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DEVELOPMENT OF DESIGN PROCEDURES FOR STABILIZED SOIL SUPPORT SYSTEMS FOR SOFT GROUND TUNNELING

VOLUME I — A REPORT ON THE PRACTICE OF CHEMICAL STABILIZATION AROUND SOFT GROUND TUNNELS IN ENGLAND, FRANCE AND GERMANY

JUNE 1977

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16. Abstract

This is the first volume of a series of three reports which will describe the results of a research project on the development of a design procedure for soil stabilization systems for support of the ground around shallow tunnels. This volume presents documentation on existing stabilization technology as practiced in England, France and Germany. The next two volumes will contain results of laboratory testing, analytical development and documentation of field behavior.

The specific purposes of the visit were:

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2) Define differences in grouting operations in various countries
3) Document the reasons why chemical grouting is used
4) Develop general guidelines about costs of grouting operations
5) Examine types of specifications and quality control measures used
6) Discuss ongoing research of behavior of chemically stabilized soils

Further, research into chemical grouting is underway at several institutes in Europe but not in the United States, and it was felt that valuable experience could be gained by discussions with European researchers.

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PREFACE

This is the first volume of a series of three reports which will describe the results of a research project on the development of a design procedure for soil stabilization systems for support of the ground around shallow tunnels. This volume presents documentation on existing stabilization technology as practiced in England, France and Germany. The next two volumes will contain results of laboratory testing, analytical development and documentation of field behavior. The work is supported by the U. S. Department of Transportation, Office of University Research, Contract No. DOT-OS-50123.

The technical monitor for the contract is Mr. Russell K. McFarland; his support of the research and aid in arranging contacts with the grouting industry are appreciated. Individuals in industry who have assisted in the work via discussions include Messers. E. D. Graf, W. H. Baker and D. J. D'Appolonia. Students who helped in assembling this report and in translating grouting literature include David Tan, Lawerence Hansen and Christian Mortgat.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

Over the period August 26, 1975, to September 13, 1975, Dr. G. W. Clough visited England, France and Germany to discuss and observe chemical stabilization projects being performed in conjunction with soft ground tunneling. This visit was sponsored by the U. S. Department of Transportation through the Research Contract No. 05-50123 for which Dr. Clough is the principal investigator. The research program involves a general study of the technique of chemical stabilization around soft ground tunnels.

The trip to England and Europe was considered necessary because chemical grouting operations of the scope used in these countries are not presently being undertaken in the United States. Further, research into chemical grouting is underway at several institutes in Europe but not in the United States, and it was felt that valuable experience could be gained by discussions with European researchers. Specifically, the purposes of the visit were:

1) Observe large scale tunnel grouting operations
2) Define differences in grouting operations in various countries
3) Document the reasons why chemical grouting is used
4) Develope general guidelines about costs of grouting operations
5) Examine types of specifications and quality control measures used
6) Discuss ongoing research of behavior of chemically stabilized soils

7) Examine types of laboratory equipment and tests used in research

8) Make contacts with European grout suppliers

ITINERARY

The trip involved visits in England, France and Germany. Projects in and around London were visited in England; while in France and Germany, work in Paris and Nuremberg respectively was observed. Metropolitan authorities, consulting engineers, grouting contractors and institutional and university researchers were contacted. In every case excellent cooperation was obtained.

A summary of the trip itinerary is given in Table 1, which describes the individuals and authorities involved, the projects visited, and the subject of the discussions. In Appendix A a listing of the individuals met during the trip and their addresses is given. The writer is grateful for the hospitality and assistance provided by all of the individuals listed in Appendix A.

DEFINITIONS

In the process of describing observations made during the trip, terminology will be used which is specialized to the grouting field. To avoid any confusion, selected terms will be defined as to their usage in this report.

1) Grouting - injection of agents into the ground to improve the engineering characteristics of the ground

TABLE I. TRIP ITINERARY

VISIT BY G. W. CLOUGH TO ENGLAND AND EUROPE

Date	Locale	Firms or Authorities Involved in Visit	Person(s) Met	Purpose of Visit
8-28-75	London, England	London Transport, Heathrow Airport, Soil Mechanics Ltd.	D. G. Jobling R. G. Mann M. Beyer	(a) Discuss grouting of London Transport Tunnels in general. (b) Visit site of tunnel grouting, Heathrow Airport. Extensive chemical grouting in progress.
8-29-75	London, England	London Transport, Mott, Hay and Anderson Consulting Engineers	D. G. Jobling M. O'Connor	Visit construction sites for Fleet Street Subway Line at Charing Cross Station and Bond Street Station. Deep tunnels and secant pile walls observed.
8-30-75 8-31-75	London London	- Weekend -		
9-1-75	Bracknell, England	Transport and Road Research Laboratory	M. P. O'Reilly J. A. Hudson S. D. Priest	Discuss tunneling research in England. Examine data available on tunneling-induced movements.
9-2-75	Dartford, England	Dartford Tunnel Authority Mott, Hay and Anderson Consulting Engineers	G. Shutter W. A. Temple	Visit site of 2nd Dartford Tunnel -extensive grouting used here-$3,000,000 program. Chemical and cement grouts. Tunneling in progress.
9-3-75	Paris, France	Soletanche Paris Metro	D. D'Appolonia G. Lescelliour F. Bonnay	(a) Visit with Soletanche to discuss grouting in general. (b) Visit the Ligne de Sceaux RATP site. Chemical grouting for underground station and four tunnels in progress. Tunnels and station under River Seine adjacent to Notre Dame Cathedral.

TABLE I (continued)

Date	Locale	Firms or Authorities Involved in Visit	Person(s) Met	Purpose of Visit
9-4-75	Paris, France	Soletanche Paris Metro	D. D'Appolonia G. Lescelliour	(a) Visit Beaujon site - deep slurry wall construction in progress. (b) Discuss details of data available for Washington, D.C. grouted tunnel project.
9-5-75	Paris, France	Soletanche Paris Metro Ordisor	H. Escoffier G. R. Jorge M. Desfougeres	(a) Discuss with Ordisor work on finite element analyses of grouted tunnel works. (b) Visit 2nd site of RATP tunneling under Seine River - Junction Lines 13 and 14, Angle Pont Alexandre III. Extensive grouting on tunnel approaches, caisson bed.
9-6-75 9-7-75		- Weekend -		
9-8-75	Nuremberg, Germany	Soil Mechanics and Foundations Institute	M. Kany K. Hilmer E. Gartung	Discuss grouting research program. Examine laboratory facilities. Review work on finite element analyses of grouted tunnels, constitutive modeling techniques for grouted soils.
9-9-75	Nuremberg,	Soil Mechanics and Foundations Institute	K. Hilmer E. Gartung	Same as 9-8-75. Make contact with Rhone Progil about new grouts. Contact at Kahrlsruhe University about grouting research.
9-10-75	Nuremberg, Germany	Soil Mechanics and Foundations Institute	K. Hilmer E. Gartung	Review grouting plans for Nuremberg subway system. Discuss controls and specifications.

TABLE I (continued)

Date	Locale	Firms or Authorities Involved in Visit	Person(s) Met	Purpose of Visit
9-11-75	Nuremberg, Germany	Soil Mechanics and Foundations Institute	K. Hilmer E. Gartung	Visit construction sites using diaphragm walls and navigation locks; give lecture to institute personnel.
9-12-75	Nuremberg, Germany	Nuremberg Transit Authority Soil Mechanics and Foundations Institute	E. Gartung P. Bauernfeind	Visit grouting and underpinning works of Nuremberg Subway.

2) Chemical stabilization - grouting using chemical agents

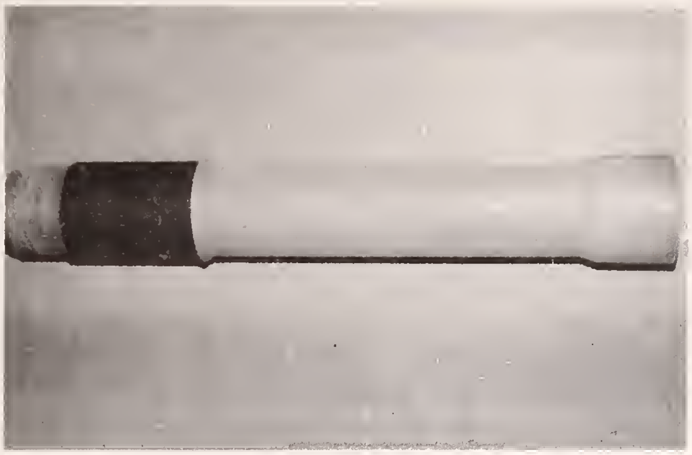
3) Two-shot grouting - chemical grouting where the base of the grout (usually silica solution) is injected into the ground separately from the hardner; the two components mix and react in the ground.

4) Single-shot grouting - chemical grouting where the components of the grout are mixed above ground and injected together in a one-shot process.

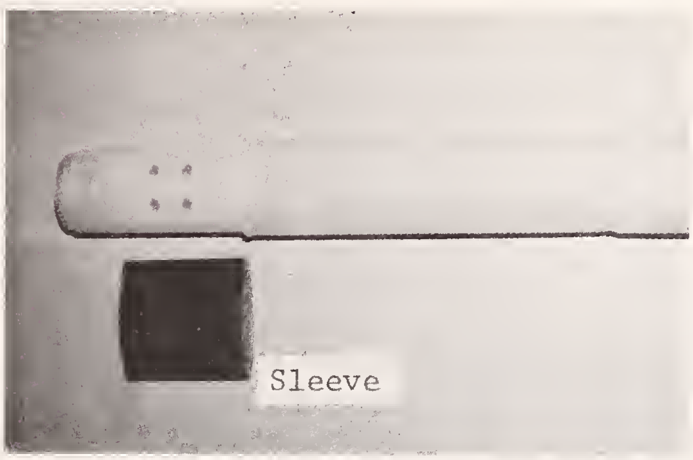
5) Tube a Manchette - a pipe perforated at intervals of about 0.5m so as to allow for controlled injection of grouts into the ground; the perforations are covered by a rubber sleeve which allows only outward grout flow. Photographs of a tube a manchette section with and without the sleeve are shown in Figure 1.

6) Tube a Manchette Grouting Technique - refers to the injection of a one-shot grout through the tube a manchette. The unique aspect of this process is that each sleeved set of perforations is grouted independently of the others. This is accomplished by isolating the sleeve to be grouted using expandable packers; the packers are attached to a small pipe which passes down the tube a manchette and which transmits the grout. Between the packers, the pipe is perforated.

For more details concerning tube a manchette grouting the reader is referred to Appendix B. It should be noted that this technique has rarely been used in the United States. This lack of use is probably because the cost



(a) 0.5m Long Section of Tube a Manchette With Sleeve in Place



(b) 0.5m Long Section of Tube a Manchette, Sleeve Removed, Perforations Exposed

FIGURE 1. TUBE A MANCHETTE SECTION

of the process is relatively high and it requires special equipment and personnel to pump the grouts and measure all the necessary parameters.

GENERAL COMMENTS ON GROUTED TUNNELING IN ENGLAND

Discussions concerning tunnel grouting in England were carried out with authorities from the London Transport Executive, the Transportation Road Research Laboratory, Soil Mechanics, Ltd., Mott Hay and Andersen Consulting Engineers and Nuttall Geotechnical Services. Certain general impressions were derived from these discussions which are considered important; these impressions are described in the following paragraphs. Specific projects are examined in the next section of the report.

Philosophy of Grouting

Chemical stabilization is commonly used in construction of soft ground tunnels in England. Why? This question puzzled the writer when considering the paucity of chemical stabilization in the United States. The reasons given for the use of chemical stabilization are as follows:

1. To minimize the possibility of runs of saturated granular material into the tunnel where the tunnel might daylight into such material.
2. To strengthen the ground and reduce surface settlements.
3. To cut off water from the tunnel.
4. To underpin or supplement conventional underpinning.
5. To reduce compressed air pressure needed for tunneling operations.

Chemical stabilization is seemingly automatically considered as a part of the tunneling plans rather than looked upon as an esoteric tool. In many instances the grouting is apparently considered a safety measure serving to minimize the risk of undue surface settlements or runs into the tunnel. It appeared to the writer that the engineers felt the price of stabilization is small relative to what might happen if it were not used. There is no hesitancy on the part of engineers to call for large scale applications of chemical stabilization although its use is confined to critical and difficult situations. None of the engineers interviewed considered grouting for support of tunnels an "untried process," a common impression in the United States.

Design and Quality Control

Design of the grouting solutions and extent of grouting zones is largely a function of experience and is determined primarily by the grouting contractors with some input by the engineers. Quality control is apparently exercized by the grouting contractor himself insofar as control over set times, chemical quality, pressures, etc. are concerned. In London, exploratory drilling is done ahead of the tunnel face to insure that the grouting zones are the correct size. Strength of the grouted soils is not used as a control item; it is seemingly assumed that if the grouting is done correctly, the strength takes care of itself. Sampling the materials in the grouted zones for tests is apparently rarely, if ever, done.

Detailed specifications concerning the grouting were not used in any of the projects studied in England. Instead, specifications were of the performance type. Payment is often on a cost plus basis rather than a fixed bid.

Types of Grouting and Grouting Processes

Both the newer one-stage and the older two-stage grouting processes are commonly used in England. Chemical grouting, in the case of the projects examined, was performed primarily using silicate based grouts or chrome lignin. Some quick-set cement grout was used to fill large voids or seams in rock formations.

Tunnel grouting is done primarily from the surface and not from the tunnel face. Grouting from the tunnel face slows tunneling operations and thus surface grouting is preferred. However, for several projects where environmental constraints prevented grouting from the surface, a pilot tunnel was drilled ahead of the main tunnel to allow grouting to proceed from within the tunnel.

In London the stabilization work is largely carried out in the Thames Ballast, a gravelly sand deposit which overlies London Clay. Because the Thames Ballast is relatively uniform, grouting procedures are essentially standardized. This facilitates the extrapolation of experience from one locale in London to another.

Problems with Chemical Grouting

While the engineers interviewed generally were confident about the usefulness and success of grouting operations, it was emphasized to the writer that grouting is not a foolproof process. Some problems which had been experienced were:

1) No grout take in silty zones of sandy or gravelly deposits, leaving soft and running silt pockets in the stabilized sand or gravel
2) Loss of grout before it sets due to moving groundwater
3) Lack of continuity in grouted zones due to improper chemical reactions
4) Runback of grout along grout pipe

Most, if not all, of these problems can be corrected using proper grouting procedures, but care in the grouting operation is necessary.

CHEMICAL STABILIZATION PROJECTS IN ENGLAND

Projects visited or discussed in some detail included the Heathrow Airport Picadilly Line Extension, Warrington New Town Sewer, the Second Dartford Tunnel and a sewer relocation for the Picadilly Line Extension. Information obtained concerning these projects is given in the following paragraphs.

Heathrow Airport - Picadilly Line Extension

The London Transport Executive is in the process of building an underground line from Heathrow Airport to London. Cut and cover and underground work underway at Heathrow was visited by the writer with

Mr. D. G. Jobling of the Transport Executive and Messers. R. G. Mann and M. Beyer of Soil Mechanics, Ltd., representatives of the grouting contractors.

Soil Conditions

The geologic setting at the site is typical of that in London itself and consists of 5 to 10m of Thames Ballast underlain by over-consolidated London Clay. The Thames Ballast is a sandy gravel; the gravel in the soil tends to be concentrated in layers so that a sequence of gravelly, then sandy layers occurs. At Heathrow the sands and gravels are relatively clean and groutable; less than five percent of the Ballast is silt. The water table is found about five meters below the ground surface so that any excavation through the Thames Ballast is subject to flow of water unless preventative measures are taken.

Grouting Technique

The majority of the chemical grouting at the site is being performed using a two-shot process. This technique is employed where access to the zone to be grouted is good and the grout holes are relatively shallow. Where the grout holes are deeper, the tube a manchette one-shot technique is used.

The two-shot grouting is done using a mixture consisting of 30% silicate, 50% water and 20% calcium chloride. Grout takes of 25% of treated ground volume are used to control the amount of grout injected. The grout chemicals are injected into the ground through simple perforated pipe which is driven into place from the surface using a jackhammer. This technique is only employed where a maximum depth of about 10 meters is to be grouted. It is cheaper than the tube a manchette technique and is well suited for the geologic conditions at Heathrow Airport.

Where longer injections are needed and the tube a manchette technique is used, the grouting is performed in two stages. In the first stage each sleeve is grouted using a bentonite-cement mixture to fill larger voids. The second stage involves grouting with an ester grout. As a percentage of volume of ground treated, 14% bentonite cement and 17% ester grout is used.

Types of Applications

The Heathrow project is particularly interesting in the variety of uses found for grouting; in Figure 2 schematic drawings depict the grouting work. Underpinning grouting is shown in Figure 2(a); here, footings of an existing car park structure are located immediately adjacent to one of the cut and cover tunnel walls. The Thames Ballast under the footing is treated to support the footing and to transfer the loads of the footing to the underlying London Clay. In Figure 2(b) grouting is used in lieu of excavation walling (Benotto piles) in areas of the excavation where service conduits are to pass. This allows the utilities to be installed with a minimum of difficulty while preventing

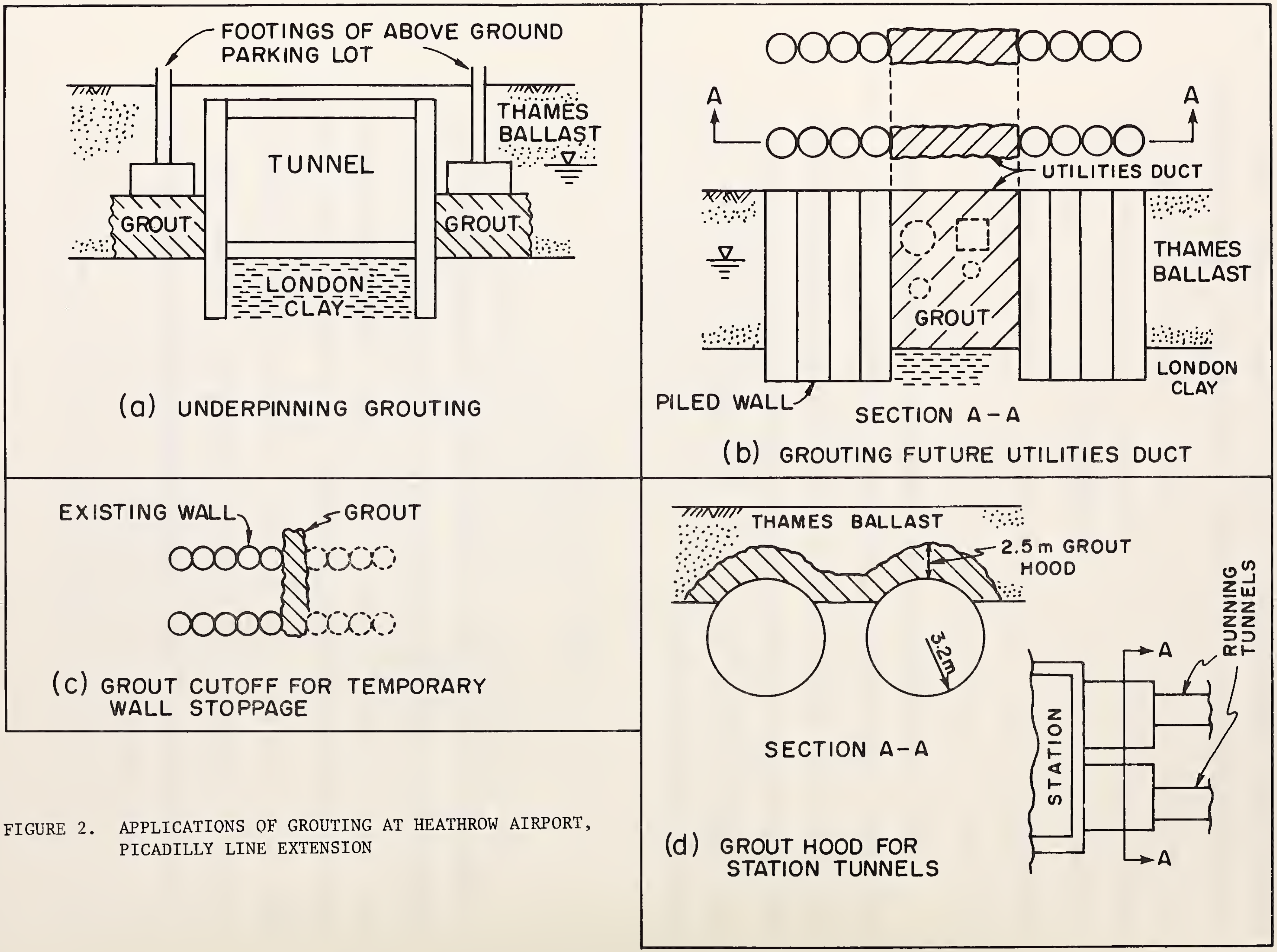


FIGURE 2. APPLICATIONS OF GROUTING AT HEATHROW AIRPORT, PICADILLY LINE EXTENSION

water flow or soil movement into the excavation.

A third application is shown in Figure 2(c); in this case, a grout cutoff is made ahead of the piled wall where a temporary stop must be made. While this type cutoff could be made using sheetpiles, grouting was found to be cheaper and more convenient. The grout cutoff does not require complicated connections and may be removed simply by excavation. The fourth use for grouting is depicted in Figure 2(d) where the Ballast is treated so as to form an impervious and strengthened hood over the central station tunnels which cut into the lower boundary of the saturated Thames Ballast. The large station tunnels extend outward from the central station about 15 meters before the smaller running tunnels begin. The station tunnels are 6.5m in diameter and the grout hood above these tunnels is designed to be 2.5m thick.

Grouting for the applications shown in Figure 2 was performed using the two-shot process for all cases except the grout hoods over the station tunnels; tube a manchette grouting was employed for the tunnel hoods. The two-shot grouting was all performed from the surface or from a temporary excavation platform. The tube a manchette grouting was carried out from a special platform built up against the end wall of the central station. Cost of the two-shot grouting has amounted to \$250,000; tube a manchette grouting has cost \$120,000.

Observations at the Site

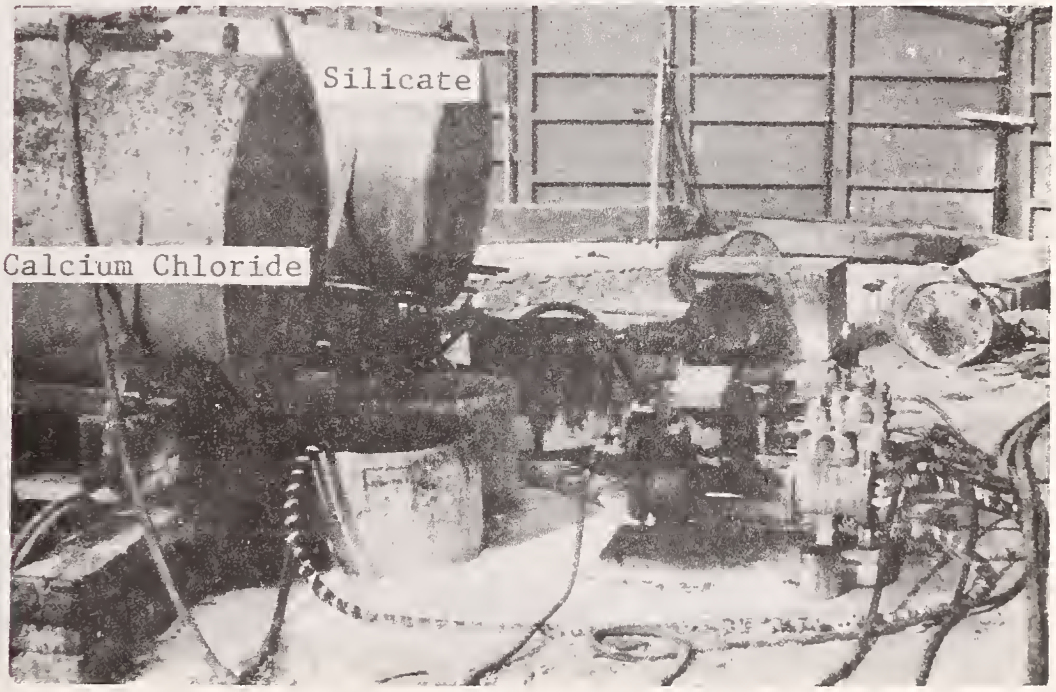
Photographs of these grouting operations and results of the grouting are shown in Figures 3 and 4. The storage silos and mixing station for the two-shot process can be seen in Figure 3. The mixing and pumping operations are relatively simple; the more sophisticated techniques required for the tube a manchette process are not used in this case. It should be kept in mind that the maximum depth of grouting here was about 7m, the pipes were not sleeved, and only one grout mixture was used.

Exposed zones of Thames Ballast grouted by the two-shot process are shown in Figure 4; these zones are in the utility duct areas depicted in Figure 2(b). Even though the areas photographed are coarse granular soils some 4m below the water table, absolutely no water was observed seeping in the tunnel. Close examination of the photographs reveals definite concentrations of grout in the more gravelly layers (grout concentrations show up as whiteish zones); these areas were extremely hard. In the sandy layers the grout was present but not in the concentrations found in the gravels; these layers were softer than the gravels, but were hard enough not to cause any difficulties with face stability.

Warrington New Town Sewer

This site was not visited but was discussed in detail with Dr. John Hudson of the Transport and Road Research Laboratory, Department of the Environment, and Dr. Hall Taylor of Nutall Geotechnical Services, the grouting contractors. The tunnel is only 2.4m in diameter and is to be used for a main sewer line for Warrington New Town. Chemical stabilization was

(a) Storage Silos for Grouting Chemicals, Heathrow Airport



(b) Mixing Pots and Pumps for Two Stage or Joosten Grouting, Heathrow Airport

FIGURE 3. GROUTING OPERATIONS AT HEATHROW AIRPORT, GREATER LONDON

FIGURE 4. EXPOSED ZONES OF CHEMICALLY GROUTED THAMES BALLAST UNDER 3M WATER HEAD, HEATHROW AIRPORT (Whiteish zones are areas of grout concentration)

employed to maximize face stability in mixed ground and to minimize water inflow. Grouting has been completed and tunneling is underway. The section of the tunnel of interest is located next to the Manchester Ship Canal along Ellesmere Road in Warrington, England. The Transport and Road Research Laboratory is monitoring surface and subsurface movements in this area primarily for the purpose of establishing movements above a bentonite shield tunneling operation. However, there is also a section of the tunnel which is chemically stabilized and will be tunneled by conventional shield techniques. This is described in more detail in the following paragraphs.

Subsurface and Tunneling Conditions

A schematic of the subsurface conditions along the tunnel axis is shown in Figure 5. The tunnel will be in sandstone until the surface of the sandstone dips downward; then for about 120 meters tunneling will be in mixed face sandstone-sand conditions and subsequently all sand. In the maxed face area and in some of the sand only tunneling area, the sand is stabilized with a silicate grout. Conventional shield tunneling will be performed in this region; the bentonite shield operation will take over once the tunnel is well clear of the mixed-face area. The groundwater table is located near the crown of the tunnel in all areas.

Grouting Scheme

Most of the grouting at Warrington was performed with a silicate based grout in a one stage process using the tube a manchette technique.

Note: Schematic, not to scale.

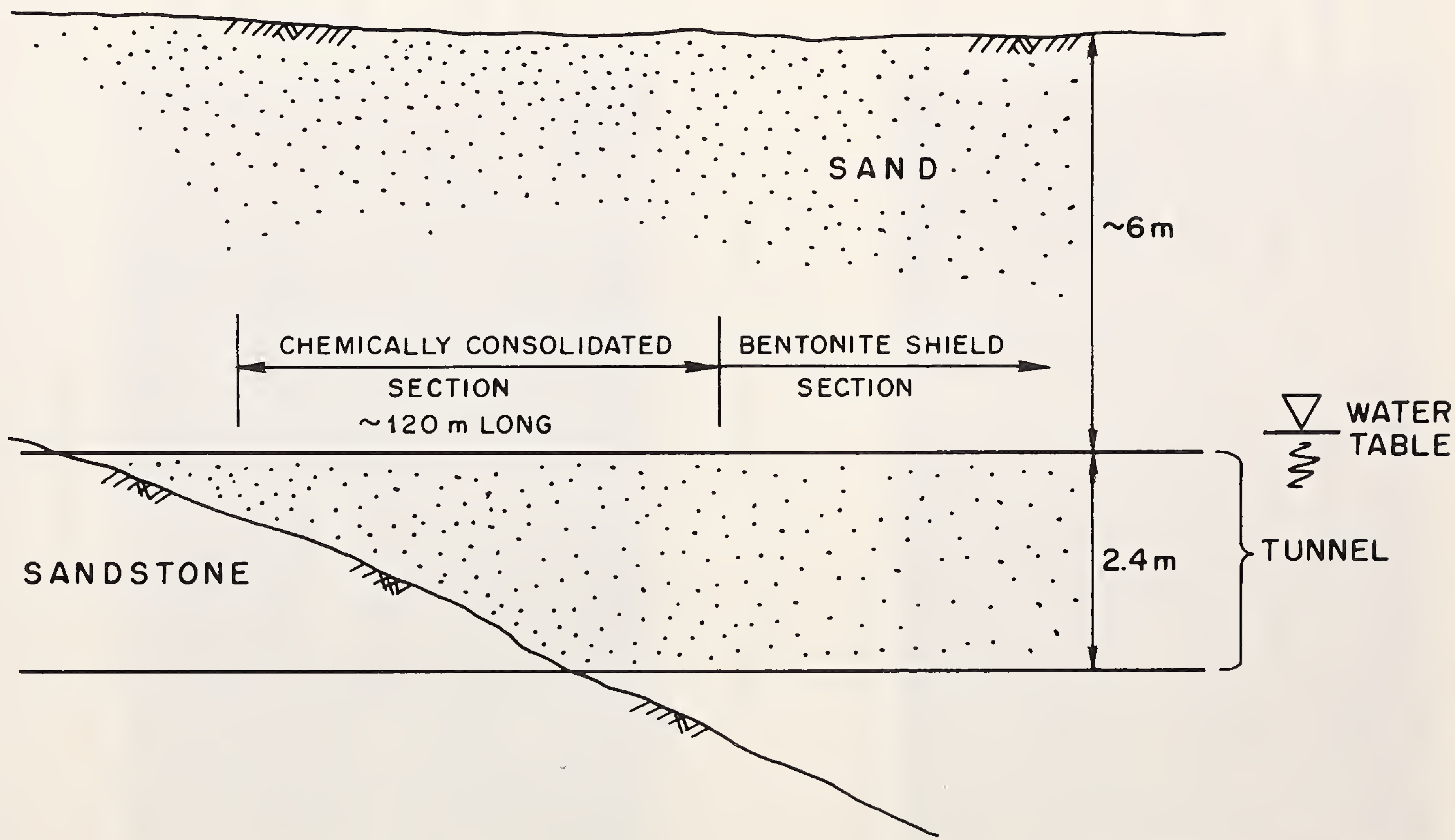


FIGURE 5. TUNNELING CONDITIONS FOR GROUTED SECTION OF SEWER TUNNEL, WARRINGTON NEW TOWN DEVELOPMENT

Percentages of the components of the grout varied slightly with the availability of silicate. On average the grout was composed of 44% Silicate, 4.5% Ethyl Acetate and 51.5% Water; gel times were about 30 minutes. Bentonite cement grout was used in a few instances to fill large voids before silicate grouting.

The grout was injected into and above the tunnel section as shown in Figure 6(a), the grout occupied the zone of soil from four meters below the surface to the tunnel invert. Grout was injected from the surface using a three hole pattern shown in Figure 6(b), with one vertical hole on either side of the grouted region and one inclined hole through the grouted region. This pattern allowed the grouting to be performed while avoiding utilities which were located immediately above the tunnel. Each set of three holes was spaced 1.5m apart along the tunnel axis.

Fifty-seven days were required for the drilling of holes for the grouting and ten weeks for the actual grouting. The total cost of the grouting was $75,000; on a per foot basis this becomes $210/lineal foot of tunnel.

Measurements of surface settlements will be made in the grouted tunnel region by TRRL personnel, and arrangements have been made for the writer to have access to the data. Unfortunately, no samples of the grouted materials are available, but thorough documentation is available otherwise and the tunneling should yield a good case history performance.

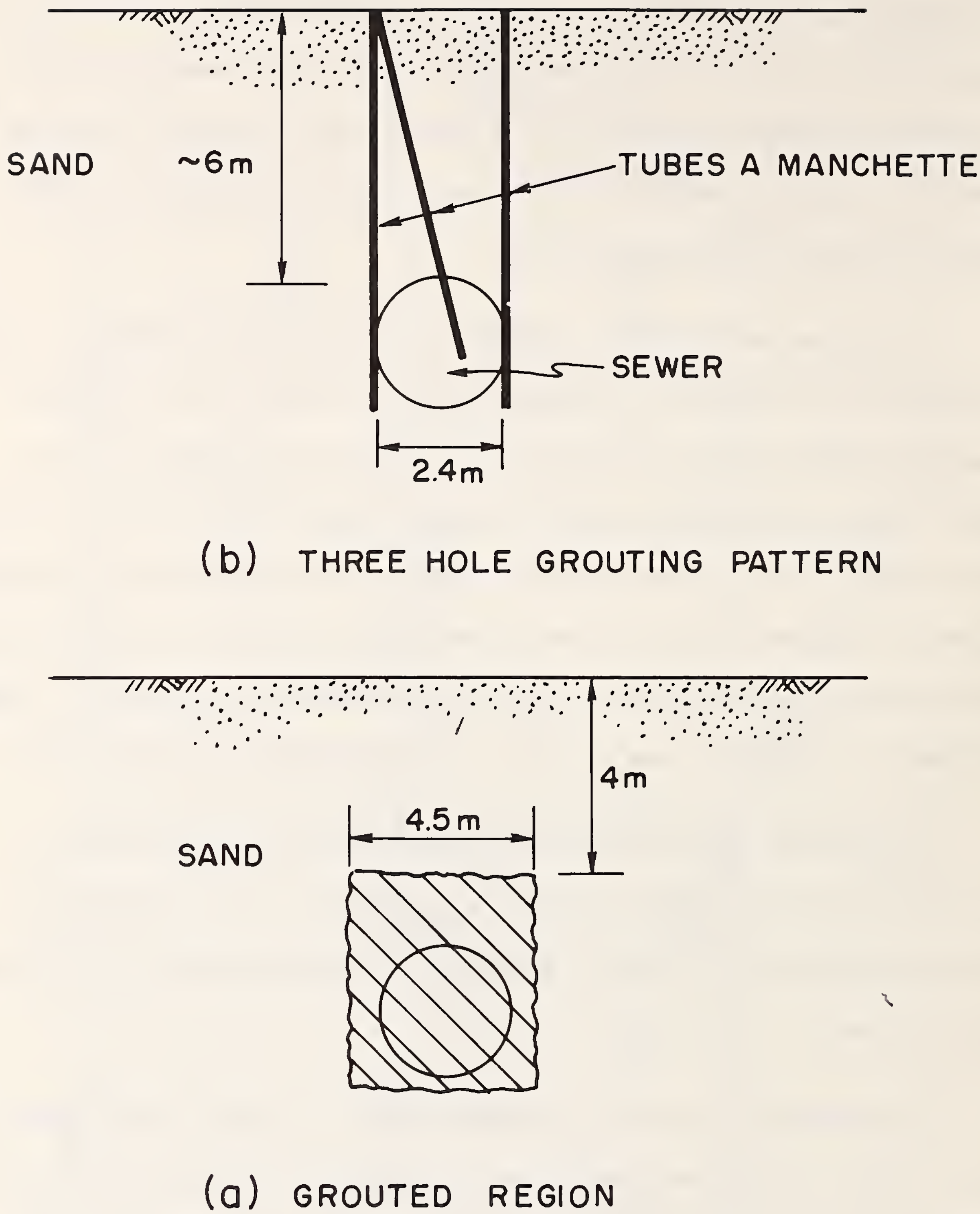


FIGURE 6. GROUTING TECHNIQUE AND RESULTING GROUTED ZONE, WARRINGTON NEW TOWN SEWER

Second Dartford Tunnel

This tunnel site is located about 25 km east of London in Dartford, England, and when visited, grouting was complete and tunnelling underway. Messers. G. Shutter and W. Temple of Mott, Hay and Anderson Consulting Engineers met with the writer and toured the site. Extensive grouting had been performed by the contractor, Cementation Ground Engineering Limited, in order to minimize the use of compressed air during tunneling. The tunnel is being built to pass highway traffic beneath the Thames River; it will supplement the First Dartford Tunnel, already in place. The main tunnel is 10.3m in diameter and is being driven full face using a shield operation. The approaches to the tunnel were built using cut and cover procedures.

Subsurface and Tunneling Conditions

A schematic of the subsurface conditions along the tunnel profile is given in Figure 7. In the approach areas the tunnel cuts through a relatively deep deposit of soft silts and clays (about 30m) and thence into a stratum of sand and gravel. As the tunnel begins to pass under the river, the underlying chalk deposit is encountered; thereafter, tunneling is either in mixed face conditions with sand and gravel overlying chalk, or all chalk conditions. The water table is above the crown of the tunnel for almost the entire tunnel length. The portal to portal length of the tunnel is 1435m; 880m of the tunnel is being bored and the remaining 555m constructed by cut and cover techniques. A deep, braced cast-in-place diaphragm wall was constructed to support the cut and cover

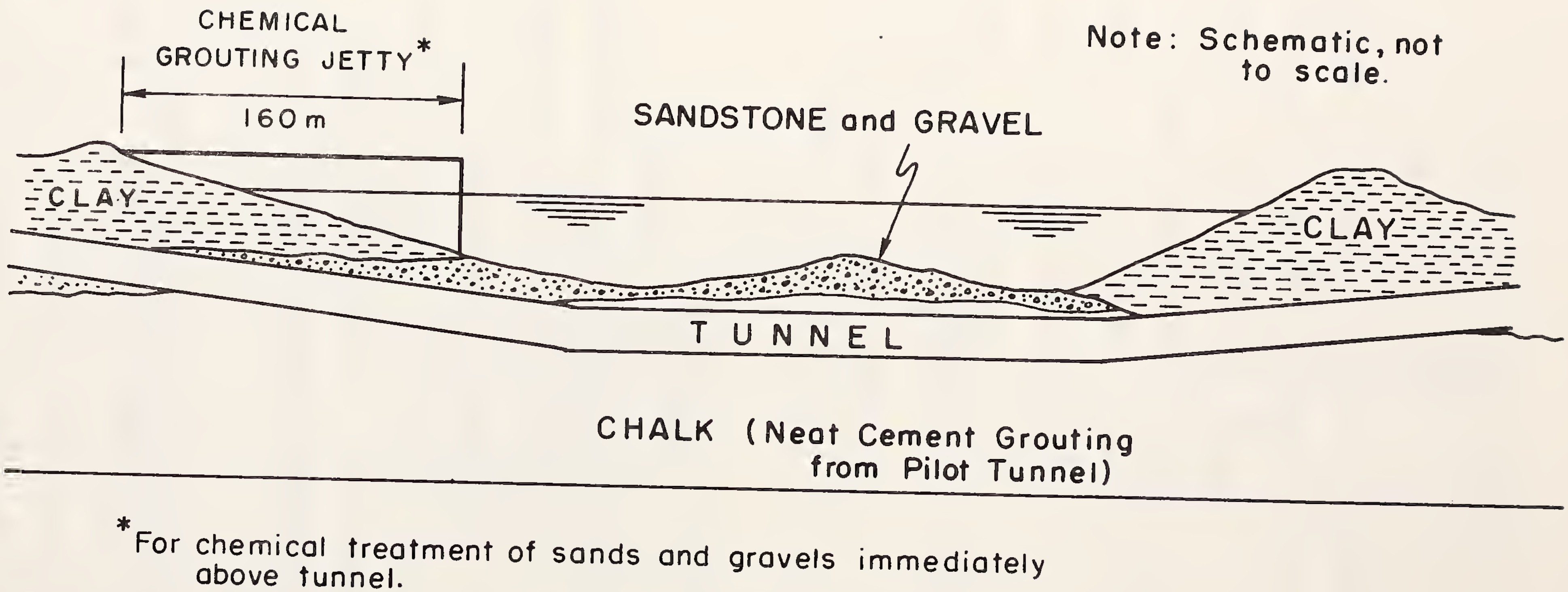


FIGURE 7. SECOND DARTFORD TUNNEL UNDER THAMES RIVER

excavation in the very weak approach soils.

Grouting Schemes

Two different types of grouting schemes were employed at the Dartford Tunnel site, the first concerned treatment of the sands and gravels in the mixed faced tunneling areas while the second involved treatment of the chalk deposit. The sands and gravels were grouted from a jetty built into the river (photograph shown in Figure 8). The tube a manchette process was employed here with bentonite cement and a chrome lignin grout injected in stages to fill the voids. Grouting pressures, grout quantity and rate of flow were monitored during injection.

The chalk was treated using only a neat cement grout designed to seal off fissures in the chalk. This operation was carried out from a pilot tunnel 4m in diameter. Grout was injected 13.5m ahead of the temporary pilot tunnel face through a series of radial holes around the tunnel as shown in Figure 9. The resulting radial grout zone theoretically fully surrounded the main tunnel section which was to be driven subsequently. After grouting at one location was complete, the pilot tunnel face was advanced 11m and grouting was again carried out in front of the tunnel face. This operation was repeated until the entire chalk deposit along the tunnel section was grouted.

The total grouting cost at the Second Dartford Tunnel site has amounted to about $3,000,000 as compared to the total tunnel cost of $48,000,000 (including grouting). Grouting in the sands and gravels

FIGURE 8. GROUTING FROM SPECIAL JETTY BUILT INTO THAMES RIVER ABOVE SECOND DARTFORD TUNNEL

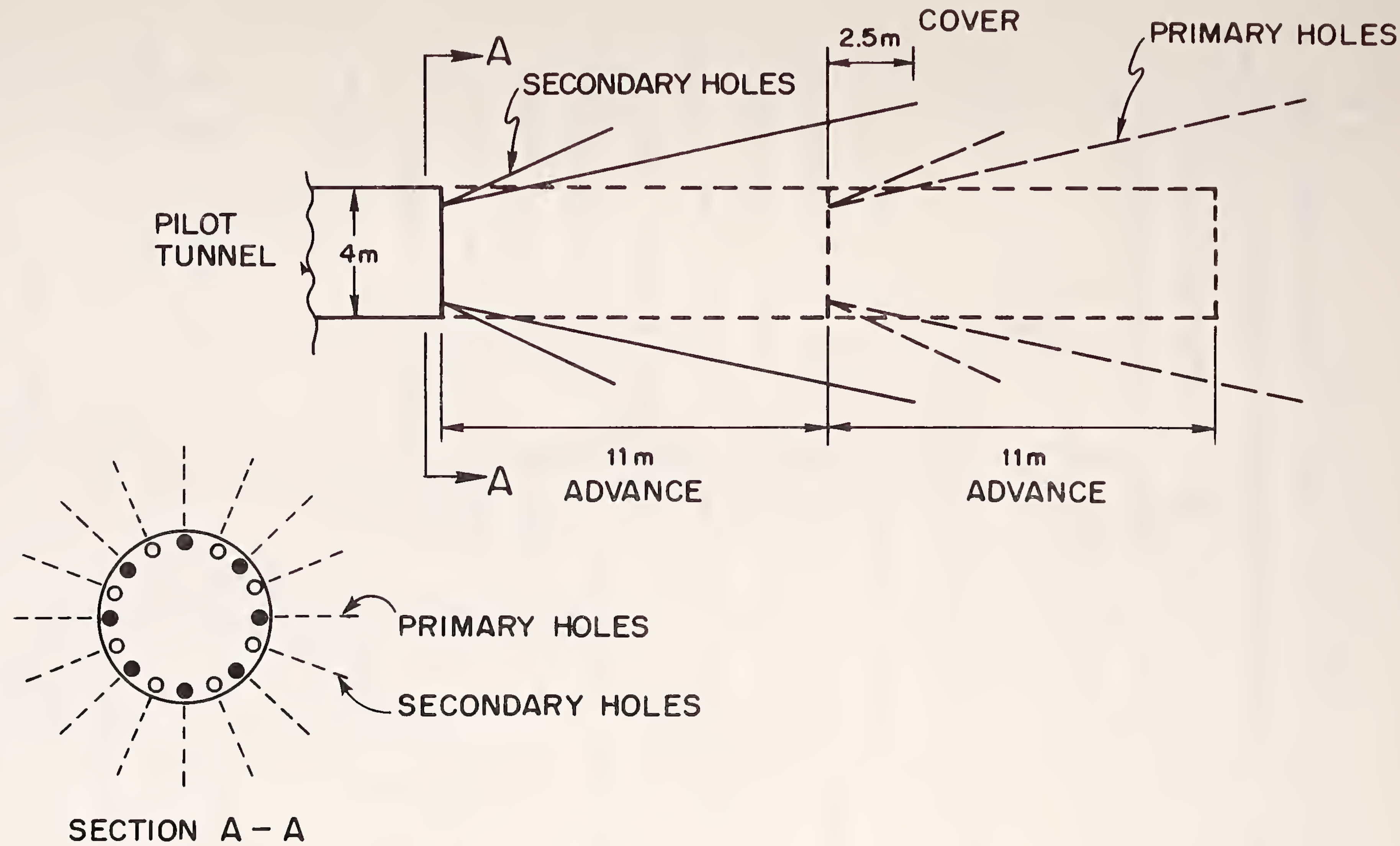


FIGURE 9. PILOT TUNNEL GROUTING IN CHALK AT SECOND DARTFORD TUNNEL

was very effective with little water observed passing through these materials. With the shield tunnel now driven near half way, compressed air pressures of 2 kg/cm^2 (30 lb/sq in), are being used to prevent water inflow through the chalk. Without grouting it is estimated that 3 to 4 kg/cm^2 would be required at this stage.

Heathrow Airport-Picadilly Line Sewer Relocation

Details of this project were provided by Mr. D. G. Jobling of the London Transport Executive; grouting and tunneling in the area were completed by the time of the visit. This case concerns a relatively small, approximately 2m square tunnel, which was being driven for London Clay for a sewer relocation in 1974. The geologic setting is shown in Figure 10. Unbeknownst to the designers, the surface of the London Clay in one area dipped below the tunnel invert over a fifty foot section because of erosion by an old channel, and the dip was occupied by saturated Thames Ballast. Upon encountering the Thames Ballast, a run of granular material occurred into the tunnel which stopped the tunneling completely.

Chemical grouting was chosen to stabilize the Thames Ballast in the tunnel area. A semicircular 2m radius section of grout was injected above and in the tunnel area as shown in Figure 10. The contractor, Soil Mechanics, Ltd., chose to use a silicate grout with a two-stage process. Grouting was conducted from the surface via a service road. The grout thoroughly solidified the Ballast and tunneling proceeded without further incident.

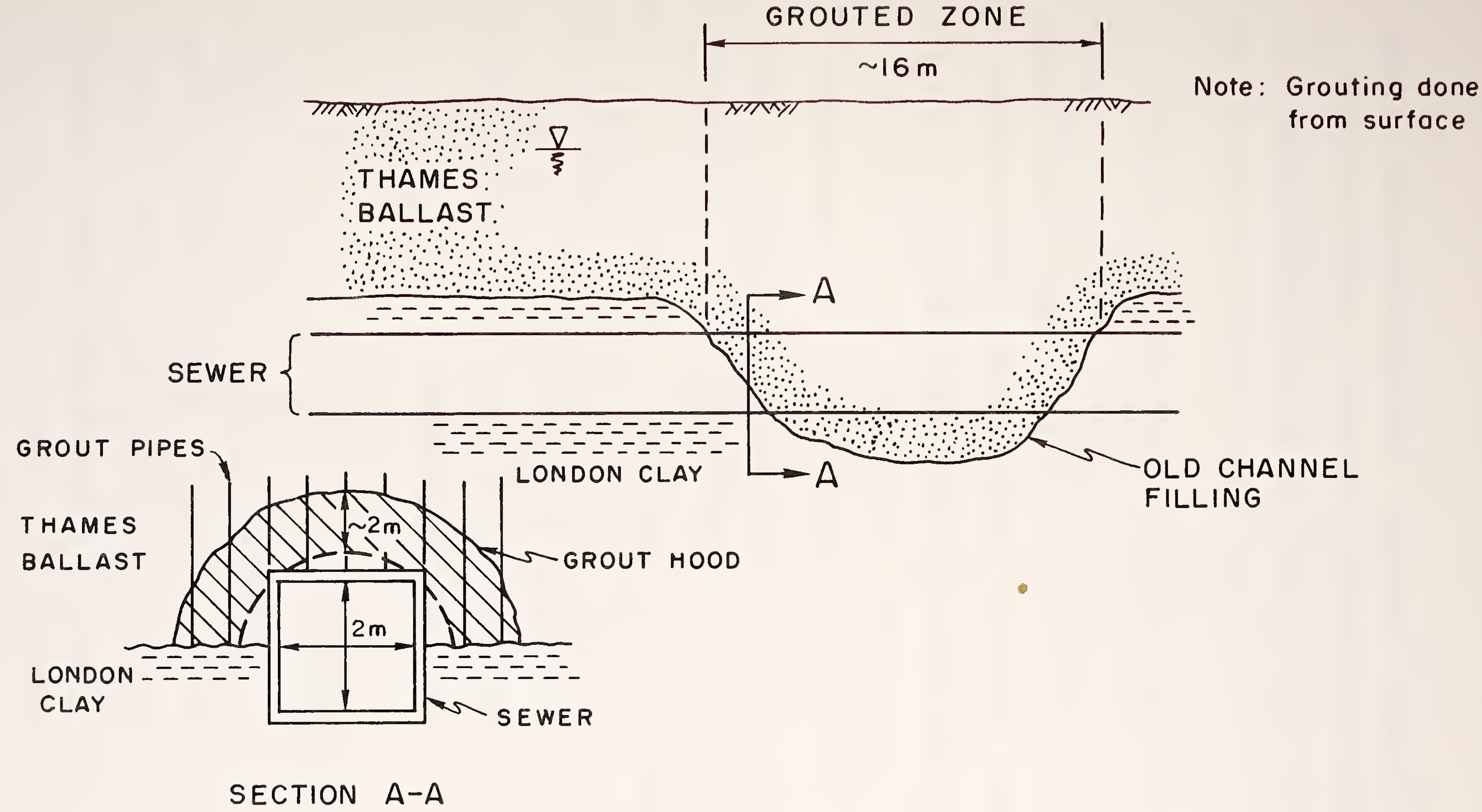


FIGURE 10. USE OF GROUTING FOR SEWER RELOCATION IN GREATER LONDON AREA

The total cost of the grouting was approximately $20,000, or about $400/lineal foot of grouted tunnel. One week of sampling and testing of the soils was needed before grouting and the grouting required four weeks.

GENERAL COMMENTS ON GROUTED TUNNELING IN PARIS

In Paris discussions were held with individuals from Soletanche, a major grouting contractor and from the Paris metro authority, RATP. The following comments were derived from these discussions.

Philosophy of Grouting

Chemical stabilization for tunnel work is apparently very common in Paris. Compressed air is rarely, if ever, used, and grouting is the preferred technique to prevent water inflow into tunnels where underground tunneling is required. Other reasons given for using grouting are similar to those encountered in England. A particular emphasis is put on prevention of settlements since for many of the older structures in Paris only 2cm is considered a tolerable settlement.

Design and Quality Control

As in England, design and quality control of grouting is largely exercised by the contractor. Recently, a committee composed of grouting contractors and municipal authorities has drafted a set of guide specifications for grouting work. These specifications have been translated and are included in Appendix B of this report. The specifications are somewhat general, but provide useful information, especially concerning quality control measures. Their basic philosophy is directed towards insuring that the grouting operations are initially carried out properly with less concern for after-the-fact testing.

Sampling or coring of the in-situ grouted material for testing appears to be little used. Some conflicting opinions on this were encountered; several interviewees suggested that coring destroys the strength of the grouted soil and that representative samples could not be obtained. Others said that coring could be done if experienced personnel and care is exercised in the operation. At one project visited, the Jonction Lignes 13 and 14, coring had been used as an aid to quality control.

Types of Grouting and Grouting Processes

In Paris, grouting is almost uniformly of the one-shot type using the tube a manchette technique. In sands, silicate gels are the most commonly used chemical grouts with resin grouts used in special cases of finer grained soils. Bentonite-cement is used in coarse sands prior to silicate grouting to fill larger soil voids.

Specifics of the grouting techniques vary with the soil type encountered. Soil conditions are more erratic than in London although a general profile may be defined which appears in many sections of the city. This profile is shown in Figure 11; relative thicknesses of the strata vary considerably and complicate grouting operations. The uppermost soil is generally a random fill, underlain by a granular alluvium.

The alluvium lies above a soil called Marne, a slightly cohesive soil which often contains lenses of hard limestone. Next in the downward sequence is hard limestone which is underlain by a fine sand, called Cuisien sand, which creates special tunneling problems in that it can "boil" when subjected to an upward seepage gradient.

Depending upon the soil or rock type encountered, the grouting technique varies. In the alluvium and fine sand, silicate gels are primarily used with some bentonite cement grouting first if the soils are coarse grained. Resins are employed if the sand is silty or unusually fine grained. In coarse grained soils typical percent of grout types (by volume of soil injected) are 5% bentonite cement and 35% silicate gel; for finer grained soils around 25 to 30% silicate gel only would be used. In the case of limestone, neat cement or bentonite-cement grouts are employed with some silicate gel grouting where needed. Quick setting cement is used and only a small quantity is needed to seal off fissures in the limestone, typically around 5% by volume. Because the grout is quick setting, high pressures are often used.

The marne soil presents special problems since it is not pervious in the sense of a sand deposit, but does contain fissures and weaker areas through which water can flow. In this case a "claquage" technique is employed where the grout is injected so as to penetrate the fissures and weak zones and create an interlocking sequence of grout "fingers" which seal off the water paths. To attain interlocking, the grouting is performed in a sequence defined in terms of location and time. For example, as shown in Figure 12, a vertical series of holes is grouted one after the other so that the grout take is forced in an orderly sequence

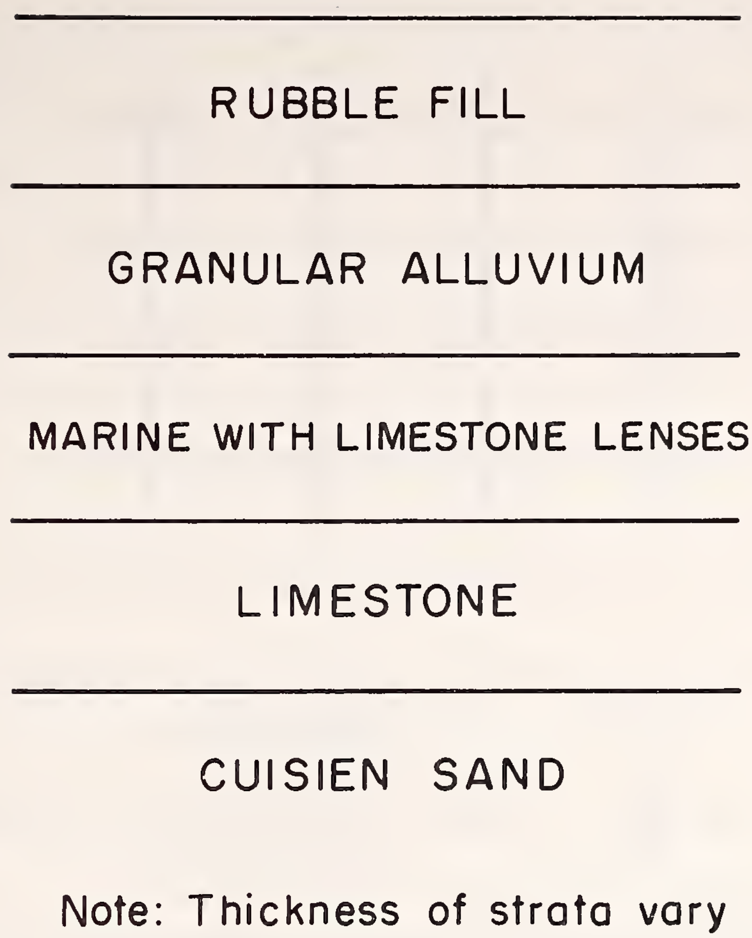
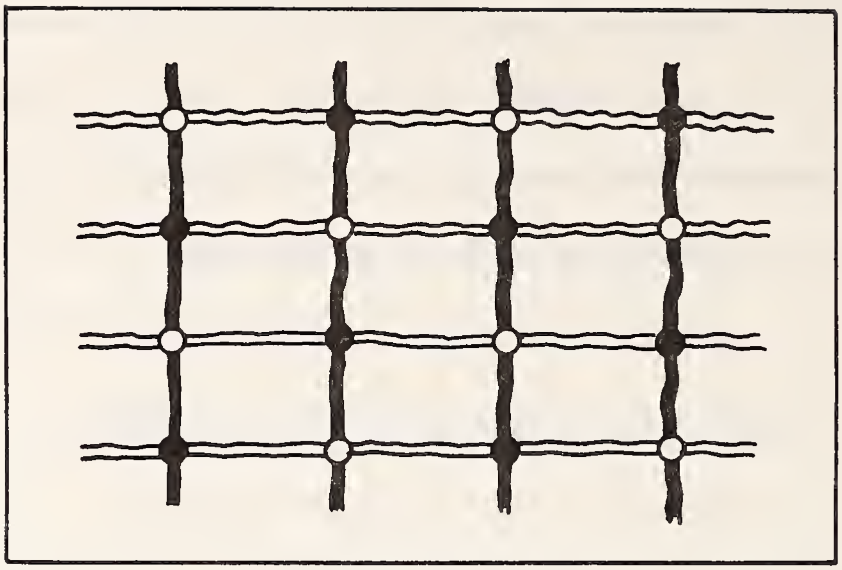


FIGURE 11. COMMON SOIL PROFILE FOUND IN PARIS



— 1st Stage grout holes and grout distribution

2nd Stage grout holes and grout distribution

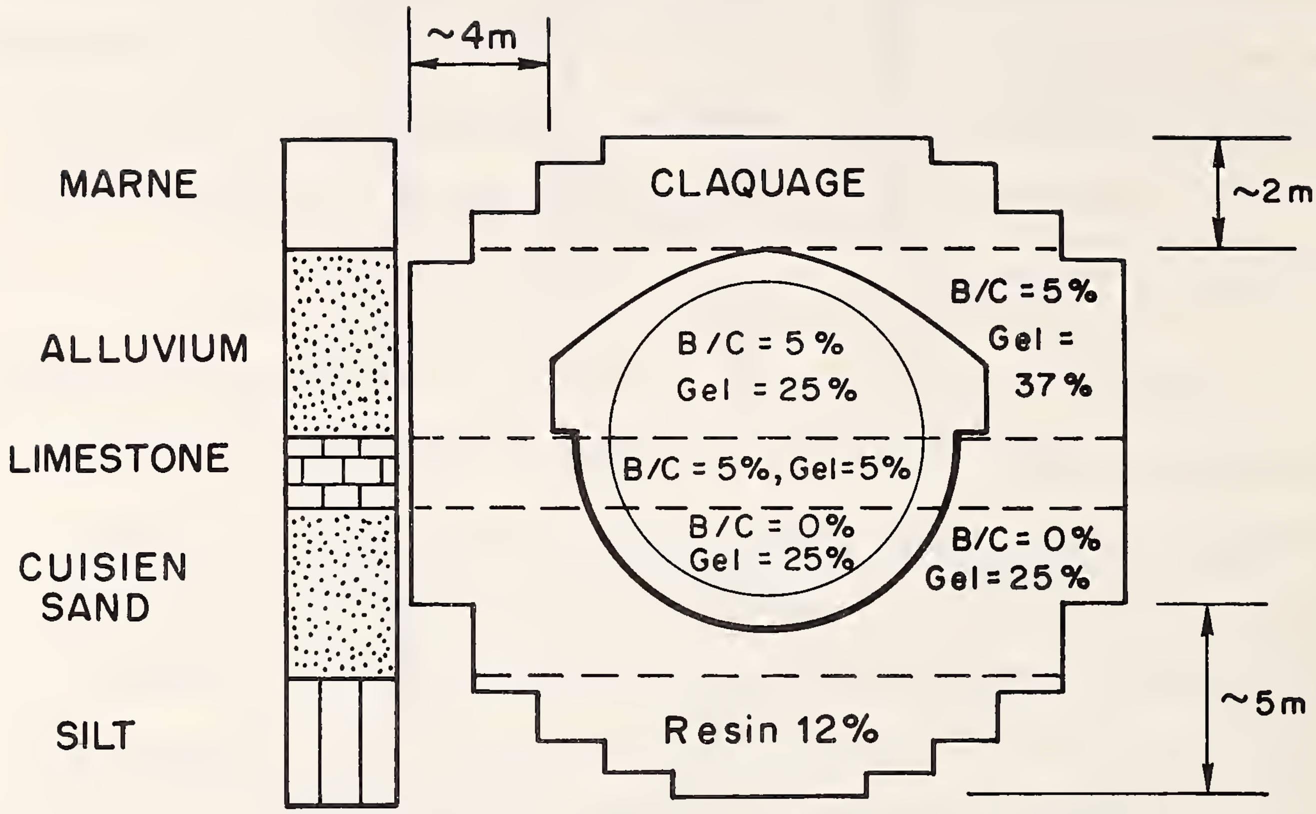
Note: Primary planes of weakness in Marne assumed horizontal

FIGURE 12. IDEALIZED "CLAQUAGE" GROUTING EFFECTS IN MARNE

into the weakest secondary structure features. After the grout has had time to set, another series of holes is grouted, and this time, because the weakest structure is already filled, the next weakest zones are filled. Higher grouting pressures may be used in the second step to insure penetration of the grout. The resulting pattern should interlock as shown in Figure 12 and seal off potential paths for water.

A typical section design for grouting of a profile with the various soil types is shown in Figure 13. A circumferential zone of treatment is defined in heavy lines; within this section are different soil and rock types and the grout treatment varies accordingly in the percentages of the grout chemicals and the type of grouting procedure. Note that the percentages of the chemicals also vary in some cases depending upon whether the grout will be in the section to be excavated or outside of it. Weaker grouts are injected in the area to be excavated to allow for ease in removal of the spoil and to prevent penetration of the hardened grouts in the excavation area. Such a complicated plan could only be carried out using the tube a manchette process where each sleeve can be grouted differently.

Soletanche personnel emphasized the importance of filling a maximum of the voids in the soil. Thus, care is taken to inject as nearly as possible the predetermined required volumes (defined as a percent soil volume). Ground surface heave is also carefully scrutinized during grouting. The heave is considered important not only as a possible source of damage to structures but also as an indicator that the grout is indeed filling the soil voids; some small amount of heave is sometimes felt to be desirable. Thus, surface movements are monitored



Note: B/C = Bentonite Cement
Gel = Silicate Basalt Gel
Percentages are by volume of soil treated.

FIGURE 13. TYPICAL SECTION DESIGN FOR GROUT TREATMENT, PARIS METRO (COURTESY SOLETANCHE, S.A., PARIS, FRANCE

to determine (a) that the heave is not so large as to be detrimental, and (b) that enough heave has occurred to insure that the soil voids are full. The necessary heave is established from experience.

CHEMICAL STABILIZATION PROJECTS IN PARIS

Two projects which involved major applications of grouting were visited in Paris. In both cases, the tunnels are for extensions to the Paris Metro and pass under the River Seine.

Ligne de Sceaux - Luxembourg to Chatelet

This site was visited in the company of Messrs. D. J. D'Appolonia, G. Lesciellour, and F. Bonnay of Soletanche, Inc., the grouting contractor. Construction was underway on two 6m diameter tunnels which pass under the River Seine and numerous historic buildings. At their shallowest depth, the crown of the tunnels are within 6m of the river bottom. Grouting is being used to impermeabilize and strengthen the soils around the tunnel. No compressed air is employed even under the river.

Geologic Conditions

A schematic of the geologic profile along the tunnel axes is shown in Figure 14. The profile is similar to the typical profile described in Figure 11. In sequence from ground surface down, the soils are, fill, alluvium, marne, limestone and cuisien sand. The tunnels in the area of the profile shown, pass mainly through Marne and limestone

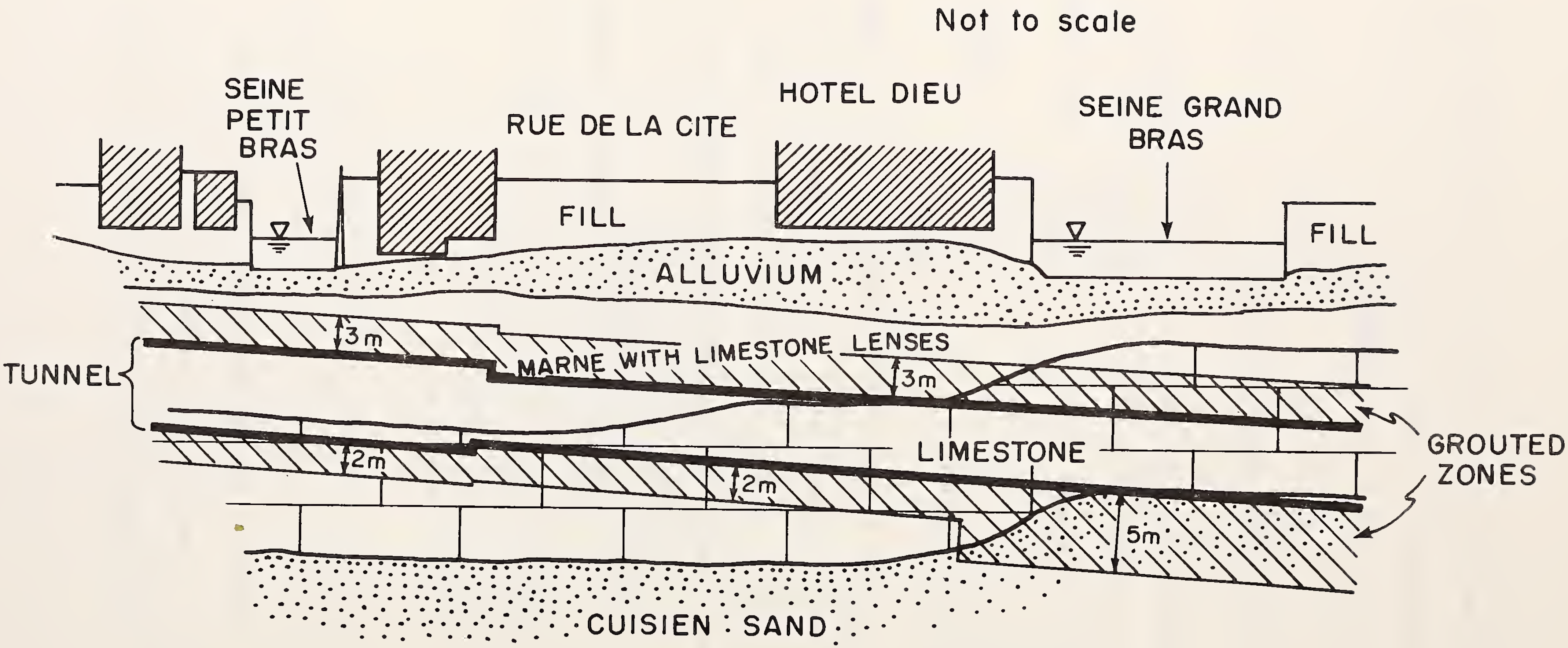


FIGURE 14. GROUTING ZONES FOR SEINE TUNNEL CROSSINGS, PARIS METRO (COURTESY SOLETANCHE, S.A., PARIS, FRANCE)

and in a few areas, Cuisien sand.

Grouting Schemes

Boundaries of the grouting zones around the tunnels are shown in Figure 14. In every case the zone completely encircles the tunnel; the zone thicknesses vary with the type of soil - 2.0m in the limestone, 3.0m in the Marne and 5.0m in the Cuisien sand. The type of grouting used to form the zone varies with the soil or rock type encountered. As described in the previous discussion of grouting in Paris, silicate gels are used primarily in the sand, claquage grouting with bentonite cement or silicate gel in the marne, and bentonite-cement in the limestone. The exact sequence and pattern of the grouting varies with the geologic profile at any given location.

Because the tunnels pass directly beneath many historic structures and the river, grouting operations at the surface must be minimized. Thus, most of the grouting is performed from the tunnel face through one or more pilot tunnels. One pilot tunnel is adequate to advance the running tunnels, but in station locations where the openings are very large two pilot tunnels may be driven on either side of the station opening so that the grouting can adequately cover the area around an opening.

The sequence of working from a pilot tunnel in a running tunnel as used at the Ligne de Sceaux is shown in Figure 15. To begin, a grouted zone approximately 9m in diameter is extended 19m in front of

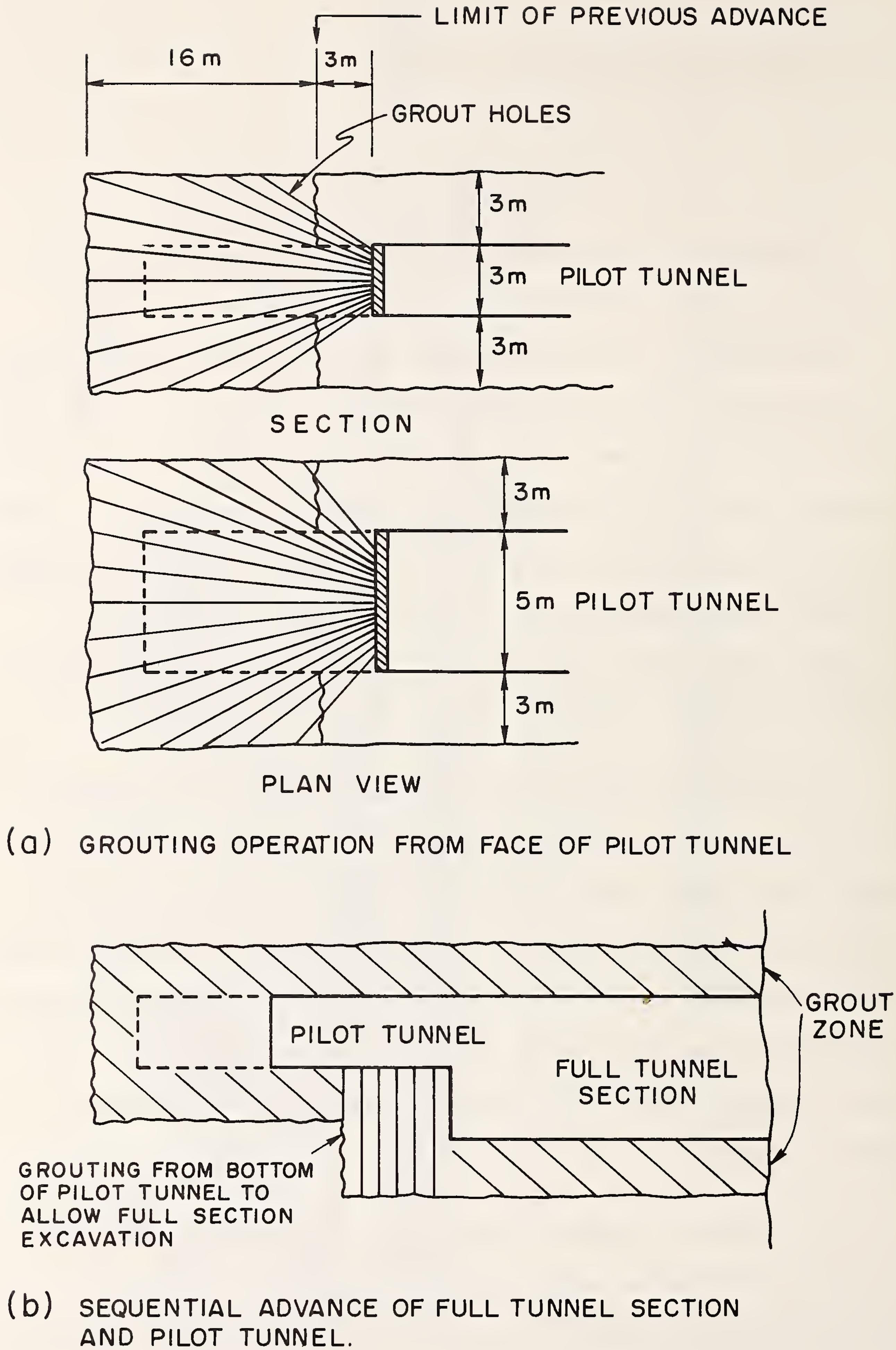


FIGURE 15. SEQUENCE OF GROUTING OPERATIONS USING PILOT TUNNEL TO ADVANCE TUNNEL FACE

the fill section face. Within this zone the pilot tunnel, approximately 3m in diameter, is hand excavated to within 3m of the end of the extended grout zone. Inside of the pilot tunnel, two operations take place: (1) grout is injected through the invert of the pilot tunnel to extend the stabilized zone around the pilot tunnel downward so as to create a grouted zone large enough to allow the full tunnel section to be advanced (see Figure 15); and, (2) a concrete bulkhead is constructed at the face of the pilot tunnel through which holes are drilled outward in front of the face up to a length of 19m; tubes a manchette are installed in the holes and grout is injected into the soil to create a stabilized zone which will surround the next advance of the pilot tunnel. The spacing of the grouting holes is a function of soil type, varying from 1.5m in sand up to 3m in limestone. After stabilization work from the pilot tunnel is complete, the face of the pilot tunnel is extended another 16m to within 3m of the newly grouted zone. Also, the full tunnel section is advanced to within several meters of the old face of the pilot tunnel. This operational sequence is then repeated until completion. Approximately five weeks is required for each pilot tunnel advance; the slowness of this operation points up the English and French preference for grouting from the surface. By grouting from the surface, the entire tunnel stabilization operation may be performed before tunneling begins.

Observations at the Site

The mixing plant operation on the right bank of the Seine is shown in the photograph (a) in Figure 16. The grouts are mixed at this location and pumped to the site of grouting. Grouting pressures, flow rate and quantities are monitored at this station. Telephone communications are maintained between the operation at the mixing plant and the workers at the grouting site.

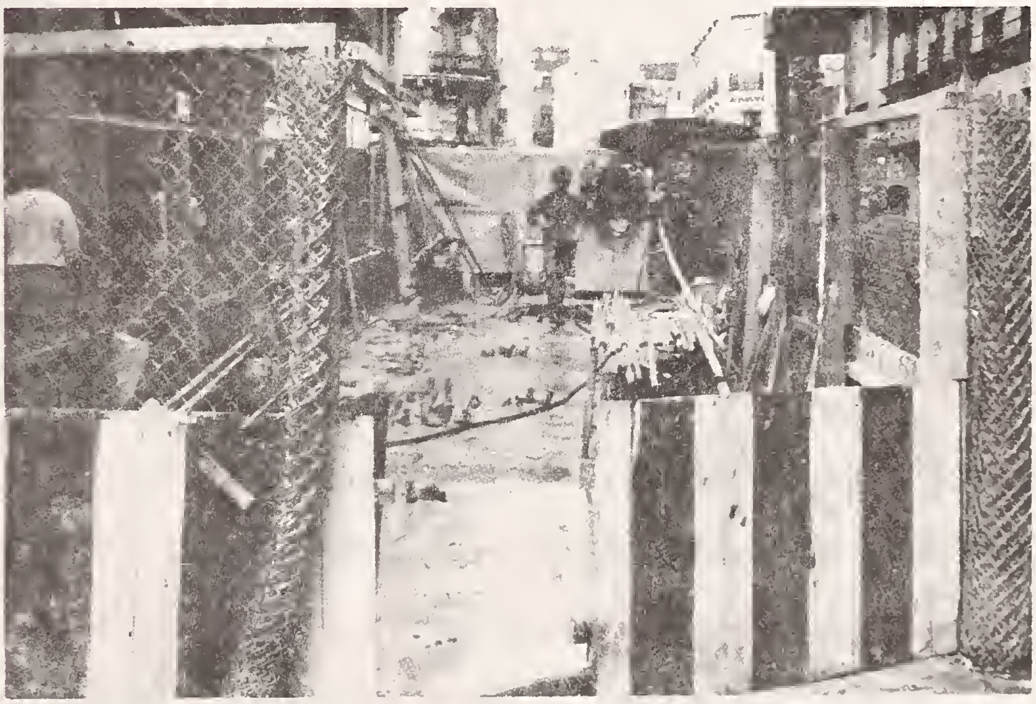
Several of the tunnels were visited and the different stages of the grouting process were observed. In a number of areas the grouted materials were exposed; the treated sands were very firm and watertight. Claquage grouting was observed in the marne in one location. The bentonite cement seams from the primary holes clearly followed weak zones in the marne which were essentially horizontal. Grout from one hole was found to have traversed along one such zone over 3m. Seams of grout from the secondary holes were largely vertical, thus producing the desired interlocking effect.

On the left bank of the Seine some grouting was being performed from the surface as shown in the Photograph (b) in Figure 16. These operations were not considered desirable since the small streets were essentially blocked.

<u>Jonction Lignes 13-14</u>

Messrs. H. Jorge of Soletanche and M. Desfougeres of RATP met with the writer at this site. The tunneling operations consist of two 9 m openings which pass under the Seine at the Pont du Alexandre III. Grouting was performed for the approaches along the river bank and in

(a) Chemical Storage Silos and Pumping Plant on Right Bank of Seine River, Paris (Notre Dame Cathedral in Background)



(b) Surface Grouting on Left Bank of Seine River, Paris

FIGURE 16. GROUTING OPERATIONS FOR LIGNE DE SCEAUX PARIS, FRANCE

the river bottom to form a stabilized bed where tunnel tubes crossing the Seine were founded.

Geologic conditions and grouting treatments at this location are not greatly different from those at the Ligne de Sceauex site discussed previously. The methods of grouting were, however, different. Along the approach areas, grouting was performed primarily from the surface. In the river crossing, sunken tubes were utilized; the tubes were placed in a river bed excavation approximately 10m deep. A section through a typical excavation is shown in Figure 17 along with soil conditions in the area. The excavation cuts through 2m of overlying alluvium thence through a 7m stratum of limestone and bottoms out in the Cuisien sand. On either side of the excavation, approximately a 5m thick zone of Cuisien sand was injected with grout to prevent slope failures and boiling of the sand under seepage flow.

GENERAL COMMENTS ON GROUTED TUNNELING IN NUREMBERG

Nuremberg was visited during this trip for a number of important reasons. First, large scale chemical stabilization is underway for a new underground transport system. Second, the use of chemical stabilization for tunnels is relatively new and grouting concepts are in a state of flux as opposed to the static ideas found in London and Paris. And, third, basic research into grouted material behavior is underway in Nuremberg. Visits were scheduled with the Nuremberg Transit Authority and the Soil Mechanics and Foundations Institute in Nuremberg. The institute provides consulting services to the city on tunneling and is

Not to scale

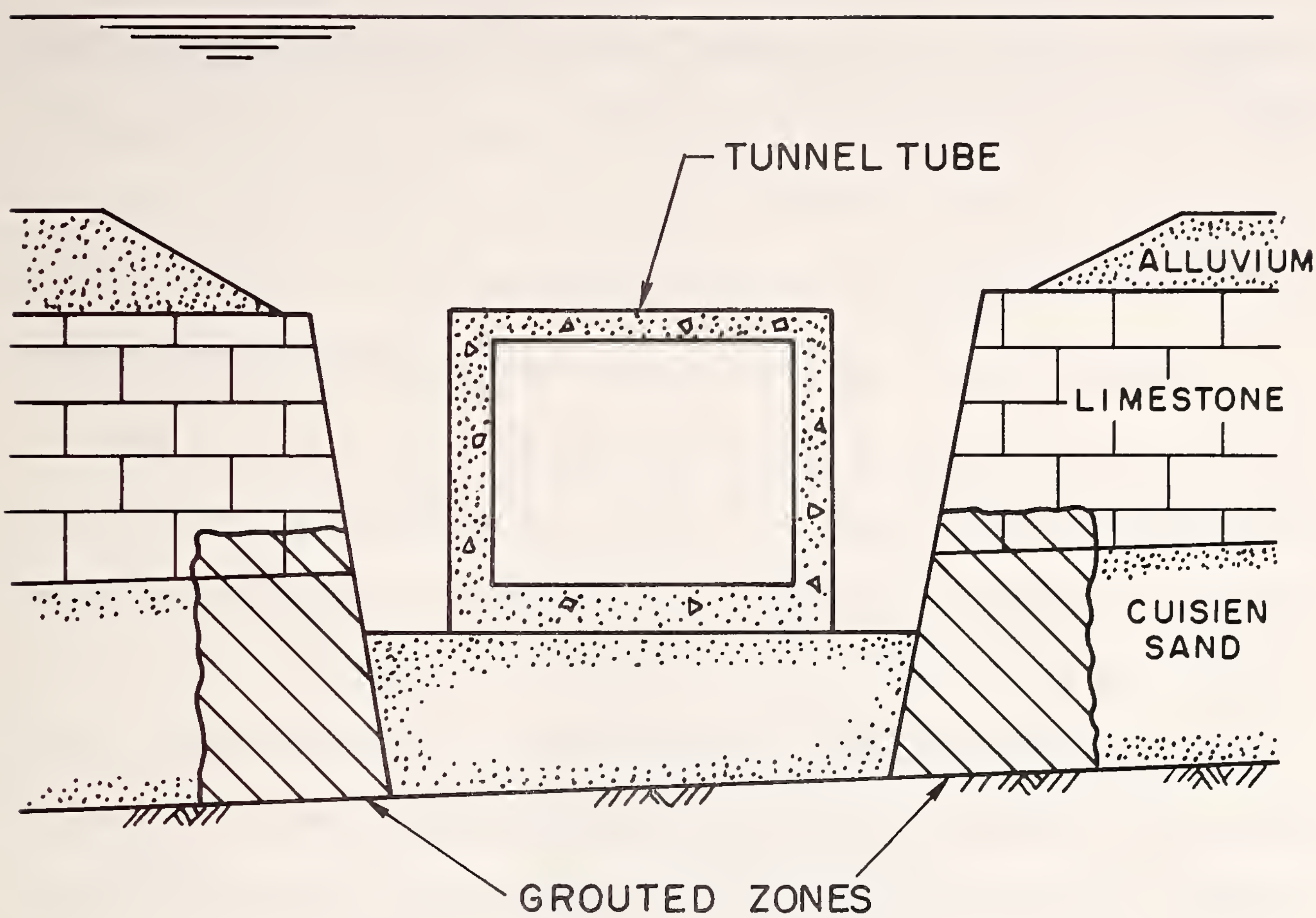


FIGURE 17. GROUTING OF CUISIEN SAND IN TUNNEL TUBE BED, JUNCTION LIGNES 13-14, PARIS METRO (COURTESY SOLETANCHE, S.A., PARIS, FRANCE)

conducting research into grouted soil behavior. Contacts were also made with researchers at the University at Kahrlsruhe, Germany where grouted material research is being performed, and with the Rhone-Prolenc Chemical Company, a major grout supplier in Europe.

Philosophy of Grouting

Chemical stabilization is employed for all of the same reasons given in the discussion of grouting in England or France. One slight difference in emphasis seems to be that more underpinning work for excavations is done with grouting in Nuremberg than in England or France. In some cases it is argued that grouting can in effect pay for itself because no excavation bracing is required and the excavation can be cut back to the extremities of the adjacent foundation lines, thus saving the space that would be occupied by the wall system. The added space in the excavation is counted as a savings to the owner.

Full scale grouting for tunnels in Nuremberg is being performed for the first time, but considerable chemical underpinning had been done prior to the present tunnel work. The use of grouting for the tunneling is still an issue of some controversy; some engineers suggest that the tunneling could be performed adequately with little or no grouting. However, the prevailing opinion was one that the grouting served to minimize risks and possibly prevented some locally disastrous runs or movement due to the tunneling.

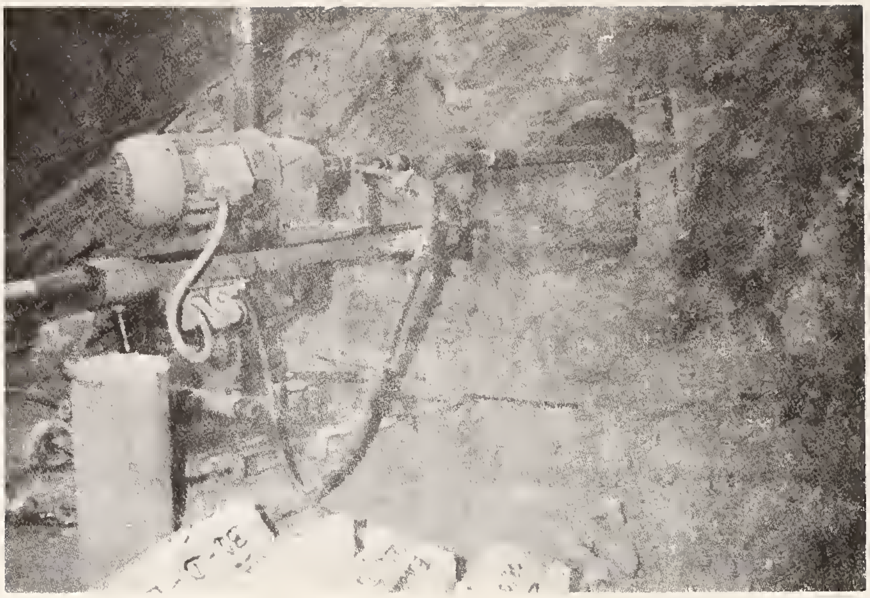
Design and Quality Control

In the area of design and quality control substantial differences exist between the Nuremberg approach and that used in France or England. In Nuremberg the design and quality control follows more along the lines of a conventional engineering approach. Design is based on structural concepts and in some cases results of finite element studies as well as experience are used.

The quality control program requires that samples be cored from the grouted areas and tested for strength in the laboratory. The samples must be able to develop a certain minimum strength (10 bars or 150 lb/sq in) and show a satisfactory resistance to creep or strength loss under constant load. This type control procedure was not encountered in any other visits; in fact, most grouting contractors maintained that grouted soils cannot be adequately sampled without destroying the grouted soil strength. Because of the requirements set in Nuremberg, however, the grouting contractor produces grouted soils which can be sampled and which are meeting the standards set for behavior.

Photographs of a sample being cored from grouted sand in Nuremberg are shown in Figure 18. Approximately six inch diameter samples are cored using a thin wall bit; water is circulated to flush the cuttings during drilling.

Specifications concerning grouting are being drafted by a National committee in Germany and Nuremberg engineers are on the committee. The specifications are scheduled to



(a) Coring Equipment

(b) Core of Grouted Material Being Removed

FIGURE 18. SAMPLING GROUTED MATERIALS IN NUREMBERG, GERMANY

be completed in 1976. A translation will be made at Stanford University upon receipt.

Types of Grouting and Grouting Processes

Grouting for underpinning purposes has been performed for some time in Nuremberg. A decade ago two shot processes were popular for this work, but more recently one shot techniques with newer grouts have been employed. However, problems have been encountered with strength losses in some newer grouts, and for underpinning work, any grouts used in a one shot process must pass a rigorous series of strength and deformation tests. These tests are designed to establish not only the short term but also the long term strength of the grouted soil. For the subway work grouting is carried out using a one shot grout with the tube a manchette technique. Details concerning these operations are given in a subsequent section of this report.

Subsurface materials in Nuremberg are typically sands or sandstones. Primary application of grouting is in the sands which are generally coarse grained with a relatively uniform gradation. Ranges of gradation curves for typical sands in Nuremberg are shown in Figure 19. The geology of Nuremberg provides near ideal conditions for grouting because of the nature of the sands and the relatively small variations in soil conditions.

Problems with Chemical Grouting

In spite of the generally good conditions for grouting in

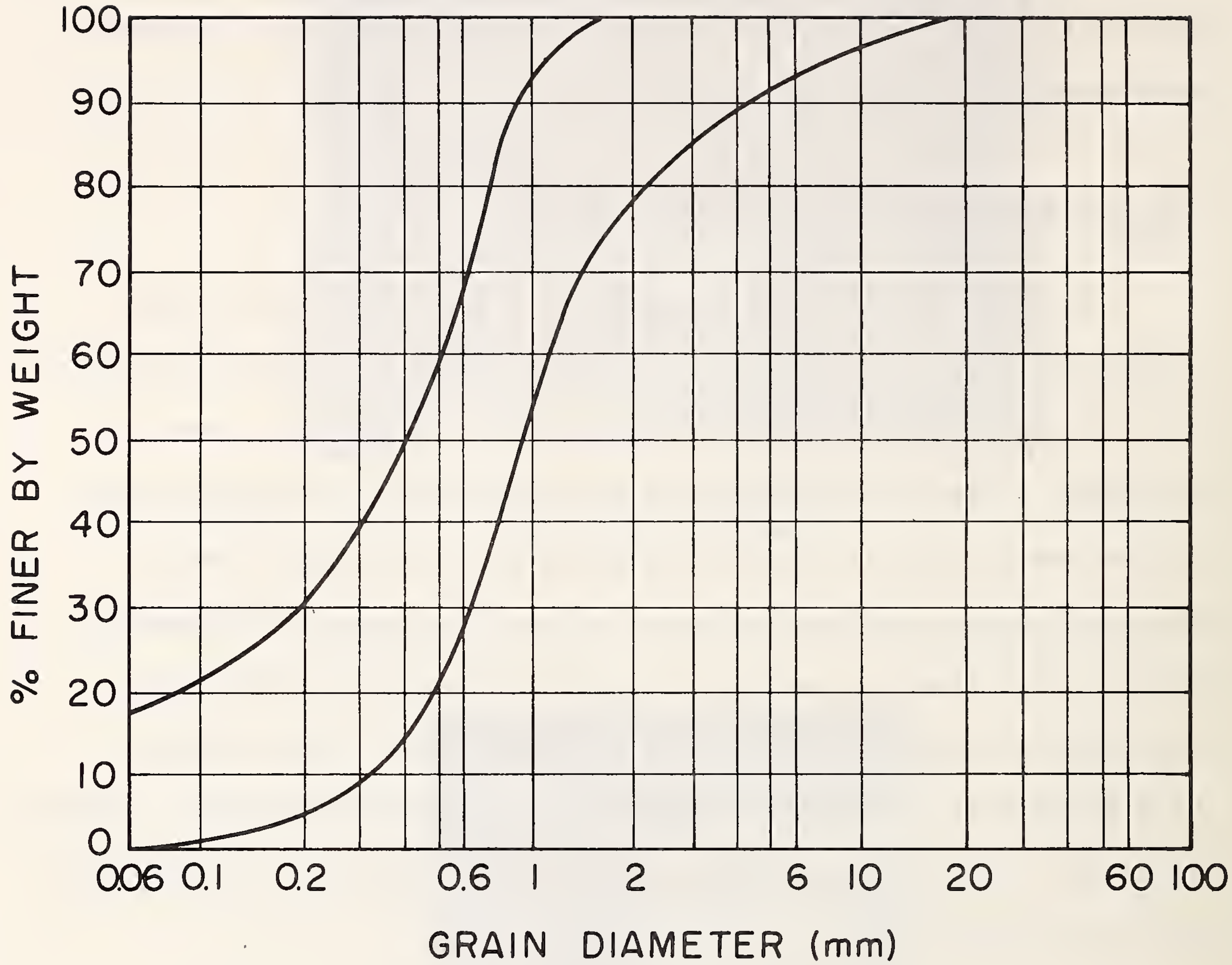


FIGURE 19. RANGE OF GRAIN SIZE CURVES FOR TYPICAL NUREMBERG SANDS

Nuremberg, the engineers there were careful to point out that even under these circumstances problems can occur if care is not exercised in the grouting. Some of the areas where difficulties had been experienced were as follows:

1) Loss of strength with time in some newer grouts (this problem is avoided by carefully testing the grouted sand in the laboratory).

2) Lack of full contact between the underpinning grout and the foundation (to solve this problem the grout-foundation contact must be probed and regrouted as necessary). The lack of contact can be due to inadequate migration of the grout or an inaccurately described location of the foundation level, a common problem for older foundations.

TUNNEL GROUTING PROJECTS IN NUREMBERG

Extensive chemical grouting has been undertaken in downtown Nuremberg for the new subway system. The purpose of the grouting is primarily to strengthen the sands above the tunnels themselves and the sands beneath foundations which will be influenced by the tunneling. The visit to the sites of grouting were made with Mr. Erwin Gartung of the Nuremberg Foundations Institute and Mr. Paul Bauernfeind, Manager of Construction of the Nuremberg Transit Authority.

Grouting Schemes

As mentioned in the foregoing paragraphs, the sands at Nuremberg are generally coarse and the authorities in Nuremberg specified strength requirements for the grouted sands. Before bidding on the job each contractor was asked to grout a small test section so that the grouted soil could be cored and tested to determine if the proposed grout formula would meet the required strength. Most major European grouting firms engaged in the bidding and a German firm won the project for a total price of $3,000,000.

The grouting is being performed from the surface using the tube a manchette procedure; the grout is silicate based and is hardened by a new additive developed by Rhone Prolenc, a French chemical firm. The additive is sold under the name of Durcisseur 1000, and was specially developed for the Nuremberg work. Preliminary indications are that this additive produces a grout which does not lose strength under constant load nor show substantial creep under sustained load. At present, however, it is only adapted for coarser sands. Work is underway at Rhone Prolenc to document the performance of the new grout.

Figure 20 shows typical grouting zones to be used in Nuremberg above and around tunnel openings and under adjacent foundations. In Figure 20(a), the left-hand tunnel passes directly beneath a building foundation (within 5m of the nearest footing); this opening is covered on top and along the sides by a trapezoidally shaped zone of grouted sand. The opening is, of course, cut after the grout is in place, and the trapezoidal zone should theoretically limit movements of the founda-

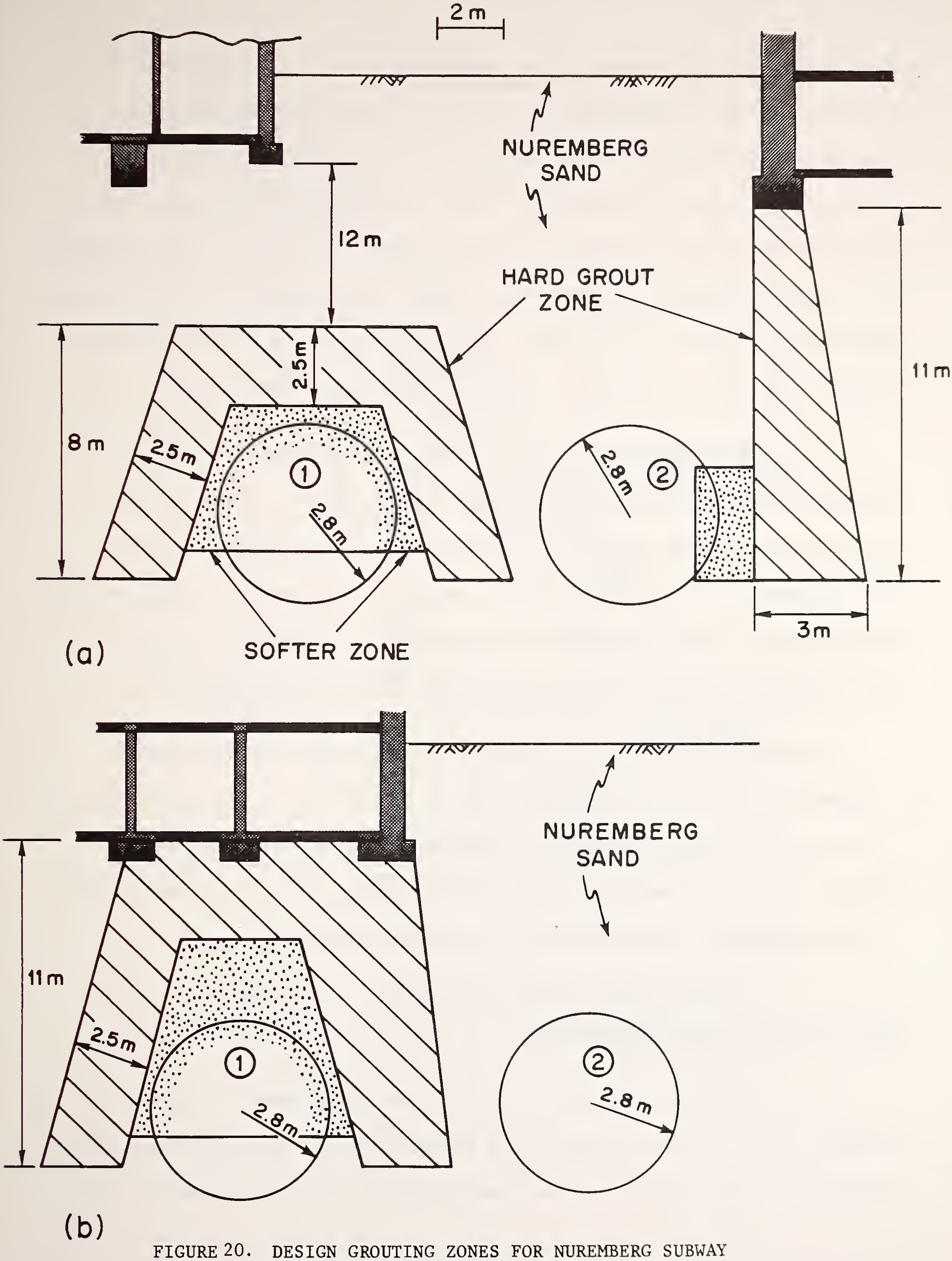


FIGURE 20. DESIGN GROUTING ZONES FOR NUREMBERG SUBWAY
(COURTESY NUREMBERG FOUNDATION INSTITUTE)

tion when the shield passes. The right-hand tunnel in Figure 20(a) is not directly under a building foundation; the nearest footing in this case is underpinned by a grout column. It should be noted that in the sections for both tunnels some of the grouted zone is shown using cross-hatching while some is dotted. The dotted zones are in the tunnel openings and represent material designed to be weaker than the cross-hatched regions. Weak grouts are injected in these areas to provide some cohesion and to prevent penetration of hardened grout into the tunneling area.

A second case of grouting is shown in Figure 20(b). Here, the left-hand tunnel again passes underneath a foundation. The grouting zone is trapezoidally shaped as in Figure 20(a), but in this case the zone extends up to be flush with the bottom of the footings. This provides underpinning to protect against the effects of the opening of the left-hand tunnel and also the right-hand tunnel which passes nearby.

Grouting of the sands is being done primarily from the surface as shown in Figure 21. Inclined holes are drilled so as to allow creation of the desired grout zone under the foundation. In plan, each row of inclined holes are spaced 1m apart. This operation will be clearly shown in the photographs discussed in the following paragraphs.

Observations at the Grouting Sites

Photographs of the grouting operations in Nuremberg are shown in Figures 22-24. In the background of photograph (a), Figure 22, the location of the central mixing and pumping plant in downtown Nuremberg can

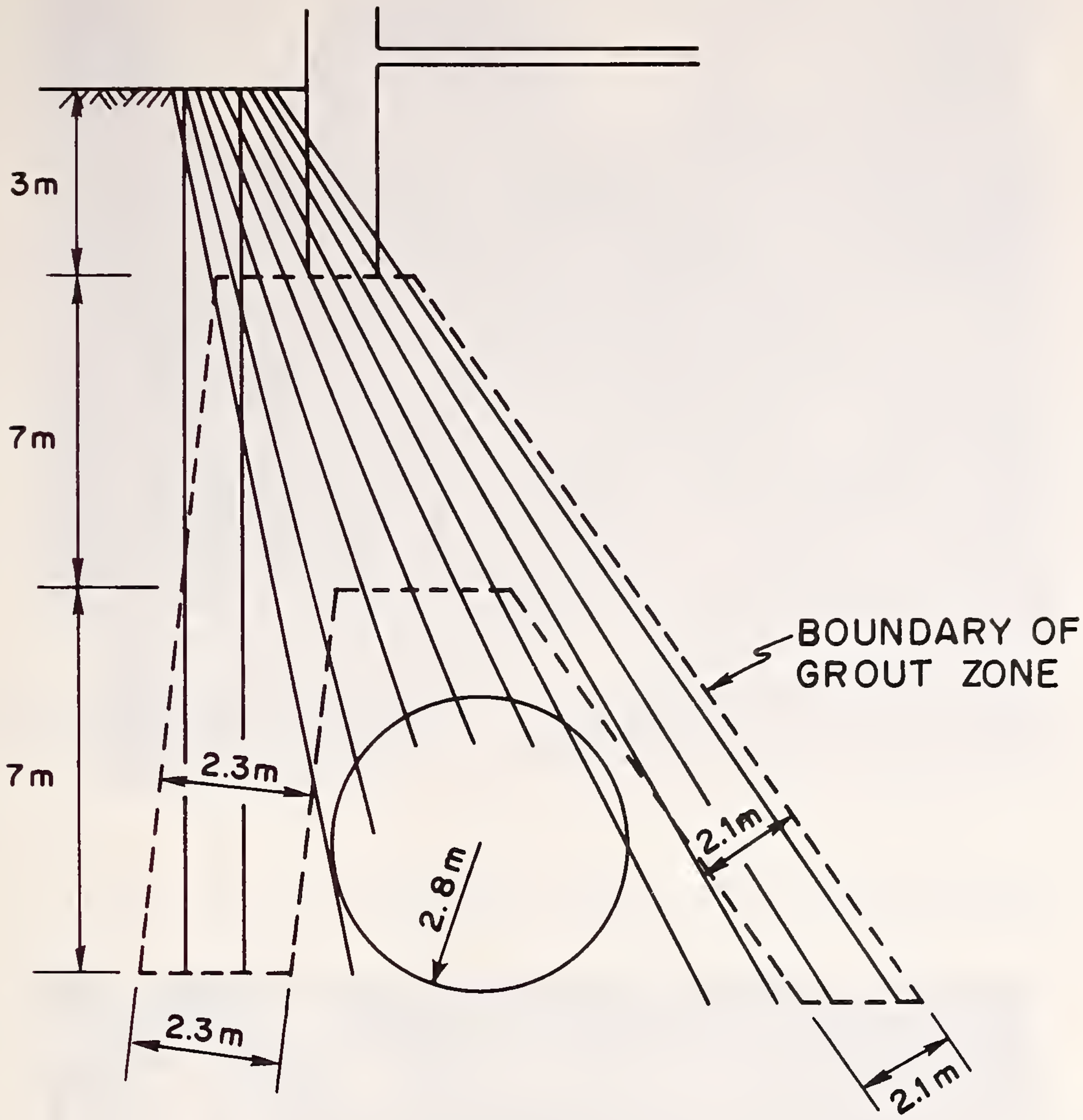
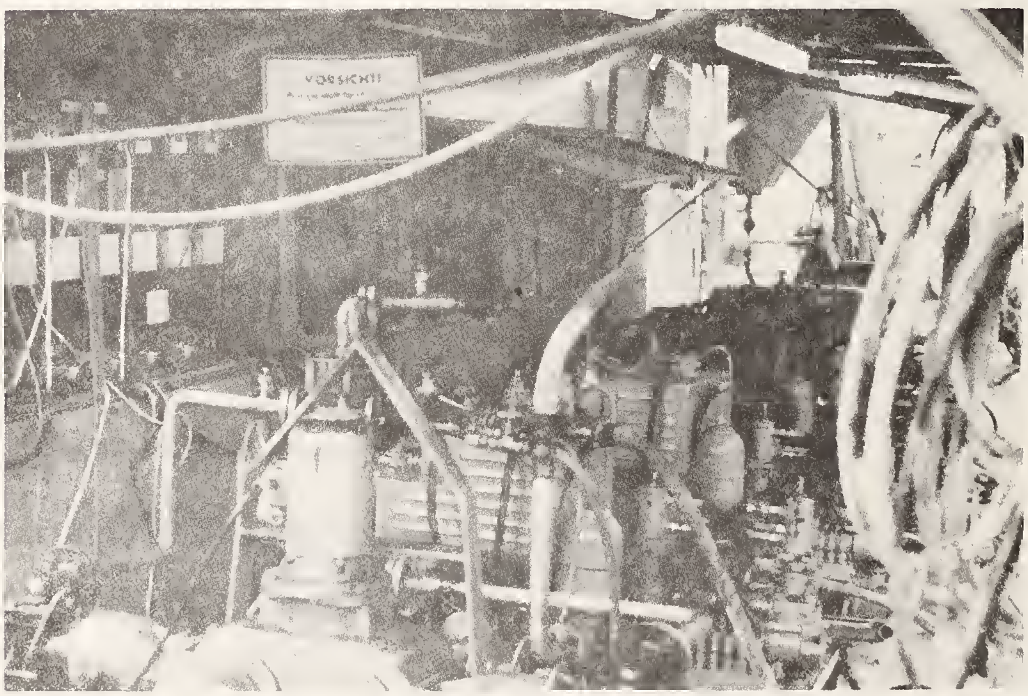


FIGURE 21. GROUT HOLE PATTERN USED TO CREATE UNDERPINNING GROUT ARCH

(a) Central Mixing Plant and Storage Silos, (Excavations on the Right and Left are Pits for Underpinning Grouting Operations)



(b) Pumps for Grouting Operations - Dosage Pump in Foreground, Double Acting Piston Pumps in Background

FIGURE 22. GROUTING OPERATIONS IN DOWNTOWN NUREMBERG, GERMANY

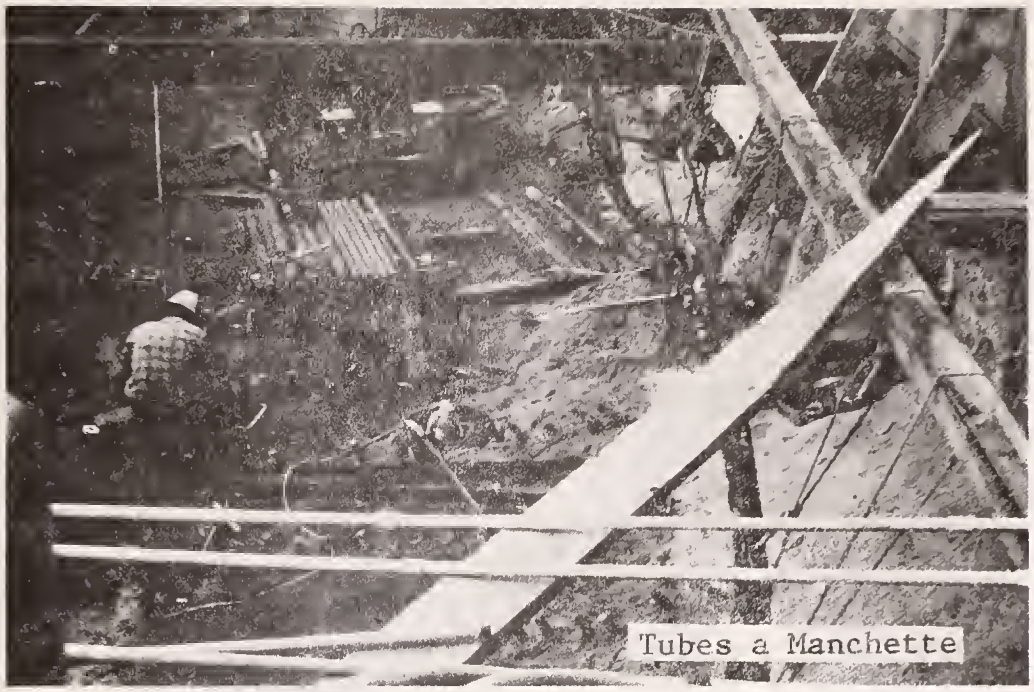


FIGURE 23. UNDERPINNING GROUTING IN NUREMBERG, GERMANY

FIGURE 24. EXPOSED GROUTED SANDS IN NUREMBERG, GERMANY - (Sand has no cohesion in natural state - must be jackhammered out after grouting - unconfined compressive strength about 20 bars)

be seen. The plant is identifiable by the storage silos; tunneling and grouting is underway on either side of the facility. An interior view of the central plant area is shown in photographs (b), Figure 22. In the foreground of photograph (b), Figure 22, the piston dosage pump may be seen; this pump controls the amounts of the various chemicals and materials being injected into the final mixing vat. Each component going into the mix is held first in the silos and subsequently in intermediate small vats which are filled automatically using a simple float controlled switch. From the small vats the chemicals are injected into the final mixing vat via the dosage pump. After final mixing the grout is pumped to the appropriate location by double acting piston pumps which can be seen in the background of photograph (b), Figure 22. Behind these pumps is the shack with controls for the grouting operations. In the shack, chart graphs are maintained for each piston pump in order to monitor flow rate, quantity of grout and pumping pressures. These data are recorded for each sleeve of the tube a manchette being grouted.

Operations at a site of underpinning grouting are shown in Figure 23. Rows of tubes a manchette can be seen spaced at about 1m; each tube is inclined at a different angle as was described earlier in the description of the general plans for underpinning grouting (Fig. 22). The foundation being underpinned is exposed on the right side of the photograph.

Exposed areas of grouted Nuremberg sand are shown in photographs (a) and (b) of Figure 24. In both cases the grouted sand was very hard and would not ravel when the surface was rubbed vigorously.

RESEARCH ON GROUTING IN GERMANY

Work on grouted soil behavior is underway at the Universities of Berlin, Karlsruhe and Munich and in the Foundation Institute of Nuremberg. The research programs are primarily directed at defining the behavioral aspects of grouted soils through laboratory and field loading tests. Some areas of overlap were found with these programs and the writer's DOT sponsored program. However, there are significant areas which are not common and the results of the studies should supplement each other well.

A full week of the writer's trip was spent in Nuremberg with the engineers of the Institute discussing their research work as well as observing the grouting operations in the city. Messrs. Erwin Gartung and Klaus Hilmer generously explained their research program, the technical details of their testing work and problems faced in developing a consistent testing effort. Important points made related to the testing of grouted soils are as follows:

1) Many grouts display time-dependent properties and rate of testing is a critical parameter.
2) Using some grouts, the grouted soils are weak enough to settle under their own weight; storage of these samples is not possible.
3) Preparation of identical specimens of grouted soil is difficult. Utmost care is needed to insure uniform penetration of grout.

4) Density and grain size of the soil significantly affects grouted soil strength; creation of the sand sample to be grouted must be performed carefully.

5) If the grout is nonuniformly pressured into a tube containing soil, the lower half of the sample will give different results than the upper half.

6) Grout will often react with sample membranes or capping compounds; this should be checked, especially before conducting creep tests.

7) Creep tests are essential because many grouted soils display creep-rupture effects.

8) The performance of sodium-silicate gel type grouts is influenced by temperature, density of the silicate, and sodium content of the silicate. All of these parameters must be carefully established.

During his visit to Nuremberg, the writer observed samples of grouted soil being prepared and tested in the laboratory. The information gained was used directly in the development of the grouted soil testing facility at Stanford.

SUMMARY AND CONCLUSIONS

The three week trip to England and Europe by the writer allowed exposure to ideas and operations regarding grouting which are simply not encountered in the United States. Grouting for shallow ground tunnels in England and Europe is commonplace and done on a scale not seen in the United States.

Perhaps the most important idea gained on the trip was that of the engineering philosophy towards grouting. Rather than thinking first of dewatering, compressed air, and conventional underpinning as solutions to tunneling problems, our overseas engineering counterpart often looks to grouting. Generally, grouting operations are designed before the project construction begins so that potential problems can be prevented; in the United States grouting is normally called upon after problems develop. In Europe, dewatering, compressed air and conventional underpinning are considered as last resort tools, somewhat as grouting is considered in the United States. Thus, our philosophies are essentially reversed.

Grouting overseas is expensive on a per cubic yard basis just as it is in this country. However, the cost of the total treatment are justified when compared to costs of use of compressed air or conventional underpinning. Experience with grouting has led to a confidence in this technique not given to other solutions. Costs of the grouting projects observed on the trip are difficult to put on a common basis. The costs vary with project size and difficulty; where price information was available, the chemical grouting treatments ran from $100 to $300 per cubic meter of treated soil.

The applications of grouting observed were numerous and varied. Grouting was used for underpinning, soil strengthening above and around tunnels, caisson bed stabilization, increasing rates of tunnel advance by soil stabilization, cutting off water through or around bulkheads and walls and reducing or eliminating the necessity for compressed air. Most of the applications were in areas of particularly difficult or critical conditions. Planning for the grouting generally was carried out in the design phase of the project.

Both two shot and single shot grouting techniques were observed. Applications of two shot grouting were being used only in the London area and primarily for shallow zones of treatment. Far more prominent was the one shot procedure, using the tube a manchette injection technique. Using this technique the grouting operator monitors quantity of grout injected, flowrate and grouting pressure. Control over the grouting mixture is exerted through gel times and viscosity. Finally, grout is injected through only one sleeve of the tube a manchette at a time to help define the location of the grout and allow different grouts to be injected at different elavations. The total volume of grout usually injected is around 25 to 40 percent of the ground volume being treated. The percentage is selected so as to completely fill the soil voids.

The types of grouts used in the projects varied with the soil conditions and the contractor. Resin grouts were used in silty-sands; in clean sands, silicate grouts were primarily used with some pregrouting of a bentonite-cement mixture if the soil was particularly coarse grained. The type of the silicate grout employed seemed to be a function of the contractor doing the job. Each contractor had a different version of the additive used to harden the grout and most of the additives are known only under their trade names, not chemical formulas.

Quality control of the grouting operations was an item of great concern with all parties. Until very recently the quality control has apparently been exercised by the grouting contractor. Stricter methods of evaluation of the grouting operations are surfacing. Guide specifications are being written in France and Germany; the French version is given in Appendix B of this report. The German specifications will be available during the course of this DOT project.

Research into grouted soil behavior is being actively pursued in a number of institutes in Germany. Of the research programs examined, none substantially overlap with that envisioned in the writer's DOT program. Based upon the writer's visit, lines of communication were established with European counterparts so that results of the various programs will be known to workers in the different countries.

It is hoped to convey through this report the very positive results of the writer's three week visit to England and Europe. Exposure to the overseas practice was invaluable in creating an understanding of grouting operations and the engineering philosophy towards grouting, both of which are different than in the United States. Information obtained during the visit provided directly useful information in the DOT sponsored research effort at Stanford. Further, contacts were established which will form a base of continuing communications concerning shallow ground tunneling. The writer is grateful to DOT for providing the monies for the trip.

APPENDIX A

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DURING EUROPEAN TRIP

APPENDIX A

INDIVIDUALS ENCOUNTERED DURING TRIP

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APPENDIX B

FRENCH GROUTING SPECIFICATIONS

RECOMMENDATIONS FOR THE USE OF
GROUTING IN UNDERGROUND CONSTRUCTION*

-FRENCH ASSOCIATION OF UNDERGROUND CONSTRUCTION-

1. INTRODUCTION

Geotechnical engineers who are interested in studying grouting as a treatment for soils, or who are involved in underground construction, will find this paper useful. The recommendations presented are not intended to solve all the problems of soil grouting. Solutions to such problems cannot be described by set rules. Whatever the quantity and precision of geological, geotechnical, and hydraulic information the planner has at his disposal to establish a construction program, the planner must always allow for some adaptation to unforseen local conditions. The results obtained during construction should guide and orientate the program, and often lead to modification of previously planned construction programs.

The main purpose of these recommendations is to define a methodology of studies and controls, and to focus attention on parameters to be considered in establishing a grouting program. Moreover, they can lead to definitions of technical and financial criteria during planning of a project that allow a comparison of grouting to alternate methods of construction.

These specifications have been established by a group of technicians and engineers who have a great amount of experience in construction projects involving grouting. The study groups created by the French Association of Underground Construction (AFTES) have received the endorsement of the Technical Committee of AFTES. The people who have been involved in the study believe that grouting techniques, when well applied, may help to solve the delicate problems of soil stability, particularly in cases where it is necessary to make excavations below or tunnel under the ground water surface.

2. APPLICATIONS OF INJECTION GROUTING

Injection grouting has a large variety of applications. These applications are influenced by the following factors:

- -- use of the building or facility
- -- urban or non urban site
- -- depth and geometry of the construction
- -- nature of the ground
- -- water tightness or strengthening
- -- temporary construction or final project
- -- preventative or curative construction

* Original version in French, translated at Stanford University under the supervision of Professor G. W. Clough, Civil Engineering Department

2.1 Ground Treatment Prior to Excavation

2.1.1 Strengthening

If the ground has no mechanical strength, the strengthening grouts, when they can be used are intended to allow

- -- easier construction and safer excavations
- -- the crossing of zones (soft ground, for example) which could not be crossed using traditional methods
- -- the crossing of zones where environmental conditions are unfavorable

2.1.2 Water tightness

Injections for watertightness result in walls or screens which greatly reduce the underground circulation of water, air, or other gases. Watertightness can insure acceptable conditions when working in

- -- generally good rock, but which has a high water content and is very fractured
- -- very permeable ground which would be unstable if acted on by water forces

Remarks:

(a) In paragraphs 2.1.1 and 2.1.2 above, one must consider that the treatment may be done before excavation either from the ground surface or from auxiliary works or during construction progress.

(b) In general, grouting to achieve strength has some watertightness effect as well.

2.2 Treatment of New Structures

Injection grouting for new structures is designed to have a strengthening and/or watertightening effect in the zones of earth situated outside the walls or linings. Stages of the grouting are given in the following paragraphs.

2.2.1 Filling Grouting

In underground work, filling grouting is used to fill the voids which can be created behind a liner or wall. These injections reduce ground alterations, and produce a favorable pressure distribution over the whole arch. They are made without pressure; as a principle, a value of 0.3 Mega Pascals (1MPa = 145 psi) should be considered as a maximum.

2.2.2 Gluing and Tightening Injections

Gluing and tightening injections are usually made after filling injections in order to improve the interface between the ground and a lining, and to give a light treatment to the surrounding ground. As opposed to the filling injections, the pressure must be higher and the grout more fluid. Pressures used are dependent on the

2.2.2 (cont.) strength of the lining; one MPa should be considered as a maximum. The gluing of concrete to steel plate is a very specific grouting application, requiring great care. The injection is usually made by hand pump, or by gravity flow caused by hammering the steel plate.

2.2.3 Strengthening Grouting

Strengthening grouting is usually made after the filling and gluing grouting. Its purpose is to improve the mechanical characteristics of a ring of ground around the structure whose thickness is dependent on the condition of the soil.

2.2.4 Other Treatments

Other treatments could include:

-- junctions to other structures, or as part of a general watertightness plan
-- circular screens for protection against damaging circulations, such as water around structures.

2.3 Treatment of Structures in Use

For these structures one can use the different methods described for new structures. However, the injection pressures will have to be lower than those described for new structures; the pressures have to be decided based on the nature and state of the ground and of the lining. Before soil grouting, regeneration of the lining may be required. Such an operation is risky in the case of a rock or brick masonry lining. In this case the deterioration of the lining, often due to the water circulation within the lining, diminishes the water tightening and mechanical characteristics of the treatment. The regeneration injection aims at decreasing the porosity of the lining, thus improving the strength and water tightness. These two results are a function of the type of treatment used.

3. GROUTS

3.1 Introduction - Principles of Injection

The main purpose of grouting is to modify the characteristics of a rock or soil in order to reduce the permeability and/or increase the mechanical strength. To obtain these results, one fills the voids of the medium to be improved with a product, either liquid or suspension, which solidifies with time. This liquid is called grout. It is pumped into the medium under pressure through holes which are drilled into the ground.

3.2 Types of Grouts

Grouts can be classified in two main categories

-- stable or unstable suspensions
-- liquid solutions or emulsions

Unstable suspensions generally are simple cement based grouts, and are homogeneous only as long as they are mixed. Stable suspensions generally are obtained by mixing a combination of cement and clay or bentonite, and possibly some additive in water. The liquids are made of chemical products and such reactives as resins or hydrocarbonized products in solutions or emulsions. In Figures 1B and 2B a summary of the available grouts, their regions of applicability, and their functions are described. In the following paragraphs, details of the grouts are given.

3.2.1 Cement Base Grouts

3.2.1.1 Properties and Characteristics

-- penetrability limits are a function of the grain size of the components
-- it is possible to vary the rheological characteristics
-- resistance to compression is dependent on the cement/water ratio
-- it is possible to fill large voids economically
-- preparation and supply are simple
-- using the right cement provides resistance to chemical attack

3.2.1.2 Cement Suspensions

-- unstable grout
-- possibility of large variation in cement/water ratio, 1/10 to 25/10
-- the deposit in the cracks consistutes a kind of hydraulic film which provides an important connection between injection pressure and the possibility of water drainage
-- mechanical resistance is very high

Uses:

-- mainly for strengthening of cracked rock: injection of open cracks, gluing injection, injection of contraction joints, and masonry regeneration.

3.2.1.3 Clay Cement

-- stable grout: mixture of cement and natural or treated clay or bentonite.
-- the addition of clay to the cement grout allows improvement of its imperviousness, its rheological properties (penetrability, thixotrophy, and viscosity) and its resistance to erosion
-- the addition of clay delays the setting time
-- mechanical resistances from a few tenths to 10 MPa can be obtained; this variation is dependent on the cement/water ratio, and the quality of the cement, especially for cement/water ratios larger than 0.2

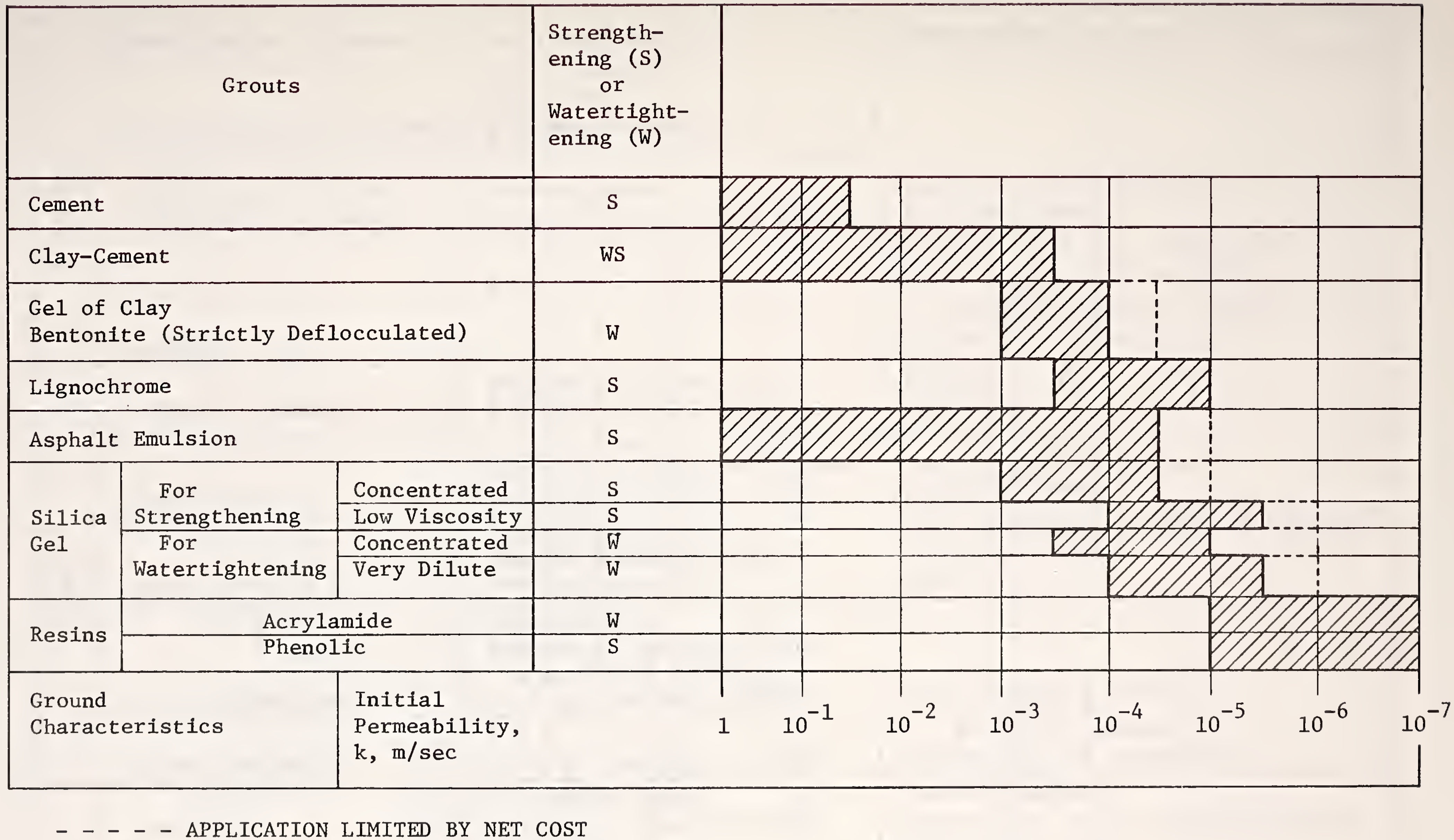


FIGURE 1B. GROUT APPLICATIONS IN LOOSE SOIL

		WATERTIGHTENING	STRENGTHENING
SOILS	Coarse Sands, Gravels	Clay-Cement Bentonite-Cement + Silica Gel	Cement-Clay Cement-Bentonite + Gel
	Sands	Bentonite Gel Silica Gel	Silica Gel + Cement-Bentonite Silica Gel (Tough)
	Silty Sands	Silica Gel (Very Diluted) Acrylamide Resin	Silica Gel, Tough with Low Viscosity Phenolic Resins
ROCKS	Voids (Openings)	Clay (or Bentonite)-Cement	Cement-Clay (or Bentonite) + Weighting Material
	Karst, Large Fissures	Clay (or Bentonite)-Cement + Weighting Material Aerated or Swelling Grouts Hot Asphalt	Grout Foam with Cement
	Medium Fissures	Bentonite-Cement Bentonite-Cement + Fine Weighting Material	Cement Cement-Bentonite Cement-Bentonite + Weighting Material
	Fine Fissures	Bentonite-Cement Very Fine Silica Gel + Bentonite-Cement (Very Fine)	Very Fine Cement Very Fine Cement-Bentonite
	Very Fine Fissures	Bentonite Gel-Silica Gel Acrylamide Resins	Silica Gel Phenolic Resins
STRUCTURES	Filling		Cement-Clay (or Bentonite) + Weighting Material = Fine
	Gluing	Bentonite-Cement	Cement + Admixtures to Make Fluid and Stable (Bentonite)
	Regeneration of Masonry with Open or Exposed Holes	Bentonite-Cement (Very Fine) Aerated Grouts	Very Fine Cement Very Fine Cement-Bentonite
	Active Cracks or Fissures	Acrylamide Resins Mixed Gels Latex Emulsions	
	Fine Fissures or Cracks	Acrylamide Resins	Epoxy Resins, Polyesters ...

FIGURE 2B. TYPICAL GROUT APPLICATIONS

3.2.1.3 (cont.) Uses:

- -- strengthening (high percentage of cement, low percentage of clay)
- -- watertightness (low percentage of cement, high percentage of clay)
- -- treatment of rocks having small or large fissures, or karst-like profiles.
- -- treatment of granular soils with very high permeability (usually a pretreatment - see paragraph 3.2.2)

3.2.1.4 Weighted Grout

- -- a stabilized suspension in which the cement or clay-cement grout is weighted with an inactive product
- -- weighting products most often used are sands and loose cinders; others sometimes used include fillers, pozzolana (volcanic ash), and diatomites
- -- the ratio of weighting product to cement may be as high as three
- -- mechanical strength generally is high
- -- economical grout

Uses:

- -- economical filling of large voids or holes, or open cracks
- -- regeneration of masonry having large holes

3.2.1.5 Special Grouts

Next to the above mentioned classical grouts, there are a variety of grouts used for very special applications.

3.2.1.5.1 Fast Setting or Controlled Stiffness Grouts

A suspension of cement or clay-cement with an additive which causes a reduction of the setting time from a few hours to a few minutes. The time is dependent on the amount and type of cement and additive used. Additives used include silicate of soda, calcium chloride, aluminous cement, and plaster. Such grouts are used to plug water leaks or stop water circulation, and to limit the distance over which other injections act.

3.2.1.5.2 Aerated Grouts, Swelling Grouts, Cement Foam Grouts

These are suspensions of bentonite cement with an additive that promotes the formation or retention of micro bubbles of gas before or after grout injection. Such grouts are used in injection filling of large holes. Sometimes aerated and swelling grouts are used to obtain watertightness.

3.2.2 Gels

3.2.2.1 Properties

-- principally a soda silicate based grout, diluted with reactive minerals (resulting in soft gels) or organics (resulting in hard gels). The setting time is controlled by the amount of mineral or organic used.
-- the injectability is dependent on the viscosity of the grout
-- optimum regions for use of gels:
   (1) soils having permeability varying from 10^{-3} to 10^{-6} meter/sec (fine to very fine sands)
   (2) rocks having permeability varying from 1 to 10 lugeon units (fine fissures or cracks)

Characteristics:

-- grout has low viscosity during injection, but increases rapidly during setting
-- injection pressure usually reduced in urban construction from 0.5 to 2 MPa, though it is possible to use large pressures.
-- mechanical strength of the treated soil is dependent on the grain size of the soil and the composition of the grout. The strength increases as the grain size decreases, but the mineralogical characteristics of the soil and the chemical characteristics of the ground water can modify the results over a large range.
-- the size of voids in the soil influences the syneresis phenomena (the contraction of a gel, with expulsion of free water), therefore a previous treatment with clay-cement or bentonite-cement grout is used to fill the large voids
-- temperature influences the setting time
-- there are two main types of gels:
   (1) watertightening or soft gel
   (2) strengthening or hard gel

3.2.2.2 Watertightening Gels

-- mixture of diluted soda silicate with a reactive mineral (most often bicarbonate of soda or aluminate of soda) added before injection
-- dilution is generally high (silicate to water ratio of 0.25). Viscosity is very low (close to that of water)

Uses:

-- watertightness treatment used for soils ranging from coarse sands and gravels (alluvium) to fine sands. If the alluvium is loose, the gel injection must be preceded by a clay-cement or bentonite-cement grout treatment

3.2.2.2 (cont.)

-- treatment of porous or fissured rock; in this case the gel injection comes before the injection of cement or bentonite-cement grout
-- treatment of finely fissured or cracked rock

3.2.2.3 Strengthening Gels

-- mixture of concentrated sodium silicate and an organic reagent. The reagent most often used is an ester type of ethyl acetate or a derivative of diacids. Lighter or heavier esters are often used in gels to lengthen or shorten the setting time. Other reagents include formamide and glyoxal.
-- viscosity varies from a few centipoise up to 25 centipose for the highest concentration gels
-- the compressive strength of sands treated with these gels can vary from one MPa to values higher than 3 MPa, depending on the dilution of the grout and the characteristics of the sand

Uses:

-- strengthening of alluvium with grain sizes down to that of fine sands. If the soil is loose (has open voids), it must be treated with clay-cement prior to an injection of gel in order to limit synerisis
-- injection in rocks with very fine fissures

Note: one should keep in mind that the presence of free sodium may necessitate special care in secondary work like paving or painting.

3.2.2.4 Special Grouts

The gels described in the previous paragraphs are most often used, but there are a number of grouts used in very special cases.

-- mixed gels: mixture of silicate gels and acrylic resins. Principally used for treatment of active fissures or cracks.
-- clay gels: mixture of clay (bentonite) with silicate and a peptic reagent.

Uses:

-- watertightness of alluvial soils with large voids
-- finish sealing a watertightening wall after the voids have been injected with a clay-cement or bentonite-cement grout
-- watertightening under weak coverings
-- watertightening of soils that are hard to treat with a cement base grout, and that do not justify the use of a gel
-- lignochrome gels: mixture of lignosulfides and bichromite of potassium or of sodium, which is the gel agent. Used for watertightening loose alluvial soils previously treated with bentonite-cement, when the presence of soda is to be prevented.

3.2.3 Resins

3.2.3.1 A solution of organic products in water or in a nonaqueous solvent, which at ordinary temperatures and in a closed medium will form a solid with adequate mechanical properties.

3.2.3.2 General Statement of Processes

In these specifications, resins are classified depending on their hardening mechanism; this defines their use. Three mechanisms can be differentiated:

- -- polymerization/reticulation: this phenomenon corresponds to the opening of a duplicate union
- -- polycondensation: this is the condensation of one or several products with the elimination, usually, of water, and the formation of a two or three dimensional system.
- -- polyaddition: this is the reaction of two or more products resulting in the formation of a two or three dimensional system.

3.2.3.3 Fields of Application

Resins are used where the long life or permanence of the treatment is necessary, and where the high viscosity of other products obviates their use. Resins have two main fields of application: the strengthening or watertightening of very fine granular soil; or the repair or regeneration of structures. In the first case the requirement of low viscosity is most important. Resins in aqueous solution to be used for watertightening or strengthening have a viscosity close to that of water, and will maintain such viscosity until hardening. Moreover, the setting time can be easily determined. For watertightening one uses monomer acrylics (polymerization/reticulation), whereas one uses monomer phenolics or aminoplasts (polycondensation) for strengthening. In the second case, adherence of the resin to the structure supports is essential. Other factors may also be important in choosing a specific resin. For a strengthening injection, a nonaqueous resin hardened by polymerization (polyesters) or by polyaddition (epoxy) is best used. Preferably, the resins should not contain a nonactive dilutant, so that their volumetric stability is maintained. If watertightness is desired, aqueous resins hardened by polymerization/reticulation (acrylamides) should be used.

3.2.4 Other Grouts

The following grouts find selected application but are not often used:

- -- Hot asphalt. Asphalt is totally inactive with respect to all corroding agents, and does not age; this is important with respect to watertightening

3.2.4 (cont.)

-- Emulsion of asphalt. Water and asphalt emulsions to which a stabilizing and rupture agent has been added (watertightening).
-- Latex grouts

4. PLACING OF GROUTS

The placing of grouts is a delicate operation; methods and technology adopted should be fitted to a specific case. Almost all projects will involve some adaption to conditions; any planning must allow for such modifications.

4.1 Drilling Equipment and Methods of Injection

4.1.1 Rock

4.1.1.1 Drilling

In rock, drilling may be rotary or rotopercussive with a circulating fluid such as air, water or mud.

The diameter of the injection hole in rock is usually between 1.5 and 3 inches (38 to 75 mm). The depth of drilling is often limited by the drift of the hole from its desired course. For strengthening or watertightening projects, preliminary test borings aid in planning the locations of drill holes. (See paragraph 5.1.3.4).

4.1.1.2 Methods of Injection

Three principle methods of injection are used currently.

4.1.1.2.1 Branching in Front of Drilling

This method is used only for shallow treatments, including filling, tightening, gluing and strengthening injections for depths less than 10 metres.

4.1.1.2.2 Injection by Upward Sections

This method consists of drilling in one step to the required depth, then injecting the rock in sections, moving up with a simple packer. The length of hole filled in each step varies from 3 to 10 metres, depending on the case. (See Figure 3B).

Advantages:
-- economical operation
-- separation of the drilling and injection operations

Disadvantages:
-- cannot be used in the case of very highly cracked rock
-- cannot be used in rock that is so cracked or fissured it would eliminate effectiveness of the packer.

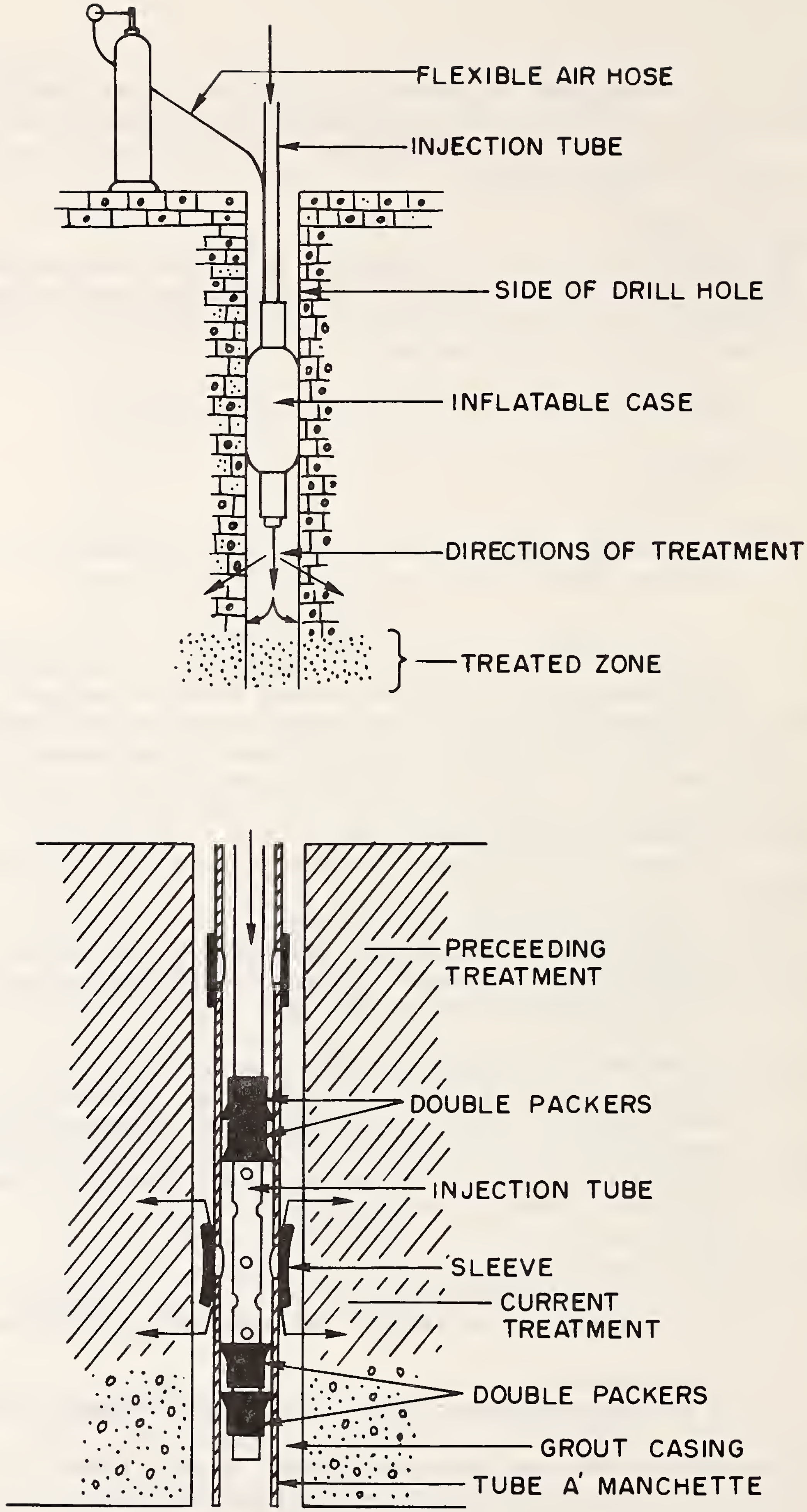


FIGURE 3B. INJECTION BY UPWARD SECTIONS AND TUBE A MANCHETTE

4.1.1.2.3 Injection by Downward Sections

This method consists of drilling a section 3 to 10 metres in length, then injecting the grout while employing a packer. For the following sections two options are possible. One, scour the section previously injected and drill the next section; the pressure in scouring the first section must be sufficient to allow the disturbance of the grout. Or two, after the grout in the first section has set, drill through it and continue drilling the next 3 - 10 metre section. This section is then injected and process continued.

Advantages:

- -- a protecting roof is formed above deeper sections, allowing higher pressures to be used in injecting deeper sections.

Disadvantages:

- -- drilling and injection operations are mixed, requiring the stopping of drilling and continuous removal and replacement of drills, possibly resulting in an alignment problem.
- -- drilling through grout placed in preceding sections.

The sequence of drilling and injecting of sections is largely dependent on the required treatment and the characteristics of the rock. In most cases one will try to accomplish the treatment by progressive tightening.

4.1.1.3 Pressure and Grout Flow

Pressure and grout flow must be checked constantly to prevent the development of problems in nearby structures or in the rock itself. This is especially true when large quantities of grout are injected. The maximum pressure attained, or the refusal pressure, is dependent on several criteria, including

- -- the purpose of the construction
- -- the nature and degree of cracking or fissuring in the rock
- -- the state of the injected section
- -- the hydrostatic pressure
- -- the type of grout injected

In some cases, especially when strengthening is desired, it is recommended to apply increments of pressure in steps until the refusal pressure is reached. Sometimes a prestressed effect is required. For cement base grout the injection is usually begun using diluted grout, then the cement/water ratio is gradually increased until the refusal pressure is reached.

4.1.2 Soft Ground

4.1.2.1 Drilling

Drilling in soft ground is accomplished in the following ways

- -- with the installation of temporary casing, which can be placed by percussion, rotation or water pressure techniques
- -- without casing by rotation or rotopercussion using a drilling mud or grout or a casing grout (see paragraph 4.1.2.3).

As in rock, the depth is usually limited by the amount of deviation of the drill hole from its desired course. For the arrangement and spacing of the drill holes see paragraph 5.1.4.2. A test boring is even more useful than in the case of drilling in rock. Information useful for determining the arrangement of drill holes, the methods to be used, and the type of grout to use (see paragraph 5.1.3.4) is provided by test borings.

4.1.2.2 Methods of Injection

The injection is usually made in one metre or smaller segments using the tube-a-manchette method. In special cases injections are made as the boring progresses, or in an upward fashion, by tube-a-brocher.

4.1.2.2.1 Tube-a-Manchette

This is the method most often used, and is the safest method for injections in soft ground. It consists of placing a tube inside the drill hole. The tube has pairs of holes, spaced at 0.25 to 0.5 metres, which are protected by a rubber valve or sleeve. The tube is sealed in the ground by a special casing grout (see paragraph 4.1.2.3). Injection through the tube-a-manchette is made using a double packer allowing injection to proceed sleeve by sleeve, either going up or going down the tube and at any level. Among the advantages of this method is that any section can be regrouted any time after the tube has been cleaned. (See Figure 3B).

One usually proceeds with progressive tightening by injecting in different steps using grouts progressively more penetrating, varying the order of injection along different lines, and by using both primary and secondary lines. Some borings will serve mainly in a confining role; in these borings only clay cement grout may be grouted. In other borings, more complete grouting is done. Sometimes injection must begin from the center of the grouting area to avoid trapping water or to reduce the risks of swelling. Finally, a second injection of grout having different properties in some of or all the section of a hole is used.

4.1.2.2.2 Grouting During Boring

In some cases the tube-a-manchette method cannot be used, as in the case of tunnel galleries with geological problems or having high hydraulic loads. It may then be necessary to treat the ground as the boring progresses by systematically redrilling segments previously grouted. In this case the drilling must be done with a blowout prevention device in the hole (screen with pressure caulking that maintains the integrity of the hole). The grouting is done section by section, either by head branching or through the use of drilling rod which maintains the pressure in the head. Such problems usually require successive injections of silicate grouts and clay-cement based grouts.

4.1.2.3 Casing Grout

Casing grout has an important role when injection is made by the tube-a-manchette method. The composition of the grout must be such that it is not too plastic to prevent its flowing in the drill hole, nor to strong to prevent the opening of the protective sleeves. This grout can be placed either during drilling or from the bottom of the hole as the casing is removed. This grout fills the largest voids and can be considered as a pre-injection which increases the efficiency of the grouting operation.

4.1.2.4 Pressure and Grout Flow

The criteria presented for rock in paragraph 4.1.1.3 are valid for grouting in soft ground. These recommendations are particularly important when grouting at shallow depth and/or close to occupied buildings, such as in an urban area. In this case a very fluid grout would be injected at a low flow rate (reduced to a few litres per minute, if need be) and under low pressure.

4.1.3 Treatment of Structures

The recommendations made concerning control of grout flow and injection pressure should be emphasized when treating structures, particularly when treating old structures.

4.1.3.1 New Structures

As the walls of new structures are generally made of concrete, treatment is usually not required except at the joints and between lifts. In this case, one can apply different products, usually made of cement and rubber or resin. However, it is often necessary to treat the openings behind walls to fill up holes which remain after the concrete has been poured (see filling or gluing injections in sections 2 and 5). For filling injections it is necessary to drill through the wall to treat the opening.

4.1.3.2 Old Structures

In general, the regeneration of masonry by injection grouting is very expensive; a cost-benefit analysis will most often result in a decision to rebuild the structure considered. However, in the case of tunnels, special conditions affecting their stability or use may require their treatment even if the cost is very high. Many types of tunnel liners can be encountered, including rock, stone, brick and concrete. Each might require different preventative measures be taken on the outside and inside of the lining to ensure the grout remains in the lining itself.

Brick lining. Regeneration by routing does not seem justified.

Stone-masonry lining. The inner side is treated by a deep rejoint. The annular space is usually filled with a cheap mortar. However, some situations may require special treatments - for example, the presence of a pipe network. In this case the treatment must be accomplished inside the joints using a fluid grout (pure cement grout, special resin grouts) being careful not to drill completely through the lining. In masonry that is in good condition, the quantity of grout injected is small, perhaps as little as a few liters per hole. For masonry that is in poor condition, the grout has to penetrate to the annular space. For tunnels where the voids are important, regeneration and filling grouting are done in one step, requiring that the drill hole penetrate to the annular space.

Concrete lining. For concrete lining the facing can be treated with gunnite or a similar product. The treatment of the annular space and further regeneration is accomplished as described for stone-masonry. It is very important to make a preliminary estimate of the liner's permeability (see section 5.3)

4.2 Preparation and Transportation of Grouts

4.2.1 Preparation

4.2.1.1 Suspensions

Mixers having a broad range of power and capacity (5 to 25 hp, 100 to 3,000 liters) can be used. Materials are supplied in sacks if small quantities are required, but silos with transport screws are generally used. Water quantities are measured with flow meters.

4.2.1.2 Liquids and Emulsions

The correct proportions are obtained from containers having automatic sluices for filling and emptying, or through pumps which can measure the proportions independently of the flow. Achieving homogeneity of the mixture may require intensive mixing. The materials required to make the grouts are generally stored in silos or containers.

4.2.2 Placing

4.2.2.1 Pumps

Compressed air equipment is no longer used for injection grouting; pumps having flow and pressure control are presently used. The pump usually has two pistons, and is activated by a pneumatic motor or by an electric or thermal motor with hydraulic transmission. In either case a satisfactory flexibility is obtained. Special equipment which allows flows as small as a few liters per minute is required when injecting chemical products. Screw pumps allowing flows of 20 cubic meters per hour are used when injecting very thick filling grouts or mortars.

4.2.2.2 Packers

Double rows of rubber spacers remain in common use for the drilling of large diameter holes. The principle of compression is also found in the modern use of single row, very manuverable expansion devices for drilling small diameter holes. These are supported by abutting the bottom of the hole, or are automatically friction anchored against the sides of the hole by drilling.

Auto-inflatable casing packers are used less and less, being replaced by inflatable cylinder packers, which are inflated by an auxiliary fluid such as air or water. This type of packer has the great advantage of being usable in poor rock, or even in soft ground because of their long length. These packers, either single or double type, are available with diameters up to 150 mm.

Finally, bell-shaped packers are used only in holes drilled in sound rock. Extensive cracking or other discontinuities in the boring will obstuuct the use of this type of packer. The packers are either a single or double type, made of leather or rubber. They are used with the tube-a-manchette method.

4.2.3 Injection Plant

In the case of a project which requires the grouting of many holes, it is indispensable to combine in a fixed plant the storage, preparation and injection operations. This facilitates automation of the different operations, and simplifies their checking and control. Thus, the equipment listed above -- silos, proportioning apparatus, mixing vats and containers, injection pumps, and checking, control, and recording equipment -- is normally found in a single location.

Note: For grouting operations treated some distance from the central plant, it is necessary to have an auxiliary pumping system. This is the case, particularly, for long tunnels.

5. PRELIMINARY STUDIES

The purpose of this chapter is to explain the methodology required to determine injection conditions. The list of procedures described in the following sections is not complete. The attempt is to define the class of problems to be considered prior to deciding to use injections, and if used, the conditions and objectives of their use.

5.1 Treatment of the Ground Before Excavation

5.1.1 Typical Study Outline

The outline described in the following sections shows in a simple manner the steps to be taken in a project study, and the objective of each step.

5.1.2 First Phase: Investigation of Project Site

The objective is to acquire sufficient knowledge of the zone to be crossed to enable determination of a possible technical solution. Different aspects to be considered include:

- -- approximate cost
- -- delays
- -- consequences to the environment (harmful effects during construction and after completion of the project)

There is no single way to make such a study. The nature of the investigation will be a function of the complexity of the site and the complexity of the project. The objectives to be realized and the principal means of investigation to be used in geological, hydrogeological and geotechnical fields are described in the following sections.

5.1.2.1 Geology

The study of the site must adequately determine the geologic structure, not only in the zone where the project will be located but in the complete sector to be influenced by construction. The nature and the disposition of the geologic zones can be determined by the following means:

- -- study of existing geologic records and historical records of neighboring structures
- -- surface geologic survey
- -- geophysical survey
- -- soundings or borings

5.1.2.2 Hydrogeology

Hydrogeologic data will have to be gathered at this stage of the study. This data will be acquired at least partially during the geologic survey. It should include the following information:

-- the permeabilities of the different zones
-- the water table (fluctuations, sources, and extent)
-- the chemistry or the chemical properties of the ground water, particularly in the case of pollution or natural corrosion elements
-- the presence of karsts

The methods used can include:
-- location of water sources
-- a surface hydrogeological survey
-- piezometric studies
-- well tests
-- pumping tests
-- circulation tests with tracers

5.1.2.3 Geotechnical

This aspect of the study is to define the geotechnical properties of the soils and rocks at the site. Initially, lab testing (identification, mechanical properties, permeability) and, possibly, insitu testing (penetrometer pressure-meter) will be conducted. Rock testing will be a function of the problems being studied and of the rock itself. Depending on the case, mechanical tests, and cracking and alterability studies will be made.

5.1.2.4 Environment

At this stage of the study, a listing of all neighboring structures which may be influenced by construction (underground structures, foundations, cellars or vaults) will be required. Attempts to collect all records describing the conditions and characteristics relating to possible easements will be made.

5.1.2.5 Conclusion of the Site Study

A synthesis of the geological, hydrogeological, and geotechnical studies must define as a whole the financial and technical conditions for the accomplishment of the project, and to forsee the possible consequences to the environment. The planner must at this stage make a choice of zones to be treated and technical solutions, leading him to the second phase of the study. During the second phase or specific study, the necessary elements for elaboration of the final project will be defined in detail. If ground treatment prior to excavation is considered, specific studies of a very special nature must be undertaken.

5.1.3 Second Phase: Specific Studies

These studies will consider the following four questions:
-- what are the properties the ground must acquire?
-- why should the ground be treated?
-- what will the consequences of the ground treatment be on construction and on the environment?
-- how can the effectiveness of the treatment be controlled?

The methods of study will be a function of the depth of construction (surveyed by borings, adit or drift). The special case of treatment during construction of a very deep project, which cannot be studied prior to the start of construction, will also be mentioned.

5.1.3.1 Geology

The geologic study will be carried out in order to describe:

-- the geologic structure of the area
-- the homogeneous zones within each formation (variation of face or bearing)
-- the details of rock and soil structure (heterogeneity, discontinuities, anisotrophy)

The detailed study of a sufficiently large area is necessary to predict the flow of grouts and the risk to the environment. On the other hand, the choice of injection conditions and the effectiveness of the treatment will be directly linked to the knowledge of the ground to be treated and adjacent ground--e.g., the exact geometry of the layers, the alternation of layers of different permeability, the network of discontinuities and nature of the fill, and the geometry of the voids. Methods of investigation to be used include:

-- undisturbed sampling
-- soundings (resistivity, natural radioactivity, gamma-gamma, neutron-neutron)

5.1.3.2 Hydrogeology - Hydraulics

The general study of the water-table must be done when the treatment of the ground may influence or be influenced by it. The permeability of the ground to be treated must be studied with great care so that it will be known with the highest degree of precision, and to classify zones having the same permeability. The tests to be accomplished during drilling include:

-- Lefranc test in soils
-- permeability measurement with "micro moulinet" in very permeable soil strata
-- Lugeon test in rocks (absorption measurement, determination of the filling behavior of cracks)

Pumping tests and/or circulation tests with tracers will complete the data acquired in the water table study. A chemical analysis of the water will establish its chemical compatability with the grout to be used. The risks of pollution and the modification of the hydraulic conditions due to grout injections will have to be studied at this stage (analog and mathematical models, as well as prototype model testing.)

5.1.3.3 Geotechnical

The results of the specific geologic study will be quantified by a sufficient number of geotechnical tests until the nature, the properties, and the disposition of the different soils is known. At this stage of the study, in order to control the results of injection, one will need to know:

- -- geotechnical and hydraulic knowledge of the zones to be treated
- -- a set of simple parameters, easily measured, which are important to the improvements to be added to the soil (permeability, piezometry, resistance to simple compression)

5.1.3.4 Field Testing

The specific studies described previously serve to define a theoretical process of injection based on a study of the available parameters. The field testing provides more specific data. The field testing is to be done in the zone most representative of the general area and of the difficulties to be met during construction. In the case where different types of zones are to be treated, attempts to have as many field tests as there are zones should be made. During field testing, three aspects of the problem are to be studied:

1. Information is obtained on influence of drilling methods, equipment, injection methods, grouts (mainly as a function of the allowable pressures), and arrangement, spacing and depth of holes to be used.
2. As to controls, the information will help provide the means of judging the effectiveness of the treatment.
3. Finally, the total treatment cost for a project, which is to be included in the specifications, will have to be estimated based on technical data on the quality and quantity of products used in field testing.

Controls to be used are presented in Chapter 6. In any case, it is advisable to check the effectiveness of field testing by excavating pits or galleries.

5.1.4 Third Phase: Conclusion of the Study

From all the studies made on the properties of the zone to be treated and on the environment, a methodology of injection grouting is defined. This definition must not be considered as a final scheme. Modification during construction is very often necessary, in spite of all previous studies.

5.1.4.1 Volumetric Amounts to be Treated

The survey determines the location of the volume of soil to be treated. This determination is important in estimating the quantity of grout to be injected. It also may affect the methodology of injection since it may be necessary to proceed with a first injection net in order to limit the flow of grout to the construction zone.

5.1.4.2 Arrangement of Drill Holes

From the geometric arrangement of the structures and the study results, the location of the boundaries of the volume to be treated can be found. These boundaries generally define the injection grid. The principal schemes are as follows:

-- radial drilling from a structure to accomplish filling or soil treatment
-- parallel or divergent drilling implemented on one or several parallel lines for the preliminary treatment of the ground, either from the ground surface or from auxiliary underground structures
-- drillings made following the generation of several cones forming a soil treatment from the front of the gallery.

The orientation of the drilling must be adapted to the subsurface conditions (orientation of discontinuities, stratification, faults, have an influence). It can also be affected by the topographic conditions and obstructions present at the site. The spacing between the holes is mainly linked to the properties and structure of the soil (grain size in the case of soil, jointing in the case of rock), but is also influenced by the type of treatment and the allowable injection pressure. The depth of the hole may be limited by the largest allowable value of deviation of the hole from its intended course.

5.1.4.3 Nature of the Grouts (see Section 3.2)

5.1.4.4 Drilling Methods

The drilling methods must be adapted to the quality of the ground, but may also take into consideration the type of injection. In particular, drilling under the action of water may have to be rejected. The different methods of drilling are presented in Section 4.1.

5.1.4.5 Methods of Injection (see Section 4.1)

5.1.4.6 Pressure, Flow and Quantities (see Section 4.1)

5.1.4.7 Estimate

The conclusion of the studies enables a first estimate of quantities (borings, equipment, products) to be made.

5.2 Treatment of New Structures

The treatment of new structures includes the following injection types (see Section 2.2):
-- filling and gluing injections
-- strengthening injections
-- other treatments (water tightening)

Two general cases may be encountered:
-- treatment was planned for the project before construction
-- treatment became necessary during or after construction

5.2.1 Definition of the Problem

During the study of a grouting project a given number of steps are necessary to define the objectives to be reached by the treatment and the general principles of the treatment. These tasks are of varying importance, depending on whether or not the treatment was planned.

5.2.1.1 Study of Construction File

This file should give information concerning conditions encountered during construction. For example,

- -- nature and stability of the surrounding ground, particularly the chemical nature
- -- excavation methods
- -- ground retaining methods
- -- liner thickness, the way the liner was installed
- -- volume of concrete placed
- -- water flow during excavation (location, type, flow, chemistry, pressure)
- -- drainage
- -- problems confronted during construction

5.2.1.2 Instrumentation of the Structure

The study of data provided by recording equipment installed during construction, such as pressure and deformation measurements, can provide important information concerning the necessity of the treatment and the conception of the treatment.

5.2.1.3 Interpretation - Approach to the Type of Work

Interpretation of information gathered from construction files and from the survey of the structure should decide the following issues:

- -- necessity of treatment
- -- locations of zones to be treated
- -- limitations, such as drainage

A first treatment can then be planned. For such a project the information may be sufficient (such as the simple case of having a filling injection plant included in the project) or insufficient (strengthening injection not planned before the start of work).

5.2.2 Survey of the Structure

Specific surveys are generally necessary to decide on the details of the treatment project when such a project was not forseen or was inadequately defined.

5.2.2.1 Soundings - Endoscope

Soundings are done to check the void area behind the lining. The borings permit examination with an endoscope; however, this method will only work in the case of rocks without water and after cleaning of the hole.

5.2.2.2 Water Tests

Water tests are used to check the permeability of the ground next to the excavation. These tests must provide information about the type of treatment to be planned and the extent of the zone to be treated.

5.2.2.3 Quality of the Lining

If there are doubts about the quality of the concrete in place, tests can be made with a sclerometer or by core drilling and testing samples. Principle problem with new linings generally occurs between lifts, or is due to erosion of the concrete.

5.2.2.4 Stresses (see Section 5.2.1.2)

5.2.2.5 Field Testing

As for the treatment of soil before excavation, field testing prior to treatment provides important information (see Section 5.1.3.4)

5.2.3 Conclusions

See Section 5.1.4: the methodology remains identical as far as the principle is concerned.

5.3 Treatment of Structures in Use

The study concerning the treatment of structures in use is very similar to the one concerning new structures. There are, however, several differences, the main ones being:

-- adequate knowledge concerning the structure may not be available; often the necessary records are missing or are insufficient, providing little information about the construction or the geology
-- the lining may be either masonry or concrete

Influence of time: the aging of the structure usually results in modification of the structure and its environment (alteration of the mortar, the bricks or the concrete, decompression of the soil, dissolution or erosion by water circulation, etc.). As the structure is in use, access is limited, making the survey and construction more difficult, and imposing a time limitation. Structures in use require longer and more comprehensive studies than new structures. After a very detailed visual inspection, an important study must be organized, including a large number of soundings and drillings, to determine the thickness and nature of the lining, and the nature and state of alteration of the ground. The measurement of stresses in the lining is very important as it allows an estimate of the loads carried by the structure since its construction.

6. CONTROLS

6.1 Control During Construction

The following objectives should be considered:

-- control of the quality of products as they arrive at the site or plant
-- control of grout mixing
-- control of grout placement
-- control of the drift of drill holes
-- control of the environment

6.1.1 Control of Products

Emphasis here will be on products other than cement or bentonite, which are usually controlled at manufacturers' plants. It should only be necessary to ensure the products which have been supplied are the ones ordered. For bentonite it is advisable to measure the hydration time and the Atterberg limits to ensure that they are constant from one delivery to the next. For sands tests to be made should

6.1.1 (cont.) include grain size analysis, density, and water content. Finally, for other products, a comparison between the quantity supplied and the quantity previously injected is required.

For chemical products, and in particular for silica gels, controls should be applied as it arrives in the field. A few easily made controls are given here for information:

Silicate of Soda: measure the density and temperature (between 15° - 30°C) which permits determining the amount of (SiO_2 + Na_2O). If possible, make an acidimetric measurement to determine the percentage of Na_2O. With these two measures the percentage of silica and the SiO_2/Na_2O ratio can be determined.

Reactives: measure the density and evaluate the degree of saponification by the setting time of the gel. The setting time is measured in a container, not corrodable by soda, using the method of "bécher renversé". For reactives that are only slightly soluable, a magnetic mixer is used; for soluable reactives this is not necessary. If the difference between the test results and curves obtained from the lab is too large, the products should be sent for further testing.

Resins: as there are a large number of resins available, it is difficult to propose a control test other than measuring the setting time, even though several parameters may change that time independently of the product. It is advisable to consult specialists such as suppliers and laboratories to make sure the resin is the one required.

6.1.2 Control of Grouts during Mixing

6.1.2.1 Cement Based Grouts

For these grouts the following measures are recommended:

-- an automatic plant for proportion control
-- viscosity measurement with a Marsh type cone
-- density measurement
-- sweating and decantation check
-- resistance to simple compression

6.1.2.2 Gels

The following controls should be made:

-- density
-- frequent verification of proportions
-- setting time
-- strength. At the present time, the multiplicity and complexity of the technical and natural parameters makes difficult any certain correlation between lab tests and real results. (see Appendix 1). Therefore, attempts to establish a correlation between mechanical testing and real results should not be made. The simplified tests are mainly shear tests on pure gels or on a normalized gel-sand mixture (see Appendix 2). These tests can only be considered as a consistency test for the gels.

6.1.2.3 Resins

The proportions, setting time, and resistance should be controlled.

6.1.3 Control of Grout Placement

Qualitative controls are used mainly to check that the work is done correctly. Also, the methods of control should provide information about the quantity of products.

6.1.3.1 Flow Control

The pumps will be equipped to measure the number of strokes, and with proportion meters and flow meters. Injection flow can range from a few litres per minute for fine sand to several hundred litres per minute for open ground or very permeable ground.

6.1.3.2 Pressure Control

As with the measurement of flow, pressures will be controlled using a graphical recording mechanism at the plant and a precise manometer at the drilling site. The manometer will have to be linked to the injecting pipe using a special protecting manometer which would prevent the penetration of the grout into the mechanisms of recording or measuring equipment.

6.1.4 Control of Drill Hole Drift

It is very important to check carefully the location of drilling equipment and the orientation of rods at the start of and during drilling. These checks are very important when drilling deep holes. The drift or deviation can be effectively measured using a deviatometer.

6.1.5 Environmental Control

Controls are necessary in urban areas, and are recommended for all project sites. Controls include placement of motion detectors prior to injection to measure swelling and cracking. This equipment can be equipped with a special alarm mechanism. Several techniques for measuring motion are available:

-- survey (topographical) control
-- settlement meter
-- slope meter
-- displacement meter

Also, heaving due to grout placement should be checked.

6.2 Control of Results

The penetration of grout into a medium is a complex phenomenon. The results can be forseen through the interpretation of pressure, flow and absorption measurements, knowledge of ground heaving and movement of the grout to the ground surface, and through control of the medium itself.

It is necessary to define a method of control for the project. The main goal of control during and after treatment is to determine if the objectives of the treatment, such as watertightness and strengthening, have been reached, and to limit the treatment to only what is necessary. However, the investigation methods described, although generally effective, will not disclose localized failures of the treatment. Some of the methods may be disregarded due to the difficulty of their use in the field, their high cost, or, sometimes, the uncertainty of the results obtained.

Control methods must help in evaluating the effectiveness of the grout during treatment (continuous control) and after treatment (subsequent control) by providing:

- -- the repartition of the grout
- -- the variation of some properties of the medium, either physical or mechanical, which will have to be compared with the required properties defined before treatment.

A few of the methods available are presented in the following sections.

6.2.1 Earth Work

The observation and measurement of the excavated ground provides the best means of checking the effectiveness of the treatment. During or after construction some types of excavations (shafts, galleries) allow observation of the grouting, including flow and distribution of the grout. Observations can be made easier by using:

- -- colored grout: depending on the nature and natural color of the medium, a list of coloring agents includes methyl blue, flourescent, rhodamine, and eosia.
- -- color indicators at ground level (phenol phthalin).

The excavation also provides for insitu testing of the treated zone, instead of sampling for laboratory tests (see following section) .

6.2.2 Undisturbed Sampling

Samples will usually be taken from the surface for shallow zones, or from shafts, pits, or other excavations for deep treated zones. It should be kept in mind that the samples may not always be representative of the treated ground particularly in the case where drilling action fragments the core. The results generally are good in grouted rock and in homogeneous fine sand if the diameter of the drill is large enough (100 mm minimum). In some cases the endoscope is very helpful in checking the results of treatment.

6.2.3 Disturbed Sampling

This may constitute a quick method (as the work progresses) to assess the overall effectiveness of the treatment (water-tigthening, for example).

6.2.4 Water Tests

The use of water tests is obvious in the case of checking watertightness. They also are an indirect test of a strengthening treatment, especially if the medium was very permeable prior to treatment. A large number of tests (Lefranc test in soils and Lugeon test in rocks) must be made to account for the variation of the ground and to detect any failures of the grouting treatment.

6.2.4 (cont.) Piezometric measurements will show the hydrogeolic disturbance created by the treatment (in the case of shallow works) and provide information about the effectiveness of the treatment (such as the decrease of water pressure around a deep gallery after treatment of a geologic problem.)

6.2.5 Mechanical Testing

The objective of mechanical tests is to quantify the improvement of mechanical properties due to injections, using tests made during drilling or made in the excavation zone after treatment. Attempts should be made to check the properties determined prior to treatment from which required improvements were determined.

The pressuremeter test is an insitu test which can be used before and after treatment. It provides short-term deformation and rupture characteristics. One may, in some cases leave the probes in place during grouting to ensure that the same area of the same zone is tested following treatment.

Penetrometer tests are not well suited for grouting work, but they may be used for treatment control of sands if the initial penetration characteristics are well known.

Other tests can also be made in an excavation to determine the deformation and rupture characteristics of the ground after treatment (plate tests, jacking tests, shear tests). The best way to check the behavior of the ground after treatment is to make the measurement in a section of the tunnel (deformation, stress on the liner.)

6.2.6 Geophysical Methods

The measurement of the geophysical properties of ground, which the treatment can change, can provide an overview of the homogeneity of the treatment. Seismic methods, such as refraction or direct wave transmission, can be utilized. Diagraphs made in drill holes used for the grouting may provide information on the distribution of grout in the ground. It is also possible to load the grout with radioactive isotopes of different concentrations. Defection can then be made in drill holes using a probe.

6.2.7 Laboratory Testing

Care in taking samples for laboratory testing must be exercised. (See sections 6.2.1 and 6.2.2) The simple compression test is the strength test most often used. Modern computation techniques require more and more that the deformation characteristics of the material be known, also. Thus, it may be necessary in the future to define and control these characteristics in the treated material.

Note: Generally, all drill holes should be filled very carefully after completion of testing. This is absolutely necessary in the case of a watertightness treatment.

6.2.8 Compression Testing of Laboratory Prepared Samples

This is a test primarily used in research and as part of the preliminary studies. The method involves injecting grout into a standard sand (Fountainbleau MN30 - see grain size curve, Figure 4B). The sand is placed inside a rigid polyester cylinder, one meter long and 40 mm in diameter. The column can be cut into eight 80 mm long samples, which are subsequently tested. In averaging the strength test results, the two extreme samples (numbers 1 and 8) are disregarded. The base of the column is equipped with an expansion packer as part of the injection equipment. The other end of the cylinder is closed by a steel disc on top of the sand. The silicate grout is pumped through the bottom of the cylinder at a speed of one meter in 30 minutes; the injection into the sand can be seen through the cylinder.

The cylinders are stored vertically for eight hours, then cut, and unconfined compression tests are run on samples 2, 4, and 7. Curves of equal strength, which are a function of the silicate/water ratio and the reactive concentration, have been established for each type of silicate and two types of reactives. An example of the curves is included with this paper in Figure 5B.

6.2.9 Field Consistency Test

Method of Moulds - This is a simple field test which permits a check on the consistency of the gel properties of the mixture. A Casagrande Liquid Limit device is fitted with a special cup that will allow it to hold a plastic cylinder. The cylinder is 100 mm high and has an interior diameter of 40 mm. The bottom of the cylinder is closed with a rubber stopper, and placed in the liquid limit device. The cylinder is filled between 1/3 and 1/2 its height with pure gel. Immediately after this, sand (Fountainbleau MN30) is slowly poured into the mould until it is full. Simultaneous with the pouring, the contents are shocked 25 times using the rotating cam of the Casagrande device (height of fall is about 1 cm). When the filling is complete a slight gel layer must be on top of the sand. Five minutes after this step, five more shocks are administered to optimize the compaction of the sand. The top of the cylinder is filled with a rubber stopper, and the mixture is allowed to age for 48 hours. After that, and after the cylindrical mould is removed, a compression test is performed. The strain rate to be used is 20 mm/minute.

VERY IMPORTANT: The strength determined by this test should not be used as the insitu strength of the injected soil.

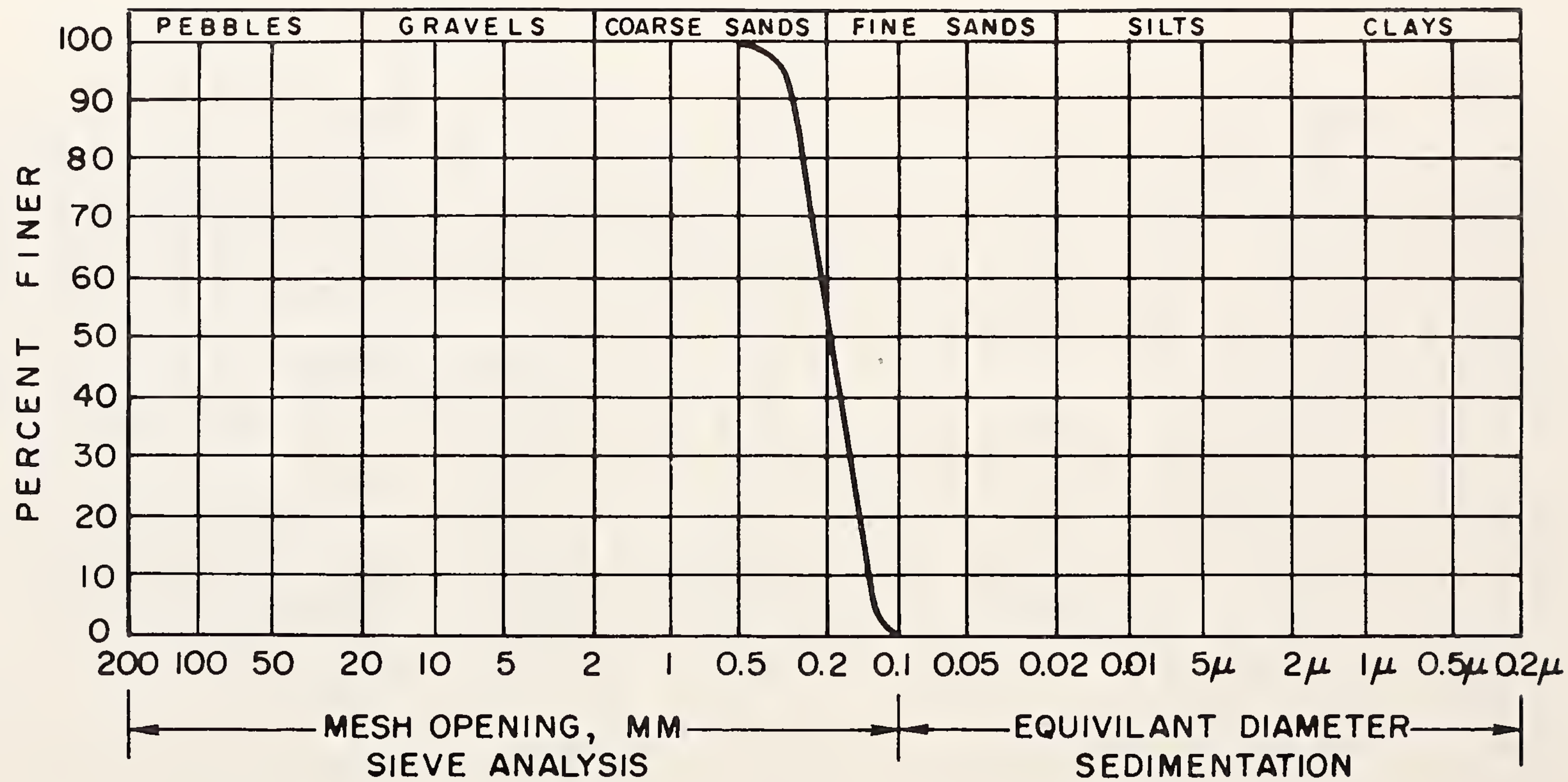
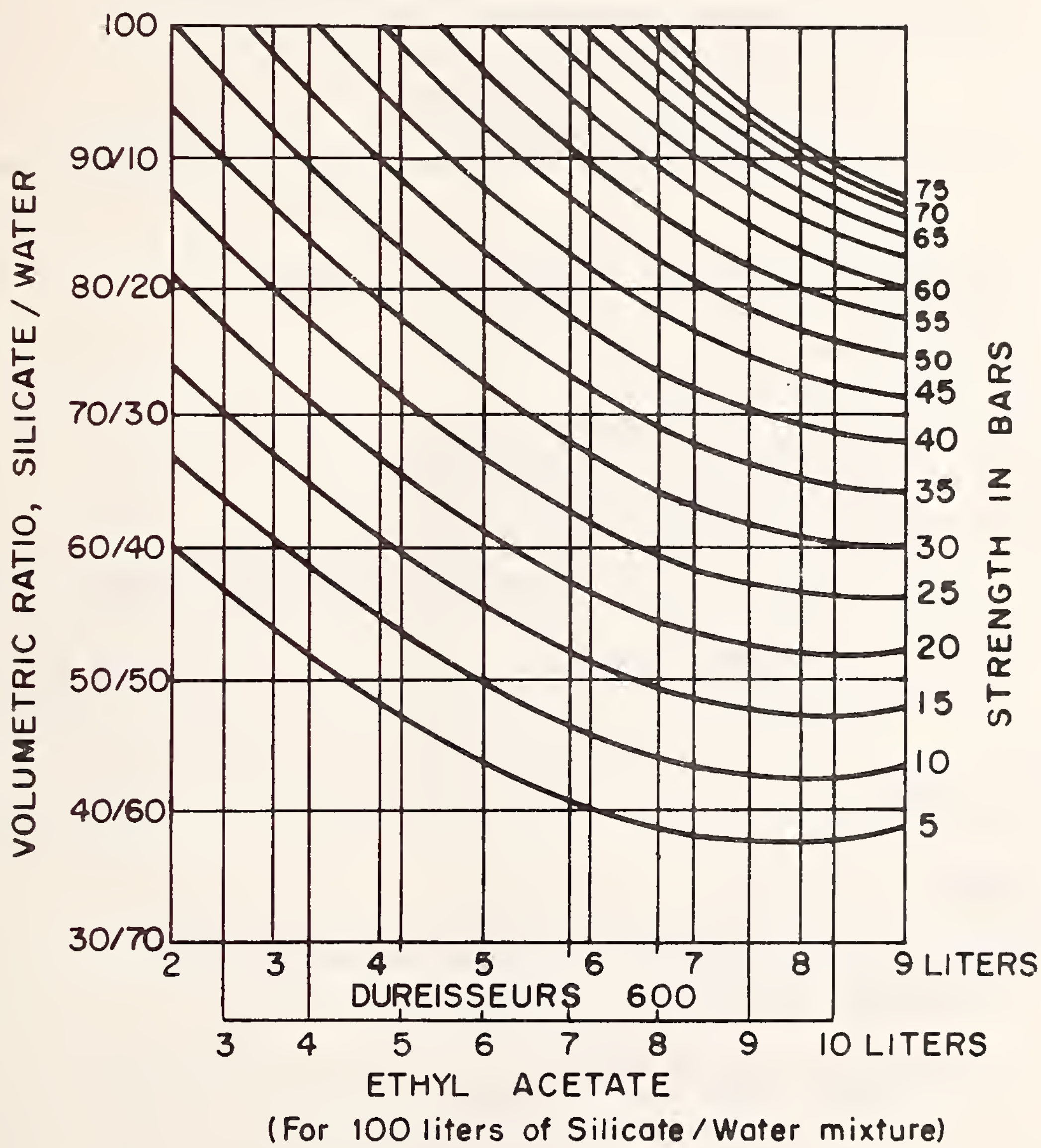


FIGURE 4B. GRAIN SIZE CURVE FOR FOUNTAINBLEAU MN30 SAND.

FIGURE 5B. CURVES OF EQUAL STRENGTH FOR STABILIZED FOUNTAINBLEAU MN30 SAND.



7. FIELD REPORTS

The field reports must allow the contractor to follow the work precisely on both technical and economical levels. The type of information can be grouped in three classifications:

- -- drilling records
- -- injection records

  each of these classes can be divided into
  - program of construction
  - recording of the construction
- -- control records

7.1 Drilling Records

7.1.1 Drilling Program (describes what is to be done).

This program must indicate:

- -- the number of the boring
- -- the diameter of the device
- -- the depth of the holes
- -- the depth of the equipment (tube-a-manchette, smooth pipes)

7.1.2 Drilling Records (describes what was done).

The record must indicate:

- -- the number of the boring
- -- the drilling date
- -- the device diameter
- -- the actual drilling depth
- -- the actual equipment depth
- -- the volume of casing grout injected
- -- driller's observations (hollows, obstacles, floating of the grout to the surface, and geological characteristics).
- -- administrative information such as personnel, equipment and schedule.

An example of this type of report is given in this Appendix.

7.2 Injection Records

7.2.1 Injection Program (describes what is to be done).

This program must indicate:

- -- the number of the boring
- -- the type of grout
- -- the injection pressure
- -- the sections to be treated
- -- the quantities of grout to be used

Also, for each hole there will be an appended sheet called a pass sheet, which will include the following information:

- -- the type of grout
- -- the maximum and minimum pressure
- -- the number of the injection pump
- -- the thickness of the sections
- -- the depths of the sections (or of the packer)
- -- the quantity to be injected for each pass

7.2.2 Injection Record

The record must indicate:

- -- the number of the hole
- -- the type of grout
- -- the injection pressure
- -- the depth of treatment
- -- the date of injection
- -- the actual quantities injected in each hole
- -- observations such as refusals, communications from one hole to another, swelling and upward flow
- -- administrative information such as personnel, equipment and scheduling

Also for each hole there will be a pressure diagram and a pass sheet including:

- -- the injection date
- -- the actual grout quantity for each pass
- -- the injection time
- -- the pressures read on the manometers

Examples of the following items have been included in this report:

- -- a drilling report (Figure 6B)
- -- an injection program (Figure 7B)
- -- a pass sheet (Figure 8B)

7.3 Control Records

These records are established periodically. They will include information about the quality control of the products and of the grout as has been defined in previous chapters. The frequency and extent of these reports will be established by the contractor and owner.

8. PROPOSED METHOD OF PAYMENT FOR INJECTIONS, SCALE OF PRICES

8.1 Important Recommendations

The complexity and evolution of the injection technique makes it difficult to draft a contract. A contract should ensure:

- -- the price list is complete and provides payment for the different tasks accomplished by the contractor
- -- the definition of the process is precise and is adapted to the specific characteristics of the work

8.2 Classification of Contracts by Method of Payment

8.2.1 Lump Sum Contract

Following the definition of the "Cahier des Clauses Administratives Generales" (CCAG), a lump sum contract is one where the work to be accomplished by the contractor is determined and the price fixed prior to beginning construction. This type of contract is quite rare in public work, and is not well suited to injection work. There are too many unknowns, making a lump sum contract risky to both the contractor and owner.

Figure 6B

DRILLING REPORT

Date: From

To

Machine No. Personnel	Boring Number	Drill Diameter	Drilling Depth			Type of Soil	Equipment		Grout Quantity	Supplies			Indicators (Voids, etc.)
			From	To	Total		TL	TM		Clay	Cement		
Total													
Observations:													

PROJECT: CENTRAL YARD: SUPERVISOR:

INJECTION PROGRAM

NO _____

DATE:

SIGNIFICANCE OF BORINGS TO BE INJECTED

Boring	Grout	Minimum Pressure	Section		Quantity	Total
			From	To		

Figure 7B
EXAMPLE OF INJECTION PROGRAM
DOCUMENT

Project: CENTRAL YARD:

SUPERVISOR:

Particular Instructions

- Grout ....
- Volume of Soil To Be Treated
- Maximum Pressure

PASS SHEET

BORING NO.			INJECTION PUMP NO.					
Date	Depth of the Packer	Grout	Quantity in Liters		Duration of Injection		Injection Pressure in MPa 5 15 25 10 20	Observations
			Fore-casted	Action	From	To		

Volume Total m^3 Duration of Injection:

Figure 8B

EXAMPLE OF INJECTION PASS SHEET

8.2.2 Cost Plus Contract

The definition of the CCAG is as follows: it's a contract in which the actual expenses of the contractor are checked and are totally reimbursed plus some percentage to allow for overhead and profit. This procedure is exceptional and must be reserved for cases where the unknowns are such that the actual cost cannot be determined prior to construction. Unknowns might include technical difficulties such as delicate injection in urban areas in ground sensitive to swelling, or field testing.

8.2.3 Unit Price Contract

The CCAG defines this type of contract to be one where unit prices are multiplied by the actual quantities used in the project. Though the unit prices form the basis of the contract, some mention of the total amount of construction and the quantities to be used is made. Also, a procedure is set forth to handle cases where there is a large variation between estimated and actual quantities. This type of contract is the one best adapted to grouting projects.

8.3 Proposal of List Prices for Unit Price Contracts

8.3.1 Fixed Installation Price

This payment includes:

- general expenses of field installation
- the expense of moving the equipment to the site, if it can be defined at this stage of the contract. If not, separate payments will be made for each drilling unit and the equipment necessary for each operation of grout mixing and injection.

8.3.2 Drilling

The schedule will include:

- unit prices for moving and positioning of drilling equipment from one site to another and sometimes from one hole to another.
- a price per lineal foot or meter of drilling, depending on the type and characteristics of the drilling (the depth, the diameter, the site, and the orientation) and the nature of the ground.
- the price per lineal metre for redrilling after injection.

8.3.3 Drilling Supplies

The list of prices will include the unit price per metre for tube-a-manchettes and other pipes.

8.3.4 Injection

The schedule will include:

- lump sum price for moving and installation of injection units

8.3.4 (cont.)

-- unit price for drilling each injection section
-- unit price per cubic metre or litre for placing the grout. Different prices will apply to different treatments (grout, injection flow, treatment site).

8.3.5 Supplies

The cost of supplies and injection products, including delivery to the site, is usually a unit cost per ton (for cement, clay, bentonite, sand, silicate and reagents) or per kilogram for resins and peptic ingredients. It is necessary to specify with care the properties of the products that will be used.

NOTE: if the composition of filling grout is well defined, as in the case of mortar, a price per ton of dry product injected may be considered.

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