiles. The high pressure grouted micropiles, as reported hereinafter, can be designed for very high load bearing capacity.
In this paper, after a brief description of micropiles characteristics, construction methods, apparatus and equipment, some consideration about the design criteria adopted in Italy for "high pressure grouted micropiles" and based on the French experience in this field, with particular reference to Bustamante-Doix will be reported.
Finally, together with a description of typical micropiles applications for foundations and tunnel projects, some case histories will be reported.

2 Construction methods

Three phases have to be generally assumed for micropiles construction: hole drilling, steel reinforcement placing and grouting.

2.1 Drilling

Small diameter drilling techniques are used for micropiles hole drilling.
The consequent main advantages, deriving by these techniques, are the possible use in a wide range of soils and rock conditions, the capability to overpass pre-existing foundations and obstructions, boulders, rocky layers and finally the use of light weigh and small drilling rigs.
Drilling is performed, according to the nature of the soil, by rotation or roto-percussion systems.
In the rotation system, the energy is transmitted to the drill bit by means of a drilling rod which is rotated and driven into the soil. Uncased rotation system is used whenever it is not necessary to support the hole walls or when the drilling fluid (water, bentonite or polymer mud) is capable of providing this support. Cased rotation system (eventually performed with two different rotaries sliding on the same mast) is used when a casing is necessary to support the hole walls.
Roto-percussion systems can be subdivided in Down The Hole Roto-Percussion system and Top-Hammer Roto-Percussion system.
By adopting D.T.H roto-percussion system the percussion energy is trasmitted to the bottom of the hole by a special air-hammer mounted at the base of the drilling rod, while the rotation and thrust forces are supplied by a rotary mounted on a cradle sliding on the rig mast. The compressed air,

operating the hammer, is fed through the hollow drilling rods.
By adopting Top-Hammer Roto-Percussion System, an hydraulic hammer, sliding on the rig mast and driving the drilling rod, generates combined rotation and percussion forces.
In both cases cased or uncased drilling system can be performed.
In table 1 standard borehole diameter and depth are listed
The applicable drilling systems versus soil type are reported in table 2, while in table 3 a rock classification chart (Tab 3.a) and the related applicable systems (Tab 3.b) are reported.

Tab. I

Drilling System	Standard Borehole Diam. (mm)	Maximum Depth. (m)
Top-Hammer	50 - 250	25 - 30
Rotation	70 - 300	50 - 70
D.T.H.	80 - 230	60 - 150

Tab. 2

Drilling System	Clay	Silt	Sand			Gravel	Peebles	Blocks
			Fine	Medium	Coarse	Fine Medium		
Top-Hammer	■	■	■	■				
Rotation			■	■	■			
D.T.H.					■	■	■	■

Tab. 3a

Rocks Classification		Types of Rocks	Average U.C.S. MPa
1	SOFT	Coal - Chalk - Marl - Fractured - Sandstone	2 - 50
2	MEDIUM	Tuff - Slayte - Dolomite - Limestone - Sandstone- Riolite	10 - 100
3	HARD	Limestone - Sandstone- Riolite	50 - 200
4	VERY HARD	Basalt - Diorite - Gneiss - Granite - Conglomerate	> 200

Tab. 3b

Drilling Method	Rock Classification 1	2	3	4
Rotation (Drag Bit)	■	■		
Rotation (Tricone Bit)	■	■	■	
Rotation (Diamond Bit)	■	■	■	■
Roto Percussion	■	■	■	■

2.2 Steel reinforcement

For gravity back-filling micropiles a steel pipe or a standard pre-assembled cage (longitudinal main bars plus stirrup) can be used as steel reinforcement.
For high pressure grouted micropiles a hollow pipe, equipped with proper non - return valves is adopted. Valves are located in the deepest section of the pipe; in general 2 or 3 valves per meter are adopted.

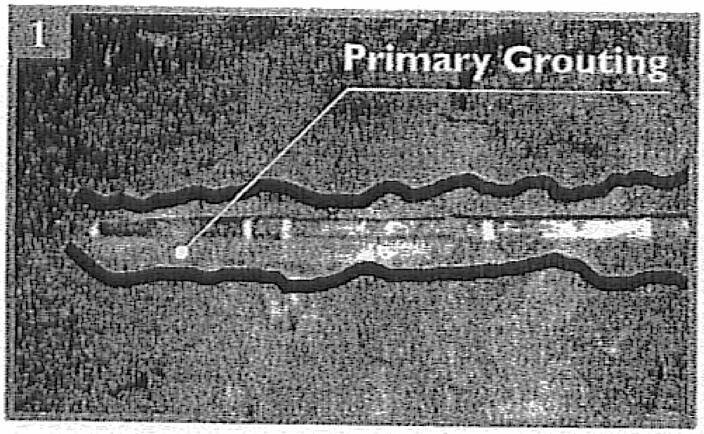
2.3 Grouting

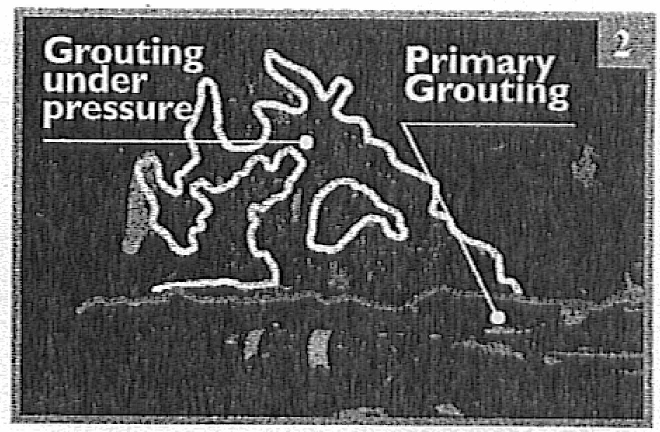
Grouting for gravity back-filling micropiles is performed adopting the same "contractor" system used for bored piles. A proper grouting pipe is lowered to the hole bottom and mixture is pumped until it flows out at the surface. The same steel reinforcement pipe can be used as grouting pipe.

For high pressure grouted micropiles, grouting is performed in two stages:

Sheath Grouting
A cement based grout is pumped from the bottom to fill the anulus between the hole wall and the outer surface of the steel pipe. This operation is performed to prevent the escape to the surface of the grout during the second grouting stage that is performed under pressure.

Bond Grouting
A cement based grout is injected through the non-return valves by using a double-packer lowered into the hollow pipe and positioned in such a way to isolate each single valve. Grout under pressure breaks the sheath grout and enter the soil. Grouting pressure range between 2 and 3 MPa, with a starting peack of about 6 MPa, necessary to crack the sheath.
The valves are grouted in continuous sequence starting from the deepest one, and proceeding upwards. Once all the valves have been injected, the inner pipe is washed in order to allow further grouting operations if necessary. In general the injection of each valve is stopped when the required designed maximum grouting pressure and/or preset grout volume have been reached.
At the end of the grouting operations the pipe is filled with grout.
Such technique is similar to the one which has already been used for several years to perform cohesionless soil consolidation, where grout is injected, throughout pvc pipes equipped with non-return valves, to fill the voids of the soil. In case of micropiles, grout is used to create a sort of "bulb" around the pipe, that allow to transfer loads to the soil itself.
In figures 1 and 2 an example of sheath grout around a pvc pipe and of high pressure injected grout through a valve is shown to give an idea of the result of such both operations.

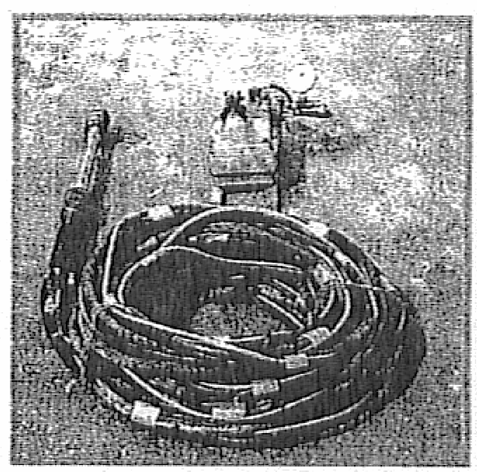




Standard grout composition and related phisical parameters are reported in table 4, together with a typical double packer used.

Tab. 4

Standard Grout Composition		
Cement	kg	750 - 1200
Water	lt	600 - 750
Admixtures	kg	0 - 14
Standard Grout Parameters		
Density	gr/cc	1,5 - 1,8
Marsh Viscosity	sec.	30 - 55
Bleeding	%	< 5
UCS (28 days aging)	MPa according to cement quantity	30 - 45



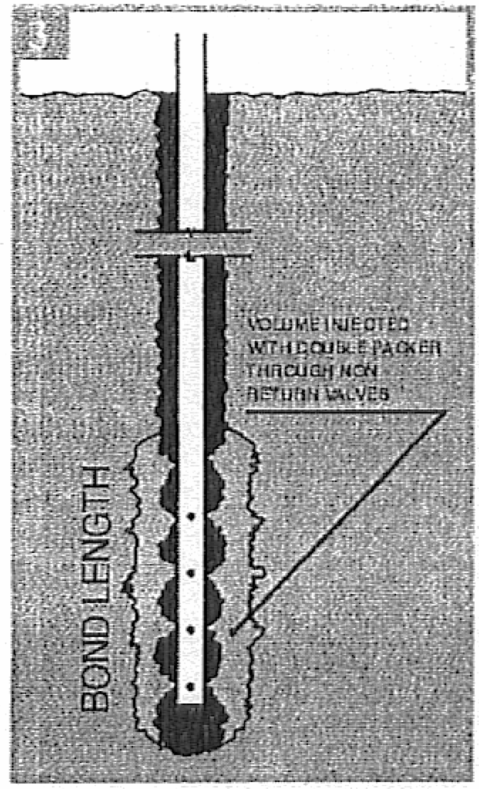
3 Design Criteria

Gravity back-filling micropiles are performed by reproducing the large diameter bored piles technique; therefore the load bearing capacity has to be evaluated by adopting the same criteria used for bored piles.
The total length of the micropile will therefore be considered, by computing the related shear strength strata by strata.

High pressure grouted micropiles are designed by considering only the bearing strata, i.e. the level where the "bond length" is injected.
The design method for high pressure grouted micropiles (in one or repeated stages) mainly refers to the french experience, in particular to the paper of Bustamante-Doix:
" *Une methode pour le calcul des tirantes et des micropieux injectes*", Bull. Liason P. et Ch. n. 140 nov-dec. 1985

Micropiles are assumed to be formed by a free length "L_f" where no load is transferred to the soil, and a bond length (or fixed length), that is the bulb "L_c" where the load transfer mechanism develops.
In this section, because of the performed grouting throughout the valves, the grouted borehole is enlarged via hydrofracturing of the grout mass to give a grout root or fissure system beyond the core diameter of the borehole (fig. 3).

The design is generally based on the assumption of uniform shear along the fixed length.



The ultimate bearing capacity of micropiles "Q_u" given by lateral friction on bond length can be estimated as follow:

$$Q_u = \pi \times D_b \times L_c \times q_a$$

$$D_b = \alpha \times D_p$$

in which:

D_b = *average effective diameter of the bulb*

L_c = *bond length*

q_a = *limit adhesion bulb – soil*

D_p = *Drilling diameter*

α = *non – dimensional coefficient depending on soil nature, injection method and volume of injected grout.*

In table 5 the non-dimensional coefficient " α " values are related to soil type and grouting method. The same table the minimum volumes of grout to be injected are given.

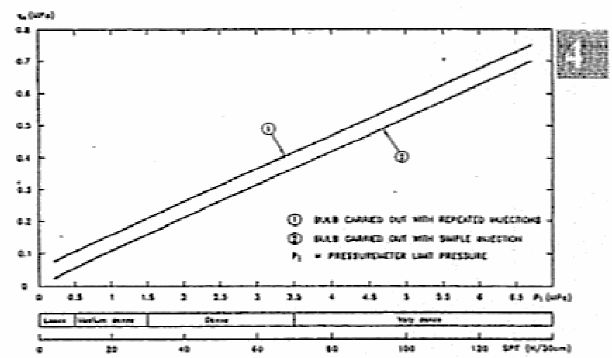
Tab.5

SOIL NATURE	α COEFFICENT Repeated Grout.	α COEFFICENT Simple Grout.	Minimum Quantity of Grout	
Gravel	1,8	1,3÷ 1,4	1,5 Vp	
Sandy Gravel	1,6 ÷ 1,8	1,2 ÷ 1,4	1,5 Vp	
Gravelly sand	1,5 ÷ 1,6	1,2 ÷ 1,3	1,5 Vp	
Sand (rough to fine)	1,4 ÷ 1,5	1,1 ÷ 1,2	1,5 Vp	
Silty Sand	1,4 ÷ 1,5	1,1 ÷ 1,2	1,5 Vp ÷ 2,0 Vp 1,5 Vp	for repeated grouting for simple grouting
Silty sand	1,4 ÷ 1,6	1,1 ÷ 1,2	2,0 Vp 1,5 Vp	for repeated grouting for simple grouting
Clay	1,8 ÷ 2,0	1,2	2,5 Vp ÷ 3,0 Vp 1,5 Vp ÷ 2,0 Vp	for repeated grouting for simple grouting
Marl,Calcareous marl, Weathered or Fractured, Sandstone	1,8	1,1 ÷ 1,2	1,5 Vp ÷ 2,0 Vp 1,5 Vp ÷ 6,0 Vp	for repeated grouting for simple grouting
Weathered or Fractured Rock	1,2	1,1	1,1 Vp ÷ 1,5 Vp ≥ 2 Vp	for low fessured rock for fractured rock

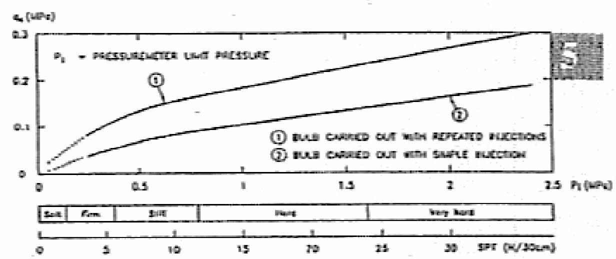
Vp = drilling volume. (The presence of steel pipe is disregarded in the estimation of the volume)

Values of limit adhesion bulb-soil "q_a" can be obtained from the diagrams reported in figure 5-8 respectively for:

sand and gravel	**(fig.4)**
clay and silt	**(fig.5)**
marl and weathered or fractured sandstone	**(fig.6)**
weathered or fractured rock	**(fig.7)**



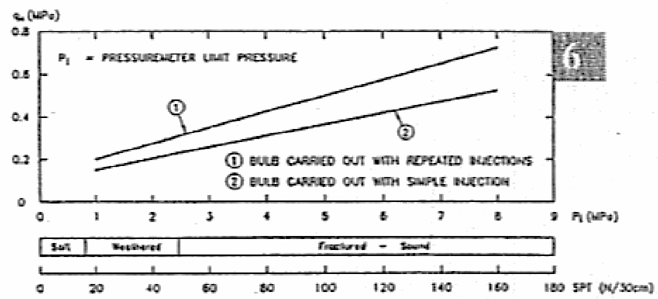
In each diagram, the curve ① refers to repeated grouting operations, while the curve ② deals with micropile performed through a simple grouting operation.



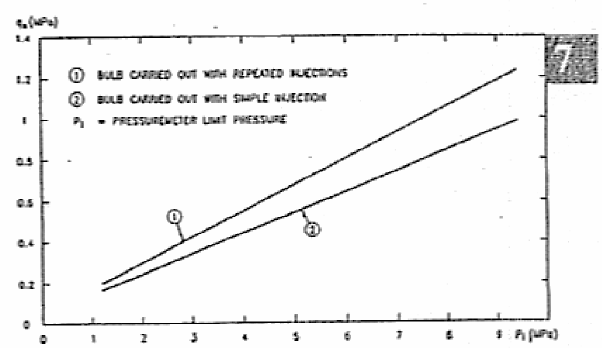
In case of stratified soil layers the ultimate bearing capacity of micropiles can be estimated by summing up the
contribution of different soils according to the following relation:

$$Q_u = \pi \times \sum_i \left(D_{bi} \times L_{ci} \times q_{ai}\right)$$

$$D_{bi} = \alpha_i \times D_p$$



Symbols meaning is the same as above, while "i" index shows that the value is estimated with reference to the i-stratum crossed by the bulb.
This last formula must be used with particular care in cases of stratified soils showing very sharp variations in stress-strain behaviour. The contribution to the ultimate capacity given by strata with very low shear strength in comparison to the adjacent one have to be disregarded. in general the bond length "Lc" should not be less than 4 m, and the "qa" values reported in the figures 5-8 may be used if the bulb is at least 5 m below the ground level.



With reference to the design method illustrated above, the use of the reccomanded safety factors to evaluate the working loads relating to use and load type are reported in table 6.

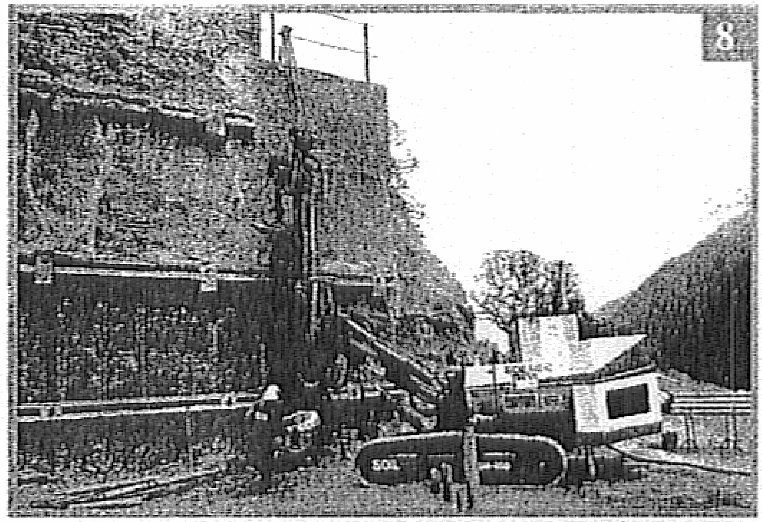
Tab .6

MICROPILE USE	SAFETY FACTOR	
	Tension Load	Compression Load
Temporary	2.0	1.8
Permanent	2.2	2.0

4 Applications

As stated before, micropiles can be adopted in many projects where foundations elements have to be executed with small drilling rigs or when soil type force to adopt drilling technologies like roto-percussion. In general the following application can be listed:

a) **Retaining walls (diaphragm walls)**
Micropiles can be succesfully adopted to support excavation mainly in presence of coarse material with presence of blocks or boulders, i.e. where the standard concrete diaphram walls can not be easily executed.



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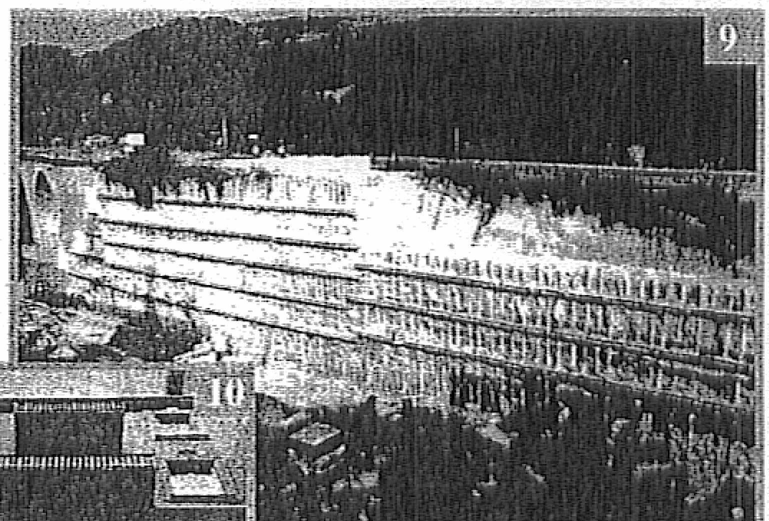

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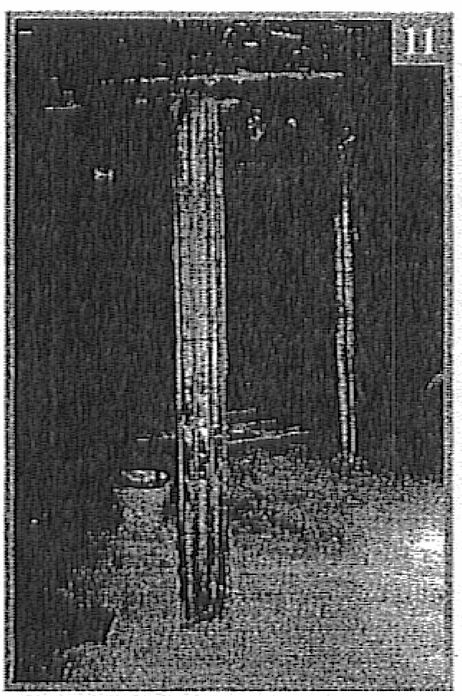
In these situation, being the main stresses a combination of bending moment and shear stress, the gravity backfilling micropiles can be adopted. During the soil excavation, anchors have to be installed to reduce the bending moment along the wall (Figg. 8 and 9). For the construction of underground car park under and nearby existing building, micropiles can be used as retaining wall in combination with slabs, cast during the soil excavation (top-down system), that works as struts (fig. 10).



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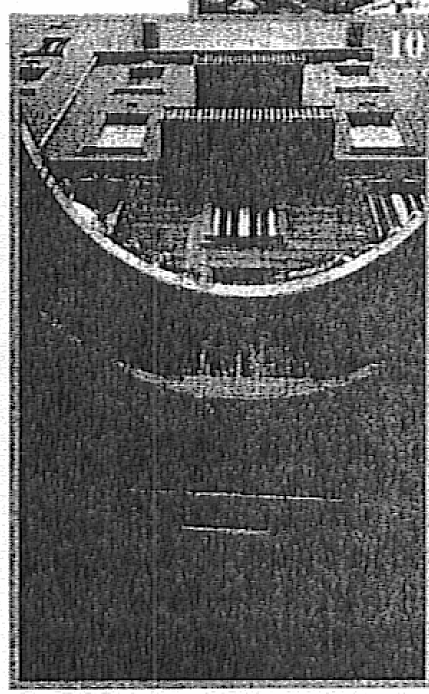

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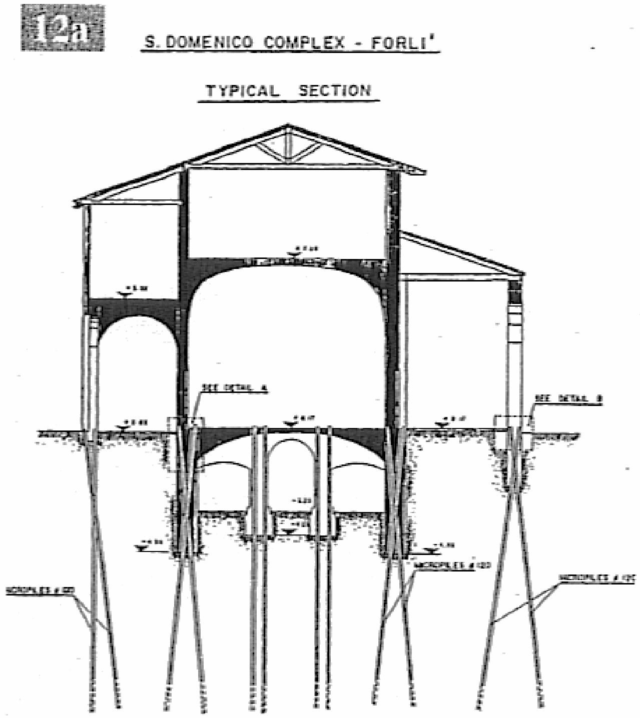
In this case micropiles have also been used as supporting pillar for the slabs; their have been performed from the surface and, during the soil excavation a steel reinforcement has been add to increase the cross section of the pillar itself (Fig. 11).

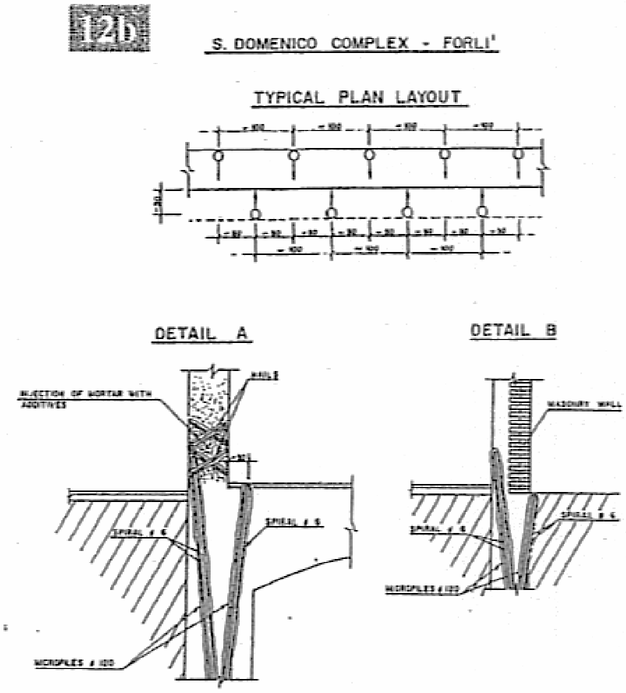
b) **Underpinning**

The reinforcement of exinting foundations can be performed by using micropiles. As a function of the characteristics of existing foundations different micropile solutions can be adopted. In case of old masonry, relatively low bearing capacity micropiles have to be adopted. The connection between micropiles and existing foundations can be performed directely, as reported in figure 12a and 12b, or by using concrete cast in-situ footings (figure 13a and 13b).

12a

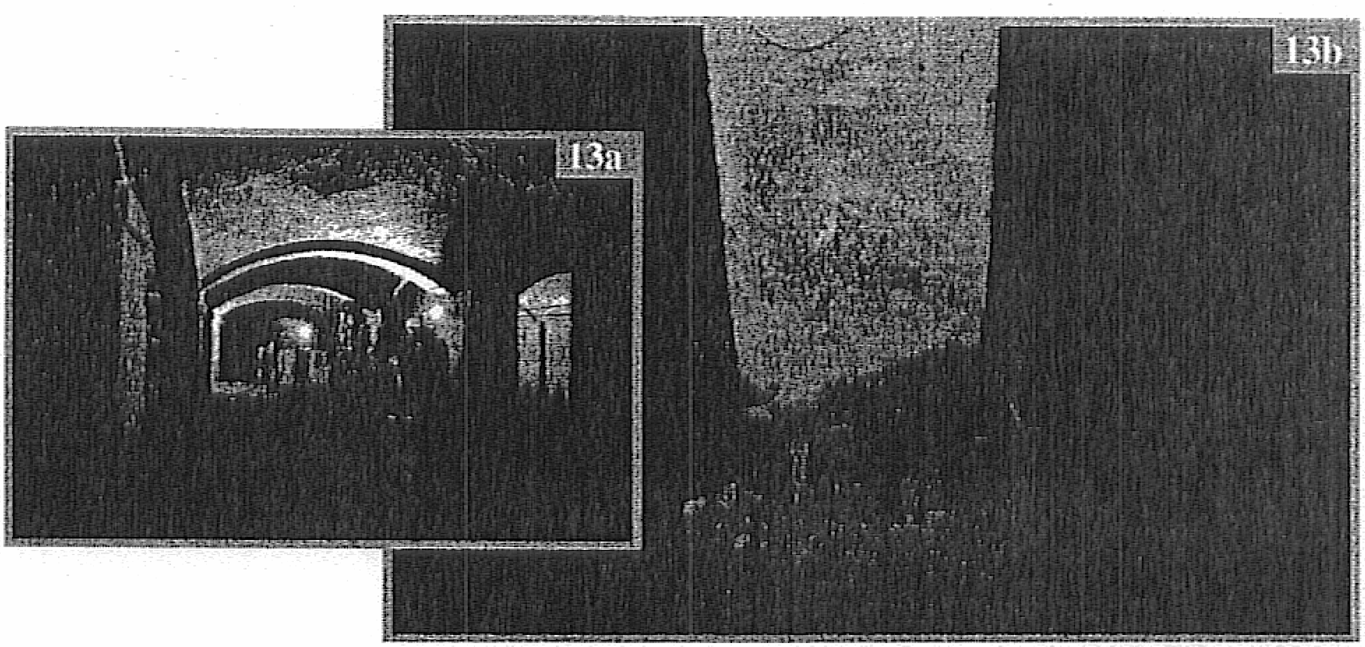


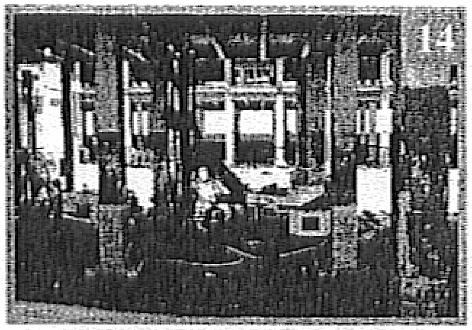
12b

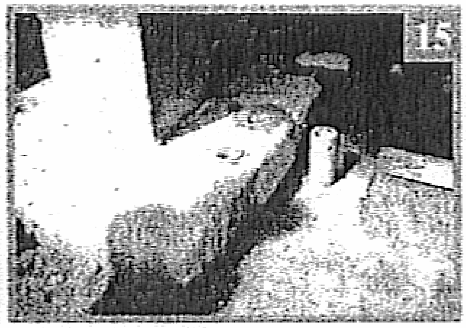


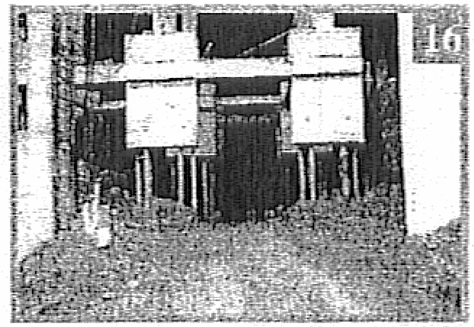
Different solutions can be adopted in case of steel reinforced concrete existing foundations.

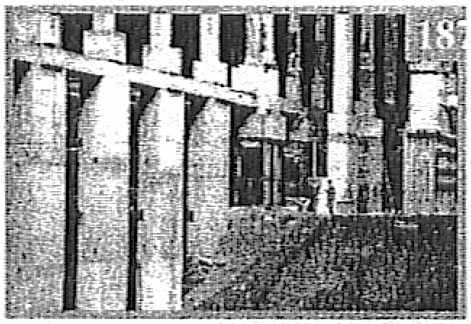
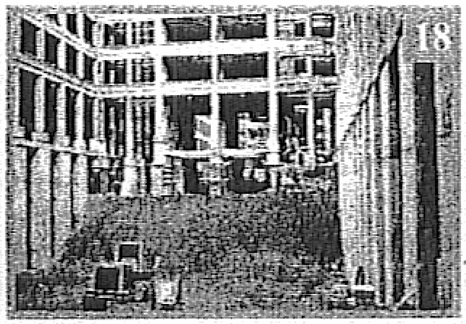
In figures 14-19 some pictures related to the construction of an underground basement under the existing spread foundations of an old industrial plant to be restored are reported. N° 6 micropiles have been executed for each foot, n° 4 passing through and n° 2 outside the footing perimeter. Excavation has therefore been performed by casting a prismatic reinforced column under the existing foot up to the final level of the new basement.

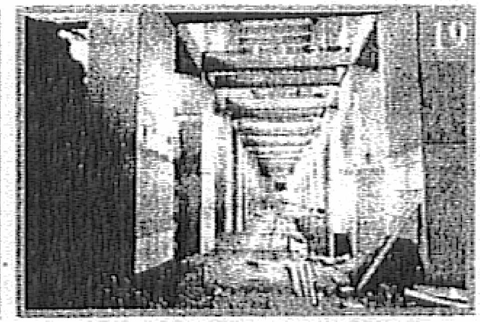








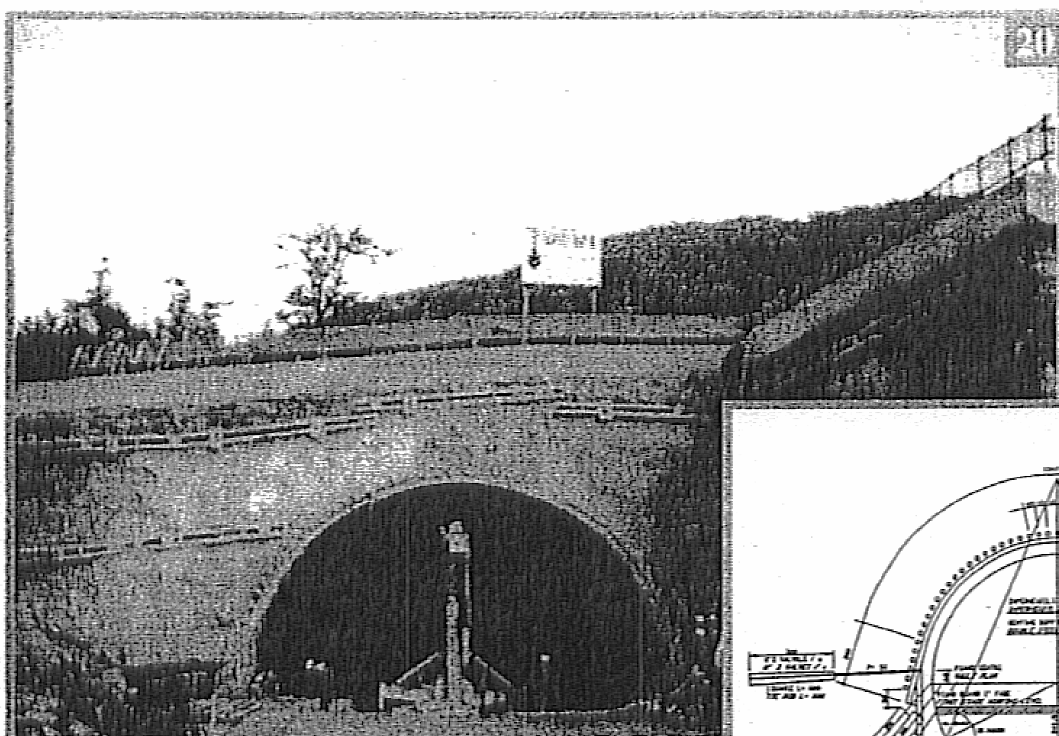



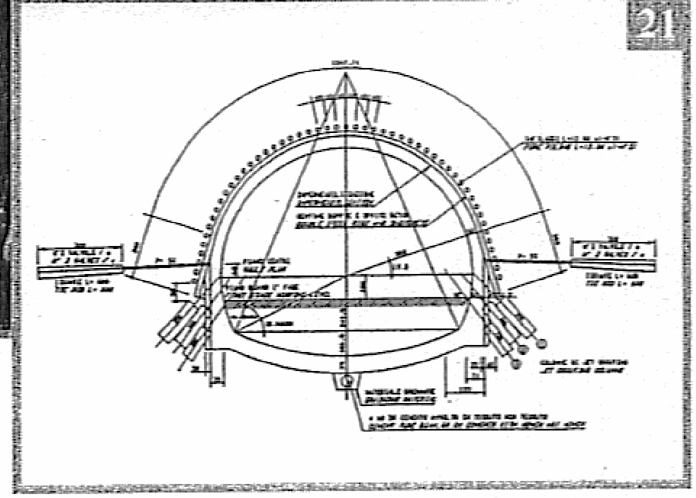


c) Tunnel Construction

In tunnel construction micropiles are generally used in-lieu of diaphragm wall, for the construction of the tunnel portal (fig. 20) and, in the RPUM application, as side reinforcement for the vault excavation (fig 21). In this particular application the aim of micropiles is to avoid the internal displacement of the ribs due to the lateral pressure induced by the excavation.

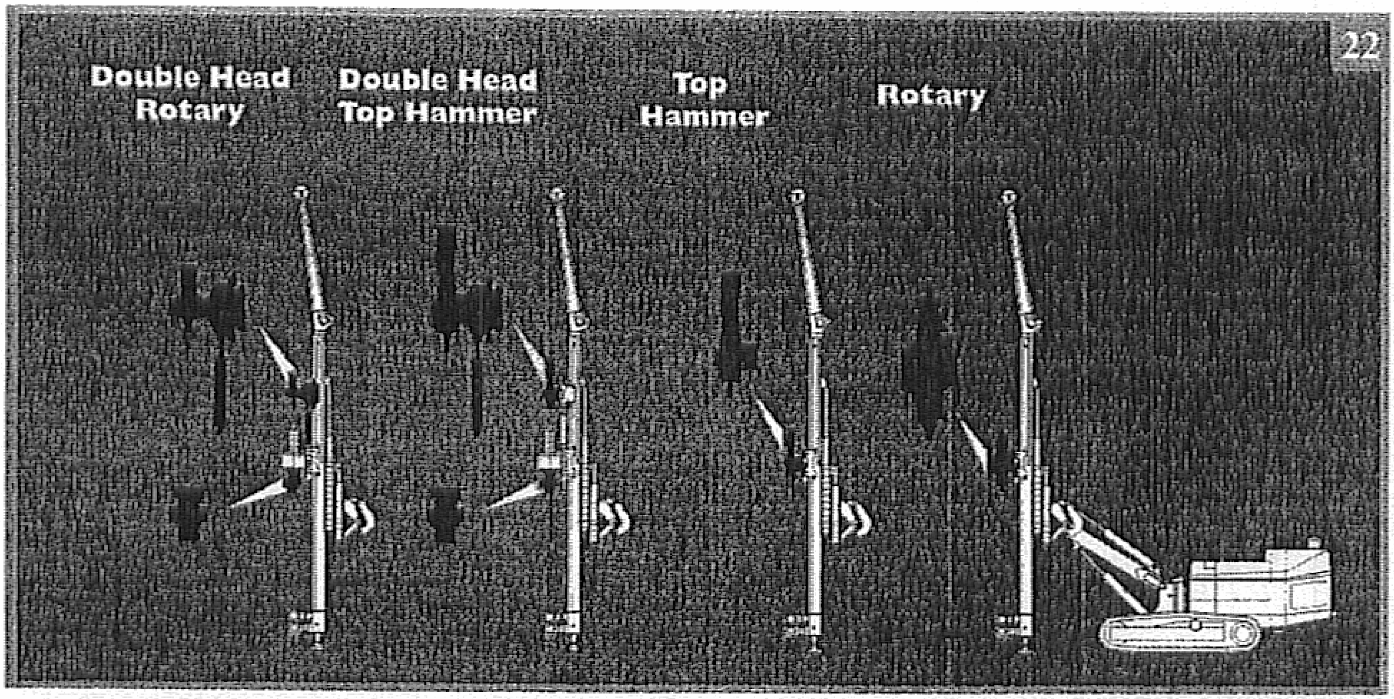
In many cases, instead of the jet-grouting colums performed at the base of the rib foot, to avoid vertical settlement and soil intrusion during the bench excavation phase, micropiles can be adopted to support the foot rib itself.





5 Equipment

Drilling rigs have been designed as "Multi-function" machines: with the same base machine it is possible to perform all drilling systems, as reported in figure 22.



Different models can be used, mainly with regards to the overall dimensions. With reference to SOILMEC production, the characteristics of the main drilling rigs adopted for micropiles construction are reported in table 7 and 8.
In figures 23, 24 and 25 respectively SM-103, SM-400 and SM-405 models are shown.

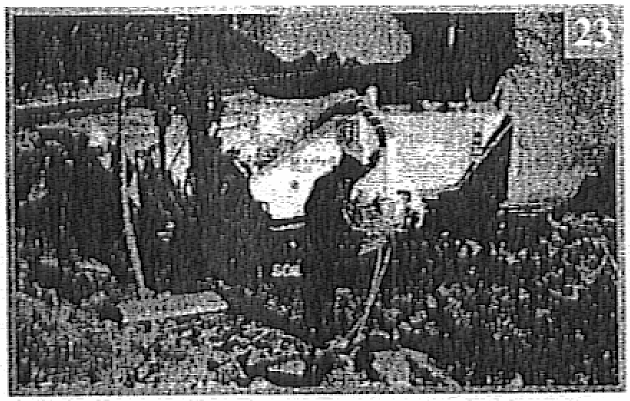
With respect to mixing unit, in function of the daily quantities to be produced, two equipment can be used. For very large micropiles projects containerized mixing unit SOILMEC GM14 type can be used. These units are equipped with automatic and manual control systems for the production of cement based grout. Production of about 8-12 cubic meter of grout per hour can be achieved (figure 26). Turbomixer and stirrer, pre-assembled on a steel platform (figure 28) will be generally used if small grout amounts have to be injected.
A production of about 3,5 - 4,5 cubic meter of grout per hour can be achieved. SOILMEC GP12 type or Peroni DE/OL 3 type injection pumps are used to carry out all the micropile injection operations.

Tab. 7

DRILLING RIG	Engine Power	Total Weight	UNDERCARRIAGE		STANDARD MAST			
			Length	Width	Cradle stroke	Max. Feed Force	Max. Hoist Force	Fast Hoist Speed
	(kW)	(kg)	(m)	(m)	(mm)	(kN)	(kN)	(m/min)
SM-103	51,4	5620	3390	750	2330	30	61,8	0 - 24,9
SM-400	108	10500	2800	2300	4000	35,8	79,4	0 - 31,7
SM-405	130	16200	3780	2450	4000	50	109,9	0 - 33

Tab. 8

DRILLING RIG	ROTARY HEAD			SERVICE WINCH		CLAMP AND JOINT BREAKER		
	Max. Torque	Rotation speed	Side Shifting Stroke	Max. Pull on 1st Layer	Max. Speed on 3rd Layer	Nominal Diameter	Max. Setting Force	Max. Breaking Torque
	(kNm)	(rpm)	(mm)	(kN)	(m/min)	(mm)	(kN)	(kNm)
SM-103	9,15	0 - 359	330	8	0 - 120	60 - 225	159	47
SM-400	13,9	0 - 457	330	35,5	0 - 68,7	60 - 315	159	43,8
SM-405	14,86	0 - 560	460	35,5	0 - 85	60 - 315	200	45



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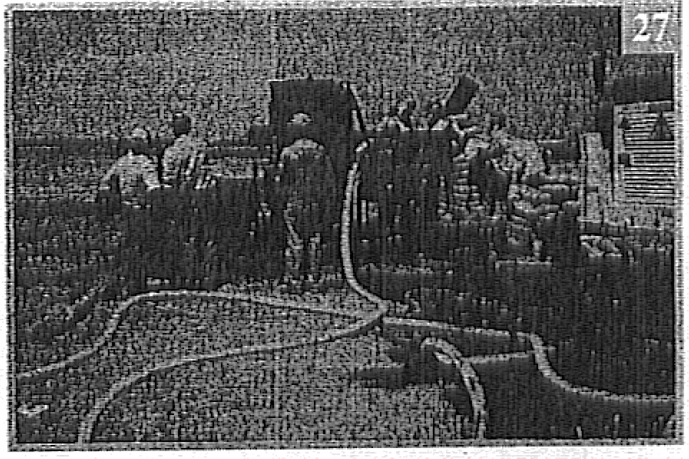

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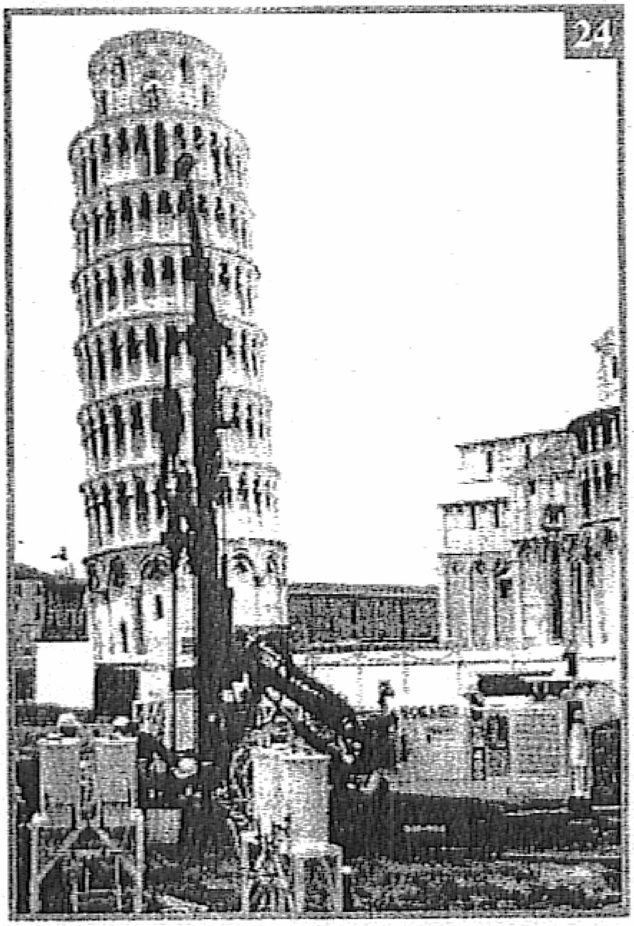

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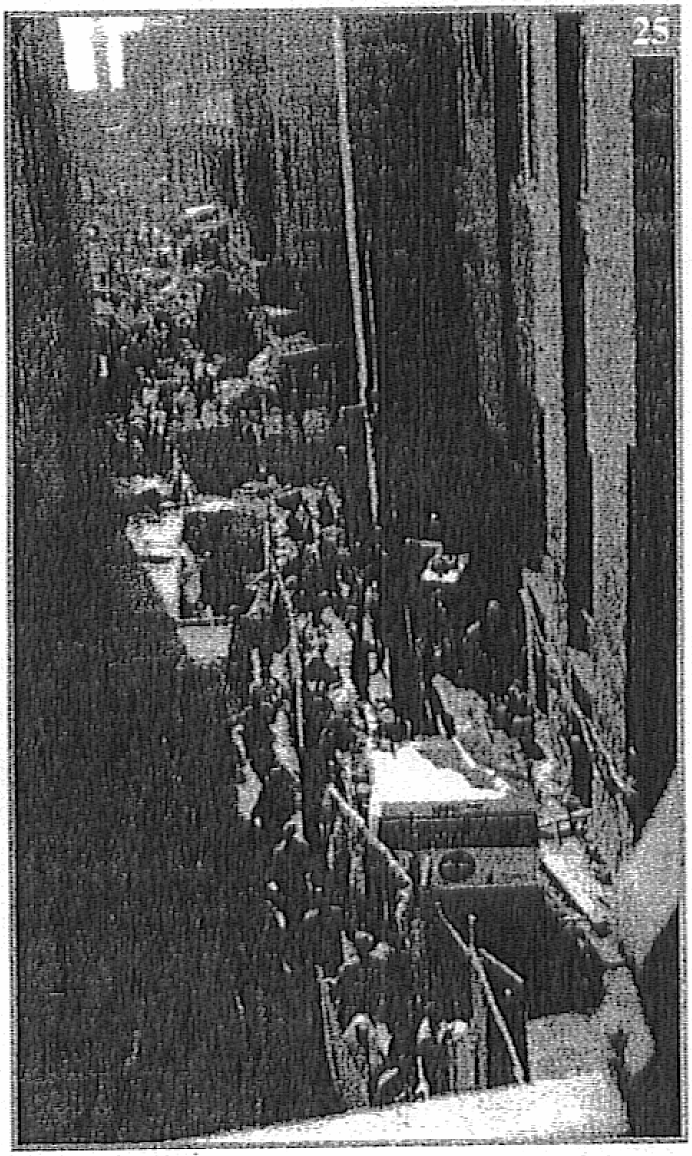

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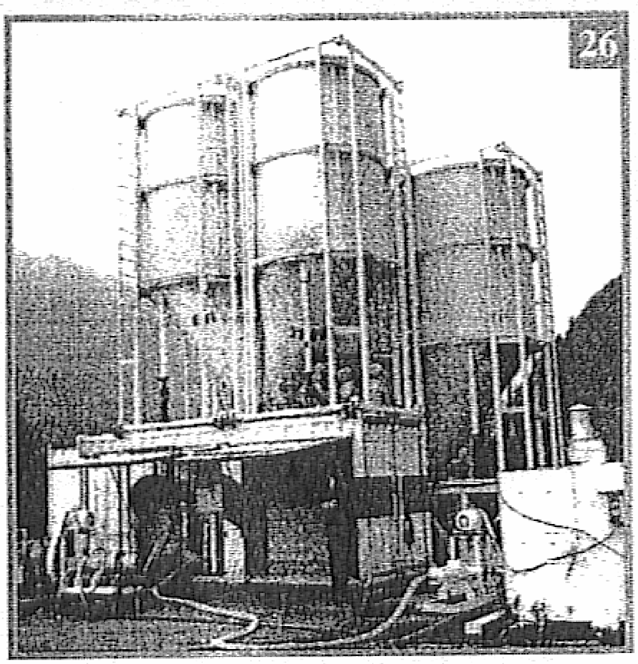

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