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GROUTING TECHNIQUES IN BOTTOM SEALING OF HAZARDOUS WASTE SITES

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16. ABSTRACT

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Grout formulations used in this study were acrylate, 30% silicate, 50% silicate, urethane and portland cement. These studies indicated that present designs do not permit close enough control to assure a bottom-seal to be formed in all media.

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ABSTRACT

Bottom sealing of hazardous waste sites involves the injection or insertion of an inert impermeable and continuous horizontal barrier in soil below the source of contamination. This type of containment strategy could be used in conjunction with other technology such as slurry walls, capping and counterpumping to insure that contaminants do not move from the site into surrounding soil or ground water. The objectives of this project were to determine what types of available grouts would be unreactive with hazardous wastes and how effective direct injection or jet grouting techniques would be in forming a grout barrier. The effectiveness of a complete barrier was not evaluated.

Grout formulations used in this study were acrylate, 30% silicate, 50% silicate, urethane and portland cement. These grouts were tested to determine their ability to set and remain intact in the presence of twelve different simulated waste solutions (acids, bases, fuels and organic solvents) that could occur at hazardous waste sites. The grouts which showed the greatest ability to set were the two inorganic-based formulations: sodium silicate and, Type I portland cement. Acrylate grout set in six out of twelve simulated wastes, but the urethane grout tested did not set in any of the simulated wastes.

When grout samples set in water environments were exposed to the same twelve solutions for 20 days, all except the portland cement product showed some swelling or shrinkage. Of the chemical grouts sodium silicate and acrylate exhibited the best durability.

In a small-scale 2 m × 4 m (6.56 ft × 13.12 ft) test bed of medium sand neither silicate nor acrylate grout injected into a grid-like pattern of boreholes formed a continuous horizontal seal. The grout bulbs either did not coalesce (silicate) or were displaced after injection (acrylate). In a large-scale test using sodium silicate grout injected at a depth of 2.44 m (8 ft) in fine sand, the shapes of the grout bulbs could not be controlled well enough to produce a seal, and grout shrinkage caused root holes to remain unsealed. Chemical grouting as employed in this test did not produce a continuous bottom seal.

Tests of jet grouting were undertaken in natural (in-place) loess, compacted silt and medium sand at a depth of 1.67 m (5.5 ft), using three holes spaced on 1.52 m (5 ft) centers. The water jet system succeeded in producing useful cavities in all media; but the shape and size of the cavities could not be controlled with sufficient precision in the loess or silt to produce a continuous barrier when the cavities were grouted. The less cohesive sand washed out more evenly and the grouted cavities overlapped to form a continuous barrier layer.

These studies indicated that present designs do not permit close enough control to assure a bottom-seal will be formed in all media.

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Scott Murrell, Geotechnical Laboratory (WES) prepared many of the drawings used in this report and supervised excavation of jet grout bulbs.

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SECTION 1

INTRODUCTION

BACKGROUND

Grouting has been used in construction for over a century to add strength to earth materials or to control water movement (Bowen, 1981). Grouting involves the pressure injection of suspensions or solutions that set or harden to fill voids and cement earth materials together. Both the grout formulation selected for injection and the technique used for placement are important for grout to produce the desired benefits.

Grouting has been used to emplace a subsurface barrier in remedial action involving radioactive waste (Spalding, Hyder and Munro, 1983; Tamura and Boegley, 1983; Williams 1983) and has been indicated as a potentially useful technique for neutralizing, immobilizing or containing toxic wastes (Tolman, Ballestero, Beck and Emrich, 1978; Truett, Holberger and Barrett, 1983). Proposals for using grout have involved shallow, low-pressure injection to consolidate contaminated soil (Shaefer, 1980); injection into waste to provide for solidification or in-situ treatment (Truett, Holberger and Barrett 1983) and injection for sealing soil around the site to form a barrier to lateral or vertical contaminant migration (Malone, May, and Larson, 1984; ICOS, 1985). Projects have also been undertaken where waste was used as a filler in the grout (US Army Engineers, 1977). In all applications of grout at waste sites (Figure 1), two properties are critical:

1) The grout must set or harden in contact with waste components.

2) The grout must not deteriorate in the presence of the waste during normal temperature or moisture cycles occurring within the expected lifetime of the grouted structure.

Two types of grouts, chemical (or solution) grouts and particulate (or suspension) grouts are available for use in producing subsurface barriers. Chemical grouts are solutions that react to produce a gel or polymer that fills the pore space. The solutions typically have a low initial viscosity that increases rapidly during setting. Particulate grouts are suspensions of fine-grained solids that move between the particles of the medium being grouted. The setting of particulate grouts may be produced by a chemical reaction or by the flocculation of the dispersed solid. The grout types differ in their injectability and their effectiveness in producing a durable seal or adding strength to the grouted medium. In applications where grout is to form a barrier in geologic media, the grout must be easily injectable (have low viscosity) and must produce a decrease in permeability.

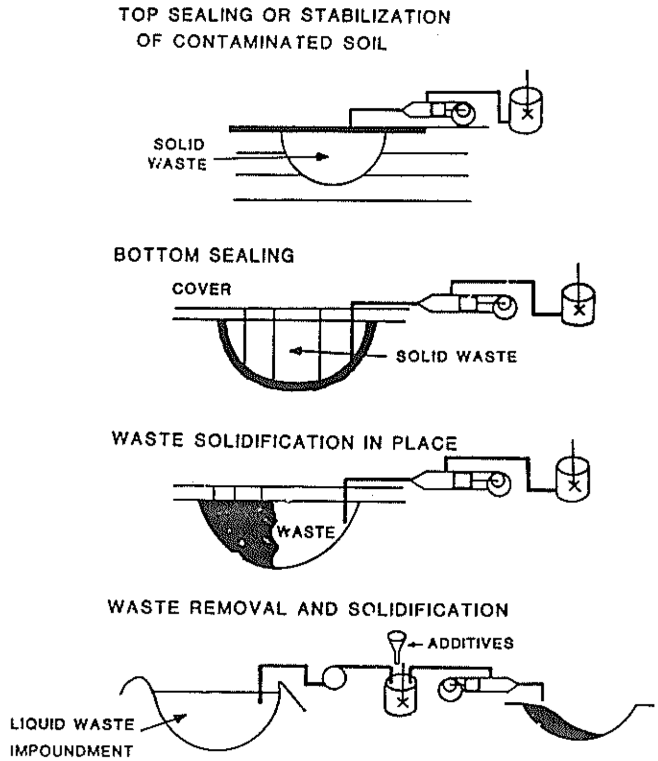

Figure 1. Uses of grouting to contain hazardous wastes.

Grouts typically are injected using pumps and mixers similar to those shown in Figure 2. For effective application it is also necessary that the grout:

1) Have a set time that can be regulated.

2) Be reasonably non-corrosive to mixers and pumps.

3) Be formulated from materials that are low in toxicity.

After a grout has been selected, a technique for grout application must be identified. Chemical grouts are generally low-viscosity liquids that can be directly pumped into porous media. The grain-size of the sediment that can be injected depends on the time available for injection and the viscosity of the grout (Figure 3). Generally, particulate (suspension) grouts cannot be injected into sediments finer than medium sand (Spooner et al. 1984; Littlejohn, 1985b). In finer grain-size material, chemical (solution) grouts must be used unless a technique for washing out a cavity is applied. Hydraulic excavation of a cavity for placing grout is usually referred to as jet grouting (Brunsing, 983; GKN-Keller Foundations Ltd., undated; Yahiro, Yoshida and Nishi, 1975).

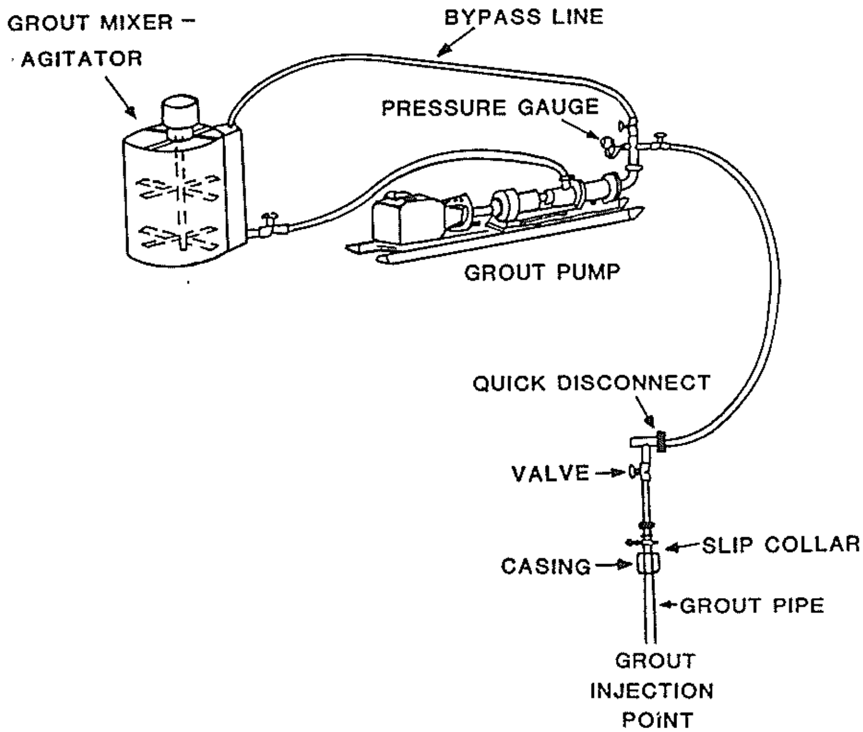

Figure 2. Schematic drawing of grout injection system. (After Water Resources Commission, 1977.)

Jet grouting is done using a wide array of techniques (Figure 4). A water jet can be operated in a water-filled cavity, or in a concentrically-placed air jet (Shibazi and Ohta, 1982). A water jet can also be operated in an air-filled pressurized cavity. A variety of fluids can be employed in jet grouting, including clean water, bentonite clay suspensions or portland cement suspensions. Cuttings are air-lifted or pumped to the surface. Air or water pressure is maintained in the cavity to prevent collapse of the roof or side walls.

PURPOSE

The purpose of this research project was to examine the feasibility of producing a continuous, low-permeability layer below an area of contamination such as a landfill or sludge lagoon, in order to limit the vertical migration of potentially toxic materials. This type of horizontal sealing could be used in conjunction with slurry walls (vertical barriers) to produce low permeability layers on all sides of a potentially hazardous disposal site.

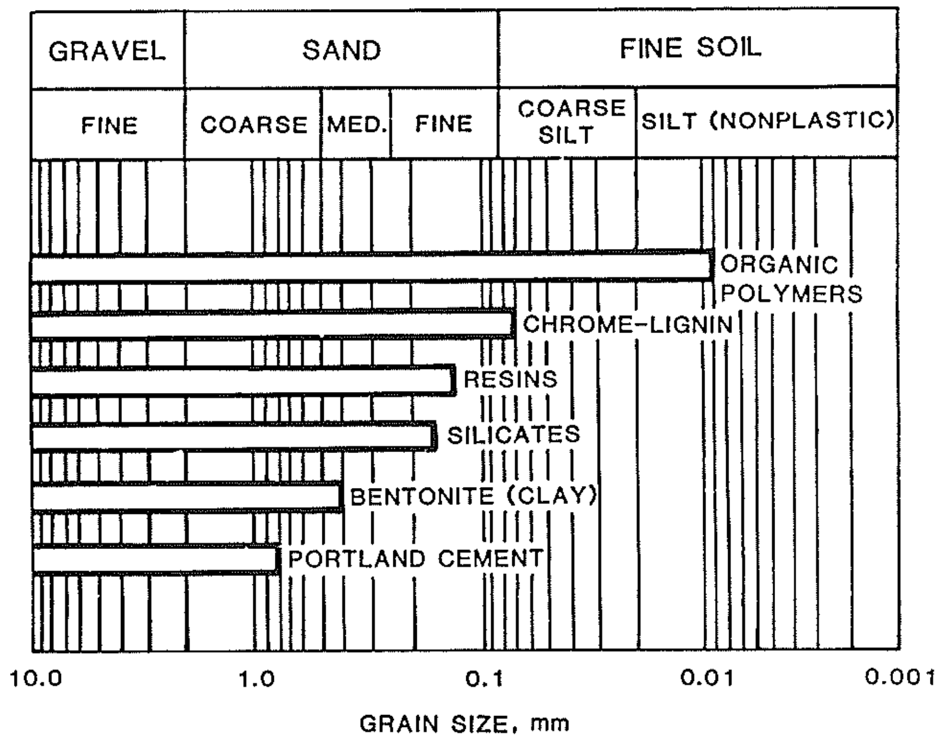

Figure 3. Injectability of particulate and chemical grout in fine and coarse soil (US Depts. of Army and Air Force, 1970).

SCOPE

The research reported here consists of three related phases:

1. Screening and selection of grouts for bottom sealing of hazardous wastes. (The ability of five grout formulations to set and remain intact in twelve simulated wastes was examined.)

2. Evaluation of chemical grout technology for producing a continuous bottom seal. (Two chemical injection tests were undertaken.)

3. Evaluation of jet grouting technology for producing a continuous bottom seal. (Jet grouting was examined in undisturbed loess, compacted silt and compacted sand.)

The three phases, grout selection, chemical grout evaluation and jet grout evaluation, combined demonstrate the currently available technology and the limitations involved in attempting to bottom-seal using current grouting techniques. A full-scale barrier test was not undertaken.

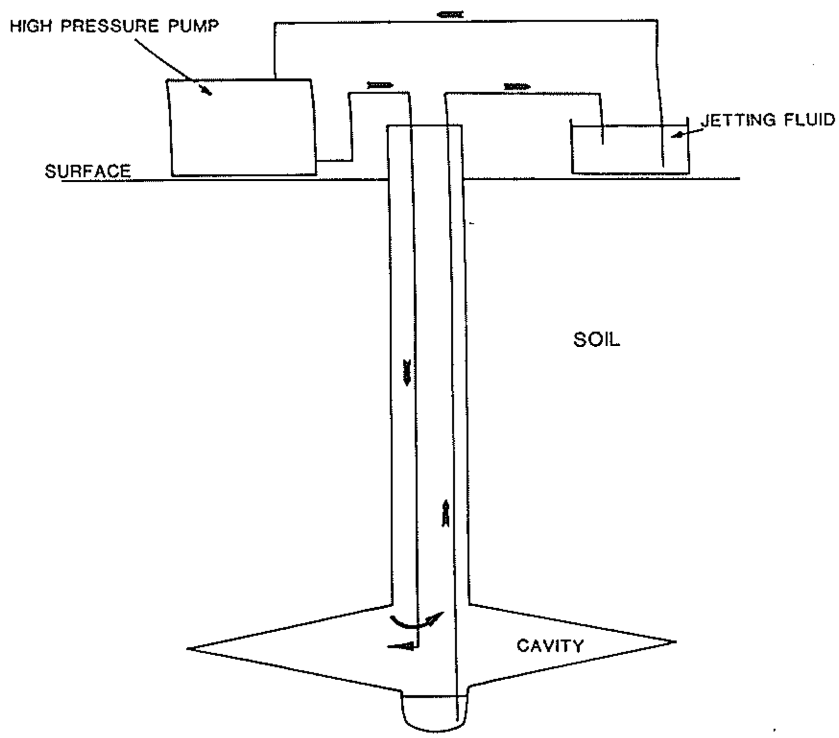

Figure 4. Schematic of jet grouting system.

SECTION 2

CONCLUSIONS

None of the commonly used chemical grouts examined in this study exhibited all of the necessary characteristics for success. Injection grouting tests using sodium silicate demonstrated the following points:

a. The shape of the chemical grout bulbs cannot be controlled due to inhomogeneity in the soil being grouted. The irregular shapes and positions of the grout bulbs make it difficult to form a continuous barrier by injecting grout bulbs that coalesce.

b. Large holes in soil masses (root holes) will not adequately seal if the chemical grout undergoes shrinkage (syneresis).

c. Coarse-grained soils and fine-grained soils in the grouted area may require different chemical grouts to assure that the chemical grout can penetrate, and after pentration will not shrink and pull away from the coarse material.

Jet grouting offers several advantages over injection grouting in the proposed application.

a. Jet grouting is effective in a wide variety of geologic media (such as silt or fine sand or mixed silt and sand) that cannot be grouted in any other way.

b. Cutting a cavity allows elimination of inhomogeneities in soil (such as root holes, channel fillings, sand plugs, etc.) when grout is injected.

c. A wide variety of grouts (chemical, particulate or mixed) can be used in jet grouting. The large variety of grouts available makes it possible to select material that is chemically non-reactive and durable in soils contaminated with hazardous waste chemicals.

d. Waste/grout interaction during grout setting is minimized in jet grouting.

Major difficulties observed with jet grouting are:

a. The size and shape of the cavity produced in jetting cannot be determined without special sensing equipment mounted in the jetting head.

b. Jet grouting requires specialized equipment, usually beyond that available from normal drilling and grouting contractors.

c. The cutting fluid must be recycled or disposed as a possible hazardous waste.

d. Jet grouting in the form evaluated in this study requires set-up and cleanup times that are far longer than required for chemical injection grouting.

e. The grout selected for injection should be thoroughly tested to assure that it will remain as an impermeable barrier.

SECTION 3

RECOMMENDATIONS

The results obtained in this investigation indicate that chemical grouts, as currently used, are poorly suited to bottom sealing. Many of the problems with chemical grouts noted in bottom sealing tests are identical to deficiencies noted in construction applications. As advances are made in grout technology in construction, the possible applications to bottom sealing should be evaluated. Jet grouting appears to offer the greater promise of being further developed to obtain a satisfactory bottom grouting procedure.

Future research needs include the development of down-hole techniques for monitoring cavity geometry in jet grouting and the development of rapid techniques for inserting a jet and producing a cavity without drilling a hole and setting a casing. Bottom sealing in soft soil possibly could be done from a soil probe (instead of drilling) with great savings of time.

SECTION 4

SELECTION OF GROUTS FOR BOTTOM SEALING

GROUT REQUIREMENTS

Grouts have been widely used in the construction industry to add strength to or stabilize soils, to increase the bearing capacity of soil and to control ground water flow. In most construction operations, the ground water and the soil are uncontaminated and personnel can operate without protective clothing other than normal safety equipment. Drill cuttings and drilling fluids can be left on site or placed in landfills. Grout mixes to be employed in the field can be designed and tested in the laboratory with reasonable assurance they will perform similarly in field grouting operations. In construction grouting, any grout seal is combined with a pumping system that will control residual seepage through the "seal". The seepage water is routinely discharged through sewers or into local waterways.

In contrast, grouting operations at a waste site may be less precise and less efficient than construction grouting because of requirements for protective gear and the difficulties encountered with contaminated drilling wastes and drilling equipment. In bottom sealing operations at a waste site, the soil that is to be grouted can be assumed to be contaminated. Contamination can include both the soil and any ground water or seepage under the site. The grout placed under the site will have to set up or harden in the presence of a variety of waste types. After the grout sets the soil must remain a low permeability mass after an indefinite prolonged period of exposure to wastes. The grout is injected in discrete bulbs or pods that must coalesce to form a continuous, impervious layer to be effective for control of hazardous waste migration.

The impervious seal formed by grouting must perform with a high degree of efficiency because any seepage that must be removed by pumping may require treatment and disposal as a hazardous waste. For waste control, the design requirements and performance standards for the grout are more demanding than in construction grouting. Table 1 summarizes desirable characteristics for grouts used in waste control.

To select grouts for bottom sealing for this study a screening program was developed to determine which grouts would set or harden in the presence of dilute solutions that simulated contaminated ground water typical of some hazardous waste sites. The grouts were further tested in the laboratory for durability by placing samples of set grout in contact with simulated waste water and examining the specimens for shrinking and swelling over time.

TABLE 1. DESIRABLE CHARACTERISTICS OF GROUTS FOR WASTE CONTROL

Characteristics
Commercially available
Sets or hardens in presence of wastes
Remains intact in soil in presence of waste
Seals maximum area using minimum number of injection borings
Has low toxicity prior to set
Has low toxicity after setting
Can be handled with moderate level of effort
Can be obtained at reasonable cost

MATERIALS AND METHODS

Grouts

Four types of grout (five formulations) were selected for testing based on reliability, durability, ease of operation, low toxicity and other factors (Table 1). The major properties of the candidate grouts are given in Table 2. All four grouts are available in a number of different formulations that can change their properties, but the basic chemical reactions that take place during setting or hardening and the chemical products obtained are the same for the various formulations of a given grout type. The test results can be considered as generally valid for specific grout types. Toxicity data on the specific formulations used in the tests are given in Table 3. Note that the unreacted grout components are more toxic than the hardened grouts. Any compound that slows or stops grout gelling increases the likelihood that the more toxic unreacted components will be injected into the soil and ground water at a waste site producing a secondary pollution problem.

Simulated Wastes

Twelve solutions containing selected compounds in the concentration range in which they could occur below a hazardous waste site were prepared. Soluble compounds were made up as 10 percent solutions (by weight) in distilled water. Where the low solubility made this impossible a saturated solution was prepared. The characteristics of the waste solutions are given in Table 4.

SETTING TIME DETERMINATIONS

Determination of Normal Set Times

Baseline data on chemical grout set times were collected by preparing 250 ml batches of grout using proportions specified by the manufacturers or using standard mixtures employed in construction. The setting of each chemical grout sample was determined using a paddle gelometer (Larson and May, 1983). Samples were maintained at 25° C during testing. The gelometer uses a rotating paddle that stops when a preset shear strength is reached. The gelometer was adjusted to stop at the point at which the chemical grouts became too viscous

TABLE 2. SUMMARY OF THE PROPERTIES OF SELECTED GROUTS

Grout Type	Viscosity (cp)	Setting Time (min)	Strength (N/cm^2)
Silicate	1.5 - 50	0.1 - 3000	0.01 - 1.5
Acrylate	1.2 - 1.6	0.1 - 1000	0.2 - 2.0
Urethane	20 - 200	0.08 - 120	NA
Portland cement	15 - 35	10 - 360*	500+

NA: Not Available
* Initial set.

Sources: Sommerer and Kitchens, 1980
Tallard and Caron, 1977a
Tallard and Caron, 1977b
Karol, 1982a
Bowen, 1981
Avanti International, 1982

TABLE 3. TOXICITY OF COMPONENTS AND GROUT FOR SELECTED GROUTING SYSTEMS

Grout Type	Components	Toxicity of** Components	Toxicity of Set Grout
Silicate*	--	--	>15,000
(30% and 50-60%	Sodium silicate	1100	--
sodium silicate)	Calcium chloride	1000	--
	Magnesium chloride	2800	--
	Dimethylformamide	1500	--
	Water	Nontoxic	--
Acrylate	--	--	5,000
	Acrylate monomer	200	--
	Methylenebisacrylamide	390	--
	Water	Nontoxic	
Urethane	--	--	5,000
	Toluene diisocyanate	5800	--
	Acetone	9750	--
	Water	Nontoxic	
Portland cement	Portland cement	Nontoxic	Nontoxic
	Water	Nontoxic	

Sources: Tallard and Caron, 1977b
Berry, 1982
Geochemical Corporation, 1982
* Two formulations of silicate were used.
** Oral LD_{50} (mg/kg) for rats.

TABLE 4. CHARACTERISTICS OF WASTE TEST SOLUTIONS USED

Waste Component	Character of Waste	Concentration of Waste
Potassium chromate	Strong oxidizer	10%
Hydrochloric acid	Inorganic acid	10%
Ammonium hydroxide	Base	10%
Sodium hydroxide	Base	10%
Ammonium chloride	Salt	10%
Copper sulfate	Salt	10%
Benzene	Cyclic hydrocarbon	Saturated
Gasoline	Hydrocarbon mixture	Saturated
Oil	Hydrocarbon mixture	Saturated
Phenol	Substituted benzene	Saturated
Toluene	Substituted benzene	Saturated
Trichloroethylene	Halogenated hydrocarbon	Saturated

to pour from a beaker. All set times are averages of duplicate determinations (Table 5). Duplicate measurements agreed within 20 percent of each other.

Setting or hardening times for the cement-based grout were determined using a needle penetrometer test. The set-time was selected at a point where the initial set made the mix too stiff to pour. Final set was designated as the point where negligible penetration occurred. Portland cement grout was tested in duplicate and the set times averaged. The repeated times were within 10 percent of each other (Table 5).

Effects of Wastes on Setting

The effects of wastes on the grout set times were determined by mixing separate samples of each prepared grout with an equal volume of each simulated waste solution. Determinations were made on single samples. The time required for setting to occur was determined by observing the time required for the grout to become too viscous to pour from the container (Larson and May, 1983). The gelometer was not used because setting was often so gradual that the paddle made a cavity in the grout and continued to turn after the grout had hardened. The penetrometer was also ineffective due to slow setting. Table 6 summarizes the effects of the simulated wastes on setting times for the grouts. Effects varied from complete retardation of set (30% silicate grout in sodium hydroxide) to production of a flash set (30% silicate grout with copper sulfate). Complete retardation was assumed to occur if no gel formed in 48 hours.

TABLE 5. NORMAL SETTING OR HARDENING TIMES FOR STANDARD GROUT FORMULATIONS

Grout Type	Setting Time* (Average of Duplicate Runs)
Acrylate	30 seconds
Silicate (30% by wt.)	41.9 minutes
Silicate (50% by wt.)	25.2 minutes
Urethane	3.3 minutes
Portland cement (initial set)	6.0 hours
Portland cement (final set)	11.5 hours

* All runs were made at 25° C.

DURABILITY TESTING

The durability of samples of hardened grout was determined by casting cylindrical plugs 32 mm × 25 mm diam. (1.25 in. × 1.0 in. diam.) or cubes 32 mm on a side (1.25 in. on a side) of grout and allowing samples to harden for 24 to 72 hours. The hardened samples of each grout were then immersed in 300 to 500 ml of each simulated waste solution. The specimens of grout were measured after 20-days immersion with a scale or micrometer and changes in the volume of each specimen were noted (Table 7). Determinations were made on single specimens (Larson and May, 1983).

INJECTABILITY AND PERMEABILITY TESTING

After completion of the setting and durability screening two grouts, acrylate and sodium silicate, were selected for further examination. Twelve 208-liter drums were filled with medium sand and saturated for one-half their depth with a simulated waste solution. A control drum was prepared with water in place of waste. Approximately 20 liters (0.6 ft^3) of acrylate or 40%-silicate grout was pumped into each drum. The drums were allowed to stand for 48 hours and then the grout pods were removed.

The acrylate grout set in every case but it formed a gelatin-like mass that broke apart or flattened under its own weight when removed. The acrylate grout masses could not be measured to determine the diameter of the grout bulbs and the deformation and splitting of the sample made the grouted sand unsuitable for accurate permeability testing.

The silicate grout formed rigid bulb-like masses (Figure 5) that could be measured and trimmed with a saw into cylinders for testing. Specimens were maintained in a moist condition and trimmed into cylinders 7 to 9-cm (2.75 to

TABLE 6. EFFECTS OF SIMULATED WASTES ON SET TIMES FOR VARIOUS GROUT TYPES

Waste Compounds	Set Times for Grout Types: Acrylate	30% Silicate	50% Silicate	Urethane	Portland Cement: Initial Set	Final Set
Potassium chromate	No set	42 min	23 min	No set	4 hrs	7.5 hrs
Hydrochloric acid	No set	4 min	Set on contact	No set	5 hrs	24 hrs
Ammonium hydroxide	No set	2.5 hrs	3 hrs	No set	5 hrs	9.5 hrs
Sodium hydroxide	No set	No set	3.3 hrs	No set	3 hrs	7.5 hrs
Ammonium chloride	5 min	Set on contact	Set on contact	No set	13 hrs	24 hrs
Copper sulfate	No set	Set on contact	Set on contact	No set	Set on contact	24 hrs
Benzene	5 min	2.5 hrs	2.5 hrs	No set	4.5 hrs	7.5 hrs
Gasoline (unleaded)	7 min	3 hrs	3 hrs	No set	4 hrs	8 hrs
Oil	7 min	5.5 hrs	5.5 hrs	No set	4.5 hrs	8 hrs
Phenol	No set	Set on contact	Set on contact	No set	4.5 hrs	7.5 hrs
Toluene	1.4 hrs*	2.25 hrs	2.25 hrs	No set	5 hrs	7.5 hrs
Trichloro-ethylene	7 min	3 hrs	3 hrs	No set	3 hrs	7.5 hrs

* Partial set only.

TABLE 7. EFFECTS OF SIMULATED WASTES ON GROUT AFTER 20-DAYS EXPOSURE

Waste Component	Effects on Grout Types: Acrylate	Silicate* Grout	Urethane	Portland Cement
Potassium chromate	SW (+83)**	SH (-88)	SH (-99)	NC
Hydrochloric acid	SH (-74)	NC	SH (-62)	NC***
Ammonium hydroxide	SW (+83)	SW (-80)	SW (+162)	NC
Sodium hydroxide	SW (+83)	D	D	NC
Ammonium chloride	SW (+70)	SH (-41)	SH (-42)	NC
Copper sulfate	SH (-42)	NC	SH (-59)	NC
Benzene	SW (+76)	SH (-12)	SW (+83)	NC
Gasoline	SW (+70)	SH (-67)	SW (+70)	NC
Oil	SW (+109)	SH (-64)	SW (+54)	NC
Phenol	SW (+70)	SH (-4)	SH (-12)	NC
Toluene	SW (+83)	SH (-64)	SW (+319)	NC
Trichloroethylene	SW (+109)	SH (-80)	SW (+83)	NC

NC = No change

SH = Shrink

SW = Swell

D = Dissolve

* Grout used was 30% sodium silicate solution but similar result would be expected from 50% sodium silicate.

** Numbers in parentheses are the percent change in volume associated with the reaction.

*** Slight surface etching.

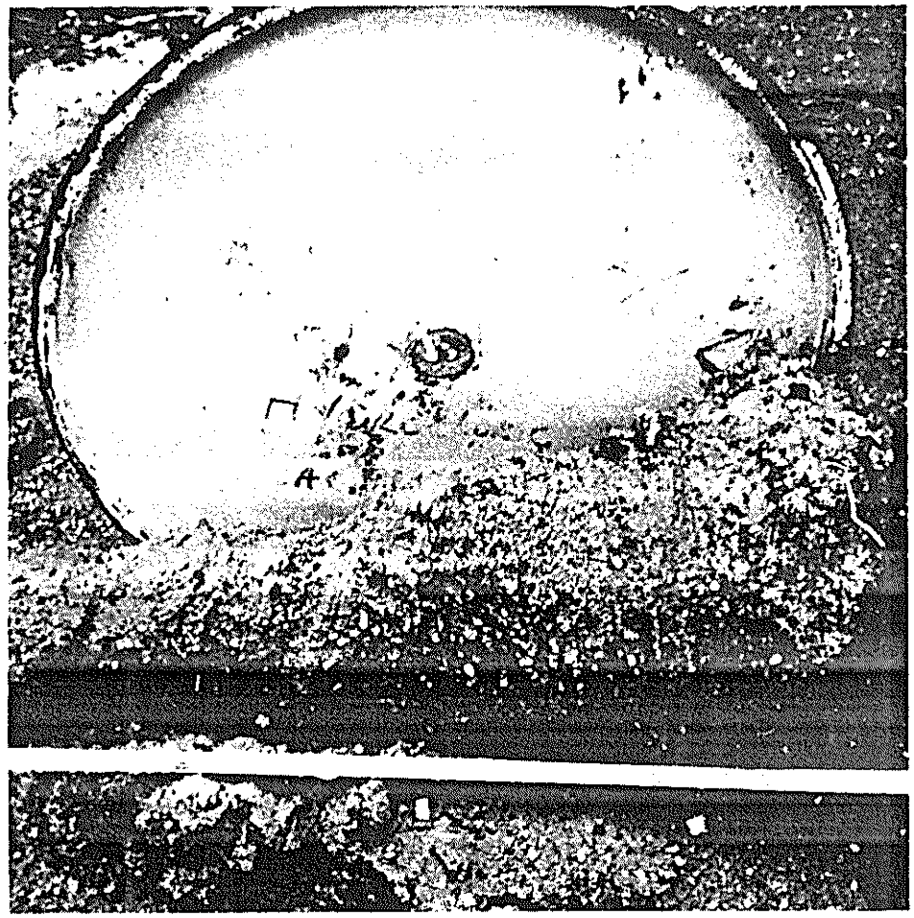

Figure 5. Silicate grout bulb formed by injecting grout into a 208-liter drum of sand containing simulated wastes.

3.5-in.) in diameter and 7 to 8-cm (2.75 to 3.1-in.) tall and tested using a triaxial constant head permeameter (Malone, Larson, May, and Boa 1984; Office of Chief of Engineers, 1970; Appendix VII). The permeability test results and the diameters obtained on the silicate test bulbs are presented in Table 8.

RESULTS AND DISCUSSION

Laboratory bench-scale testing conducted on five selected grouts has shown that solutions simulating wastes at a hazardous waste site can significantly alter the setting time of grouts or can completely inhibit setting. Setting of the urethane grout tested was completely inhibited by every simulated waste tested. Acids, bases, oxidizers and copper sulfates inhibited the acrylate grout. Sodium hydroxide solution (10%) inhibited the 30%-sodium silicate grout, and it slowed the setting of 50%-sodium silicate grout. Ammonium chloride slowed the set of portland cement but produced a flash set with

TABLE 8. CHARACTERISTICS OF TEST PODS PRODUCED BY INJECTION OF 40% SODIUM SILICATE SOLUTION

Liquid Phase	Maximum Diameter of Pod (cm)	No. of Samples Tested	Permeability Average (cm/sec)	Permeability Range (cm/sec)
None	--	3	1.12×10^{-4}	9.54×10^{-5} - 1.27×10^{-4}
Water (saturated)	33.0	3	1.72×10^{-4}	1.39×10^{-4} - 2.29×10^{-4}
Potassium chromate	--	3	7.74×10^{-4}	7.62×10^{-4} - 7.96×10^{-4}
Hydrochloric acid	--	3	4.88×10^{-4}	4.82×10^{-4} - 4.88×10^{-4}
Ammonium hydroxide	38.1	3	4.33×10^{-4}	4.17×10^{-4} - 4.46×10^{-4}
Sodium hydroxide	38.1	Specimens could not be trimmed; no cementing occurred		
Ammonium chloride	58.4	3	3.52×10^{-5}	3.03×10^{-5} - 3.99×10^{-5}
Copper sulfate	43.2	3	1.42×10^{-4}	1.36×10^{-4} - 1.46×10^{-4}
Benzene	40.6	3	5.85×10^{-4}	4.71×10^{-4} - 6.46×10^{-4}
Gasoline	--	3	8.08×10^{-4}	7.98×10^{-4} - 8.20×10^{-4}
Oil	--	3	1.60×10^{-4}	1.50×10^{-4} - 1.69×10^{-4}
Phenol	45.7	3	1.03×10^{-4}	1.00×10^{-4} - 1.10×10^{-4}
Toluene	45.7	3	8.18×10^{-4}	8.08×10^{-4} - 8.26×10^{-4}
Trichloroethylene	43.1	3	8.06×10^{-4}	7.82×10^{-4} - 8.25×10^{-4}

sodium silicate. Copper sulfate produced a flash set with both portland cement and sodium silicate.

In the 20-day waste exposure testing, silicate grouts and portland cement grout showed the least interaction with the simulated waste utilized. Only sodium hydroxide dissolved the silicate grout. Ammonium hydroxide caused swelling. Other simulated wastes caused shrinkage of the silicate, probably by removing water from the set grout. Acid caused minor etching on the surface of the portland cement but produced no serious effects. Urethane dissolved in sodium hydroxide and shrank or swelled in all other media. Acrylate showed some swelling or shrinkage in every simulated waste.

The results of the setting and durability testing are summarized in matrix form in Figure 6. The overall results indicated that of the grouts tested, silicate and portland cement were the most dependable grouts for use in contaminated soil and water. The acrylate grout formulation employed was considered less useful because it was retarded from setting in oxidizers, strong acids, strong bases, copper sulfate and phenol. Acrylate showed some swelling and shrinkage but remained intact in the twelve simulated wastes tested. The results for acrylate are comparable to those obtained in other testing (Clarke, 1982). Urethane was easily retarded from setting and was changed by exposure to any waste solution.

Grout pods made by injecting acrylate or sodium silicate into partly saturated sand containing simulated waste solutions demonstrated that, with the exception of silicate in sodium hydroxide, grout pods could be formed from these two chemical grouts. Samples of the acrylate suitable for testing could not be recovered. Permeability testing of silicate grouted sand indicated that at the level of contamination employed, the maximum decrease in permeability observed was only one-fifth of the permeability obtained when wastes were absent. Samples of grouted sand prepared by injecting grout in water containing phenol or ammonium chloride had lower permeabilities than those observed for grout injected in clean water. The performance of the silicate grout as a hydraulic barrier may be degraded or improved depending on the type of contamination. Each waste site will have a different combination of wastes and the effects of mixed wastes are not completely predictable from existing data on single components at one concentration. Selection of a grout for use at a waste site will have to be based on laboratory and field tests obtained using contaminated soil and ground water from the actual site.

CHEMICAL GROUP \ GROUT TYPE	ACRYLATE	SILICATE GROUT (30%)	SILICATE GROUT (50%)	URETHANE	PORTLAND CEMENT
OXIDIZER - POTASSIUM CHROMATE	2d?	2d?	2d?	2d?	1a
ACID - HYDROCHLORIC ACID	2d?	1a	3a	2d?	1d
BASE - AMMONIUM HYDROXIDE	2d?	2d?	2d?	2d?	1a
BASE - SODIUM HYDROXIDE	2d?	2c	2c	2d?	1a
SALT - AMMONIUM CHLORIDE	1d?	3d?	3d?	2d?	2a
METALLIC SALT - COPPER SULFATE	2d?	3c	3d?	2d?	3a
CYCLIC HYDROCARBON - BENZENE	1d?	2d?	2d?	2d?	1a
MIXED HYDROCARBON - GASOLINE	1d?	2d?	2d?	2d?	1a
MIXED HYDROCARBON - OIL	1d?	2d?	2d?	2d?	1a
SUBSTITUTED HYDROCARBON - PHENOL	2d?	1d?	3d?	2d?	1a
SUBSTITUTED HYDROCARBON - TOLUENE	2d?	2d?	2d?	2d?	1a
CHLORINATED HYDROCARBON - TRICHLOROETHYLENE	1d?	2d?	2d?	2d?	1a

KEY: Compatibility Index

EFFECT ON SET TIME

1 No significant effect
2 Increase in set time (lengthen or prevent from setting)
3 Decrease in set time

EFFECT ON DURABILITY

a No significant effect
b Increase durability
c Decrease durability (destructive action begins within a short time period)
d Decrease durability (destructive action occurs over a long time period)

? Short duration of the test prevents full assessment of the durability, but swelling or shrinking was observed

Figure 6. Grout compatibilities based on experimental data.

SECTION 5

CHEMICAL GROUT INJECTION

MIXING AND INJECTING TECHNIQUES

Chemical grouts consist of compounds that are in solution and are generally made from liquid components. Blending liquid ingredients in grouts can be done rapidly with little equipment and energy requirements. Chemical grouts can be batch mixed and injected or the components can be pumped together through a static in-line mixer.

In some chemical grout systems, two components are pumped into the ground separately but through the same injection point. Two-solution processes allow for better penetration of the grout; but, the mixing of the reactants cannot be controlled in the soil and pockets of ungrouted soil may be produced (Office of the Chief of Engineers, 1973; Littlejohn, 1985a, 1985b). All grouting systems used in this project were treated as one-solution grouts, although the silicate grouts can be injected in a two-solution system.

In-line mixing is typically used where large volumes of one-solution chemical grout are being placed and short set times are needed to assure that the grout is properly placed. The uniformity of the mix depends on the quality of the metering pumps and the care taken in calibration.

Batch mixing involves combining all the components of the chemical grout in one container. The container is emptied by a pump which forces the mixed grout into the soil being treated. Batch mixing allows the quantity of each grout component going into the mixer to be measured precisely. Batch mixing uses more time than in-line mixing and grouts injected this way are designed with longer set times to compensate for the delay in moving the grout to the injection point. Any changes in the grout batch, can be noted immediately, and if a premature set starts to occur, the grout can be discarded. Samples from each batch can also be monitored to assure that a set occurs within a specified time after injection. All chemical grouts used in this project were batch mixed to allow for better quality control and to permit the setting time on each batch to be verified.

Two separate chemical grouting tests were developed. A small-scale chemical grout testing project was performed using two identical sand beds to examine the ability of acrylate and 30% silicate to form a continuous seal when injected in a series of discrete bulbs. In the large-scale chemical grout injection project, 30-percent silicate grout was injected into a 85-sq m (915 sq ft) area underlain by fine sand. The test was intended to produce a series of coalescing grout bulbs at a depth of 2.43 m (8 ft). A hole spacing of 1.52 m (5 ft) was employed.

SMALL-SCALE CHEMICAL GROUT TEST

Materials and Methods

Silicate and acrylate grouts were selected for test injection in the small-scale grout testing project because they demonstrated the ability to set in the presence of most contaminants examined and showed a reasonable degree of durability in a diluted waste environment. The small-scale tests were performed by injecting each grout into a 1-meter deep layer of medium-grained sand in a separate test bed. Each test plot had an area of 2 m × 4 m. Grout was injected at a depth of 30 to 50 cm in a grid-like pattern (Figures 7 and 8) with a maximum spacing between holes of 40 cm. Grouting was done in three stages to assure complete coverage of the test bed and insure that grout bulbs met.

The silicate grout used was a 30-percent solution of JM-grade (technical) sodium silicate. The hardener employed was a proprietary mixture containing calcium chloride, magnesium chloride and dimethylformamide. The silicate grout was made up according to the manufacturer's specifications using tap water. The acrylate grout was made up from a proprietary mixture of acrylate monomer and methylenebisacrylate. Ammonium persulfate was used as an initiator. The grout was made up to the manufacturer's specifications using tap water.

Grouts were batch mixed by hand and injected using a progressive cavity pump. Each injection hole received 7 liters of grout. Setting times were established in the laboratory to allow five minutes for mixing and injecting the grout. The grouts were mixed in 7-liter batches so the set time for each batch could be checked. In all cases the actual set time was equal to or less than the design set time. No retarding of set was observed. The sand beds contained only sand and uncontaminated water. No simulated wastes were present, and the test bed did not interfere with the hardening of the grout.

The test beds were a poorly-graded medium sand with less than 10 percent pebble-sized material (Figure 9). The test beds were saturated, but were allowed to drain prior to grout injection. A 7-cm diameter slotted pipe was installed under each sand bed to assure free draining. Grout was injected in three stages, working continuously from one sequence of injection points to another. After grout injection each test bed was covered with a polyethylene sheet to allow the grout to set and cure without being washed out by rain. Both water and grout were observed discharging from the underdrains during grouting suggesting that displaced capillary water and grout were being lost to the drains.

The plastic pipe used for grout injection was withdrawn from the sand after grouting. In all cases some liquid grout remained in the injection holes indicating the bottom and sidewalls of the hole were saturated with grout. In both of the freshly grouted test beds there was evidence of stiffened grout in the surface sand around the injection holes. Only the silicate

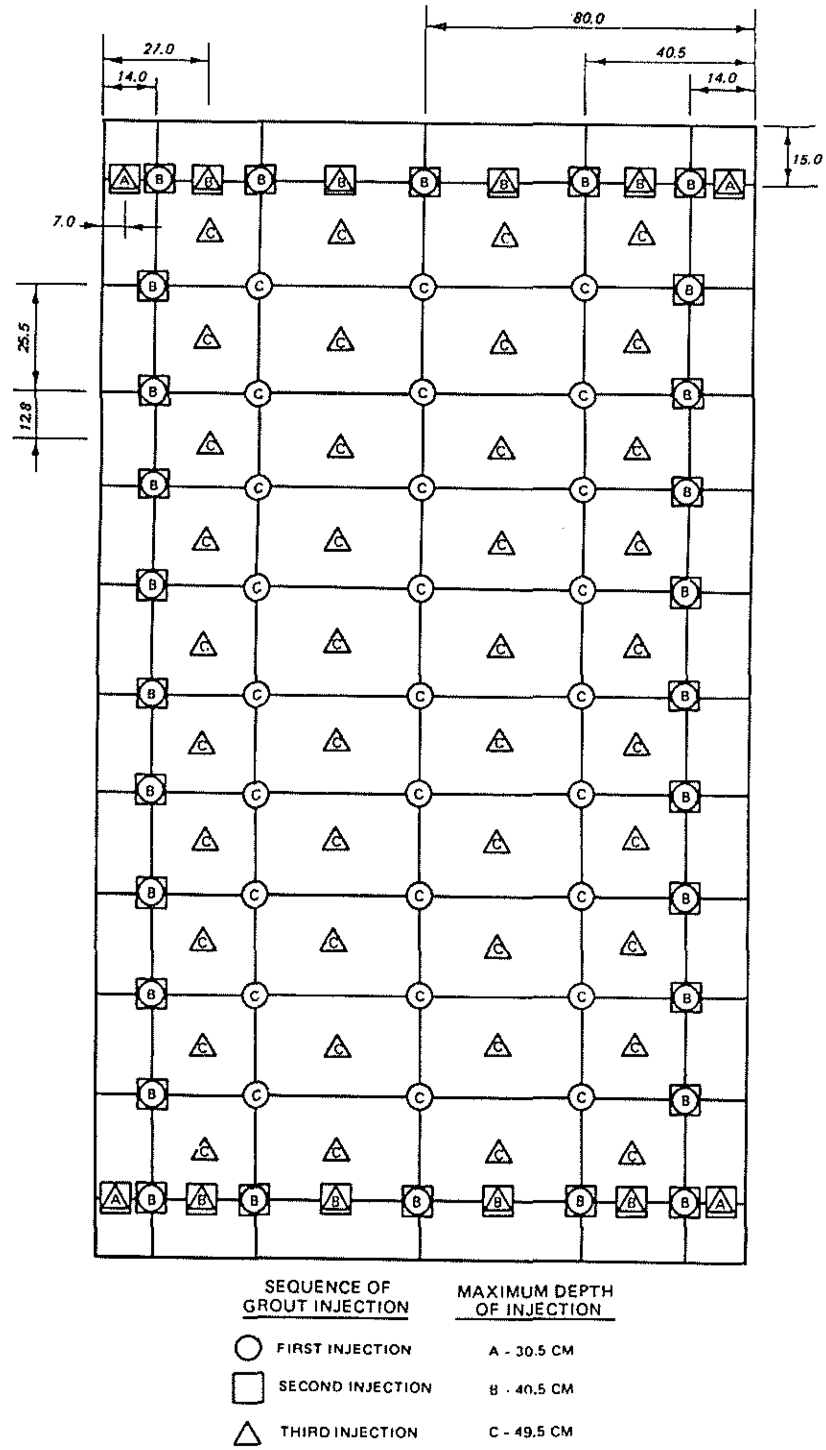

Figure 7. Diagram showing positioning of injection points in the small-scale chemical grouting test program. All measurements are in centimeters.

Figure 8. Test bed for small-scale chemical grouting. The exposed vertical pipe sections mark the grout injection points.

grout made a hard, cohesive pod in the area of the injection hole. The acrylate grout formed thin, rubbery stands of grout in the surface sand around the injection point, but the sand containing injected grout, was not a coherent mass.

Results

Both the silicate- and acrylate-grouted sand beds were tested to determine if a continuous impermeable layer had been formed. A shallow (10-cm deep) trench was dug in the sand over the center of the grouted layer and water containing a dye (fluorescein or rhodamine) was poured along the center of the grouted area. To assure that the dye tracer did not overtop the pan-like grout seal, only 80-100 liters of water was placed in each trench and water was added only when all of the tracer had drained through the bottom of the trench. The times required for the tracers to appear at the test bed drains and the quantities of water and dye added were not significantly different when grouted and ungrouted sand beds were compared. The tests using a dye tracer indicated no impervious grout layer had formed in either the silicate or the acrylate test beds.

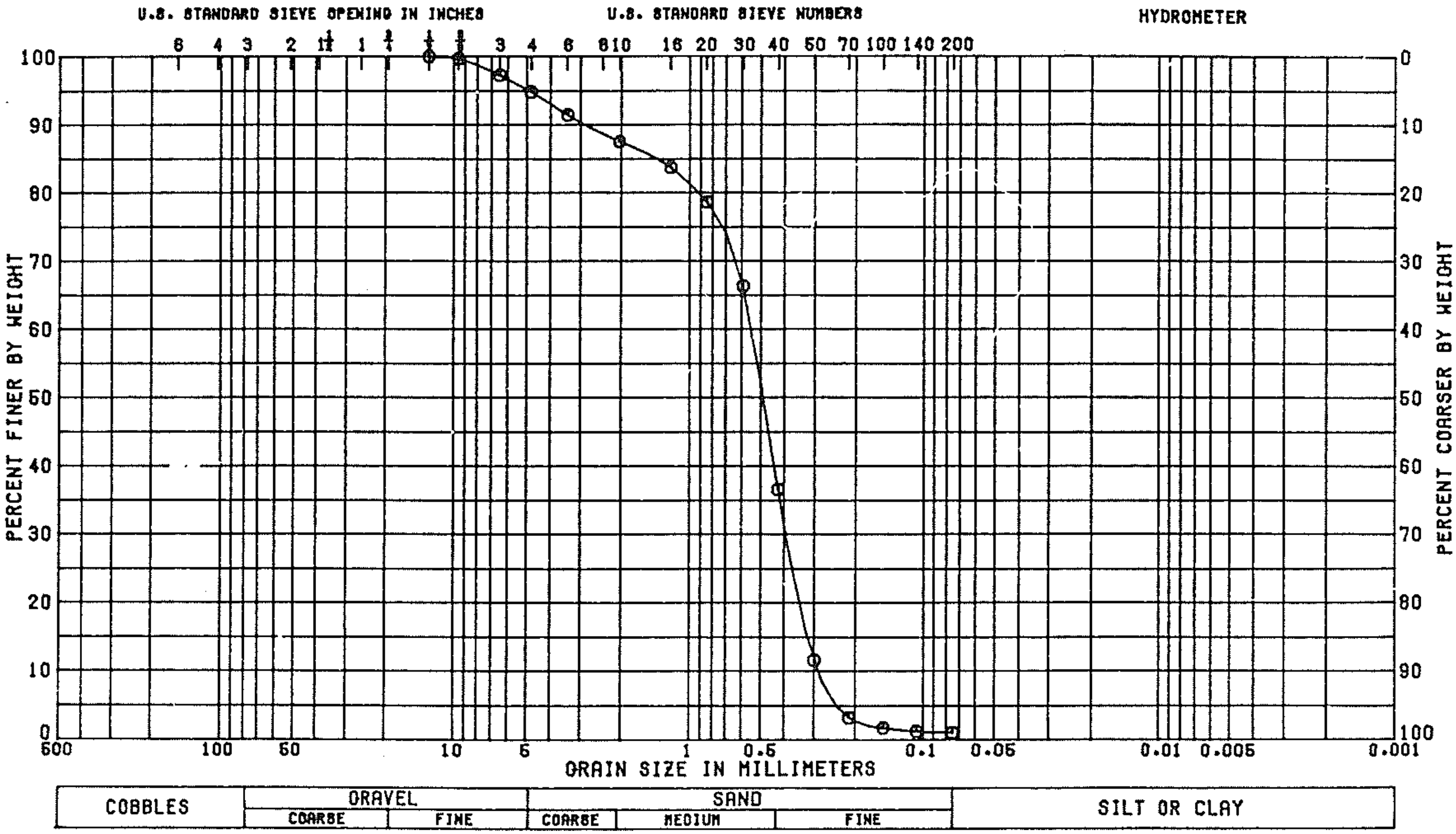

Figure 9. Grain-size distribution of sand used for the small-scale field test.

The grouted test beds were excavated and the position and character of the grouted sand was noted. In the silicate-grouted test bed two problems were apparent; (1) gaps existed between adjacent grout bulbs where water could migrate through the grouted layer into the drain (Figure 10) and (2) the center portions of many of the grout bulbs were not cemented (Figure 11). The grout bulbs in many cases were in contact, but gaps existed that allowed the rapid movement of a dye tracer through the grouted layer. The lack of cementation in the centers of the bulbs was due to shrinkage caused by the loss of water (syneresis). The shrinkage moved the grout to the outside of the bulbs.

The acrylate grout did not form bulb-like masses and very little grout was found in the top of the sand layer. Most of the acrylate grout was found in irregular masses at the bottom of the sand bed (Figure 12). The grout had not plugged the slotted pipe that formed the drain, but was covering portions of the pipe. The dye could easily pass through the injected layer into the drain. Inspection of the sand test bed during grouting indicated that grout set within minutes of injection. The grout may have migrated after setting or been partly displaced by water added during testing.

LARGE-SCALE CHEMICAL GROUT TEST

Results from the small-scale sand bed tests were used in developing a large-scale chemical grouting test. Sodium silicate was selected as a test grout and a field test site underlain with fine sand was used to reduce the problems of grout shrinkage. To minimize gaps between pods, the injection holes were spaced in a staggered pattern on 1.5-meter (5-ft) centers and grouted to refusal or until the grout take was 0.76 cubic meters.

Materials and Methods

An 85-square meter (915 sq ft) plot underlain by fine sand with 12-22% silt and clay (Figure 13) was made available for this study in a test area at Fort Polk, Louisiana. Ten borings were laid out on 1.52-m (5 ft) centers using the pattern shown in Figure 14. Injection holes were drilled to a depth of 2.75 m (9 ft) and each hole was backfilled with coarse filter sand to a depth of 2.44 m (8 ft). A 3.05-m (10-ft) section of 5-cm (2-in.) plastic pipe was inserted in the boring and the outside of the borehole was sealed with pelleted and powdered bentonite. Water was added after each batch of bentonite to assure the bentonite would hydrate and swell. A 4-m (13-ft) long, 2.5-cm (1-in.) diam. plastic pipe, sealed at both ends with tape, was inserted into the 5-cm (2-in.) pipe. The lower sealed end of the pipe was pressed into the filter sand. The inner pipe was cemented in place with a mixture of 50 percent portland cement and 50 percent mortar sand. The portland cement and sand mixture was also used to fill in the bore hole outside the 5-cm pipe and to complete the seal around the pipe. A 1.5-cm (0.6 in.) plastic pipe was inserted alongside the 5-cm (2-in.) pipe and agitated to assure the thin cement/sand mixture would flow to points where sealing was needed.

The cement/sand mix forming the seal was allowed to cure at least 24 hours before grout was injected. The grout was injected by untaping the top of the 2.5-cm (1-in.) pipe and running a 1.5-cm (0.6 in.) pipe with a

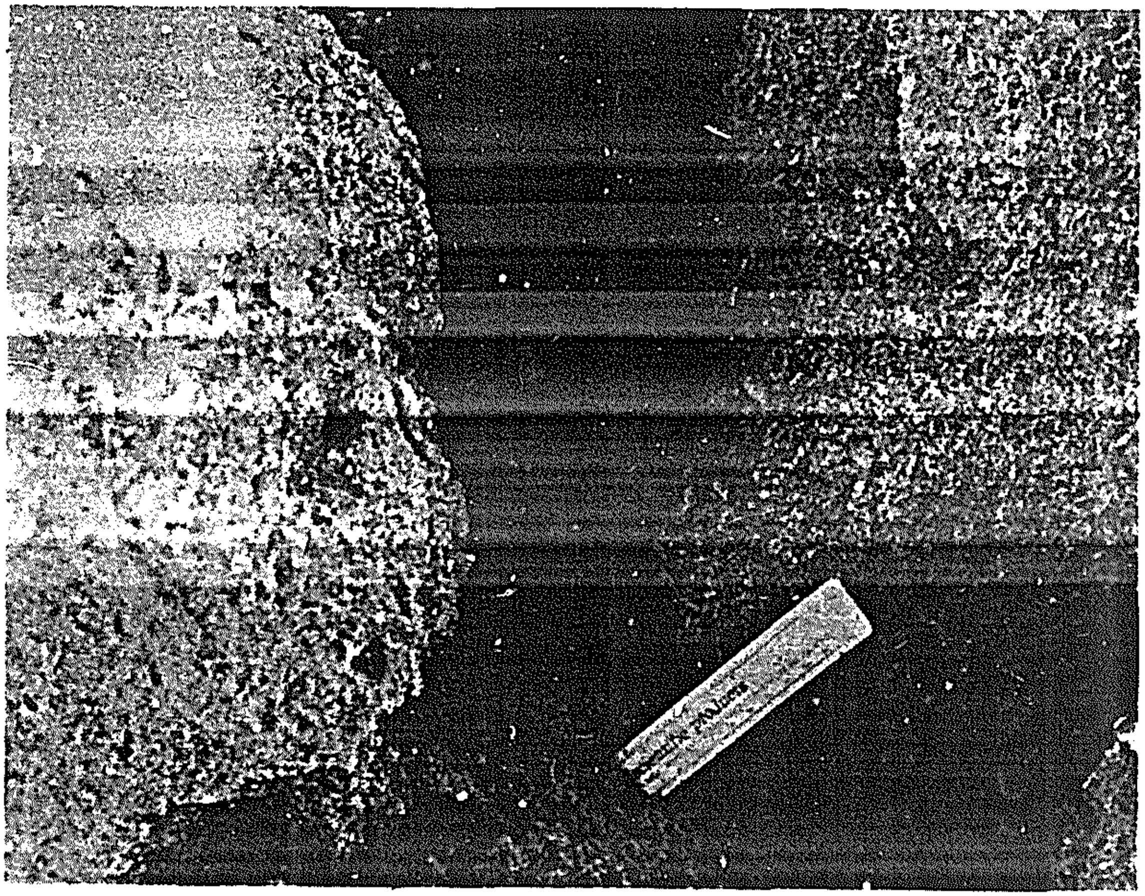

Figure 10. Gaps between adjacent silicate grout bulbs formed in the small-scale field test.

solid, pointed end down through the lower seal and 3 to 5 cm (1.2 to 2.0 in.) into the filter sand. This technique assured that the grout pumped into the 2.5-cm (1-in.) pipe had clear access to the filter sand. The water table was 2.94 m (9.6 ft) below the ground surface. The injection point was 50 cm (19 in.) above the water table, when the grout was injected.

A 30-percent sodium silicate grout similar to that used in the laboratory testing was mixed in batches and injected using a progressive cavity pump. The composition of the grout was adjusted to allow for a 20-35 minute pumping time for each batch. Grouting was continued at each hole until refusal was obtained or 760 liters (200 gal) were injected. Refusal was indicated by a rapid pressure rise in the grout pump followed by stalling of the pump or by a "blow-out" of grout to the surface either through the soil or the injection hole annulus.

The injection holes on the outside of the test plot were grouted first. The two inside holes (B2 and B3 in Figure 14) were grouted last. Only one

Figure 11. Silicate grout bulbs formed during the small-scale field test. Note the shells of bulbs indicating the outer layer of sand cemented and the inside of the bulb did not.

hole (B4) was not successfully injected. The grout set prematurely at this boring and stalled the pump after approximately 100 liters had been injected. An adjustment in the grout formulation corrected this problem at subsequent injection points. Samples of grout were taken from each grout batch to assure that the grout did set. Food coloring was added to each grout batch to allow the solidified grout to be identified. Color could only be detected when fragments of set grout were recovered intact. The brown or red color of the sand masked the color of the grout in the bulbs.

Results

Test borings were made in the grouted area and in adjacent ungrouted areas approximately 30 days after grouting was complete (Appendix A). Locations of the test borings are given in Figure 14. Permeability tests were run on undisturbed samples recovered from the grouted horizon and from the adjacent ungrouted sand using triaxial constant head standard techniques (Office

Figure 12. Sand mass cemented with acrylate at the bottom of the small-scale test bed.

of Chief of Engineers, 1970). Additional in-situ permeability tests were run in two test wells in the grouted area and two in the ungrouted area. The in-situ permeability testing was performed using a standard constant head test procedure (US Dept. of Interior, 1974; p 573). The results of the permeability tests are given in Table 9.

The grout pods formed in the large-scale chemical grout were excavated after 120 days. The plot was given no protection against rainfall during this time. Figure 15 shows the distribution of the grout bulbs over the test area. Many of the borings made in the sealed area did not intercept grout bulbs. Large areas between the injection points were not grouted.

In areas where the test borings were in grouted sand, the changes in permeability before and after grouting were not impressive. All of the permeability determinations made on cores of grouted sand samples fell within the range observed for ungrouted sand (Table 9). Even in the in-situ measurements, the difference in permeability between grouted and ungrouted sand was

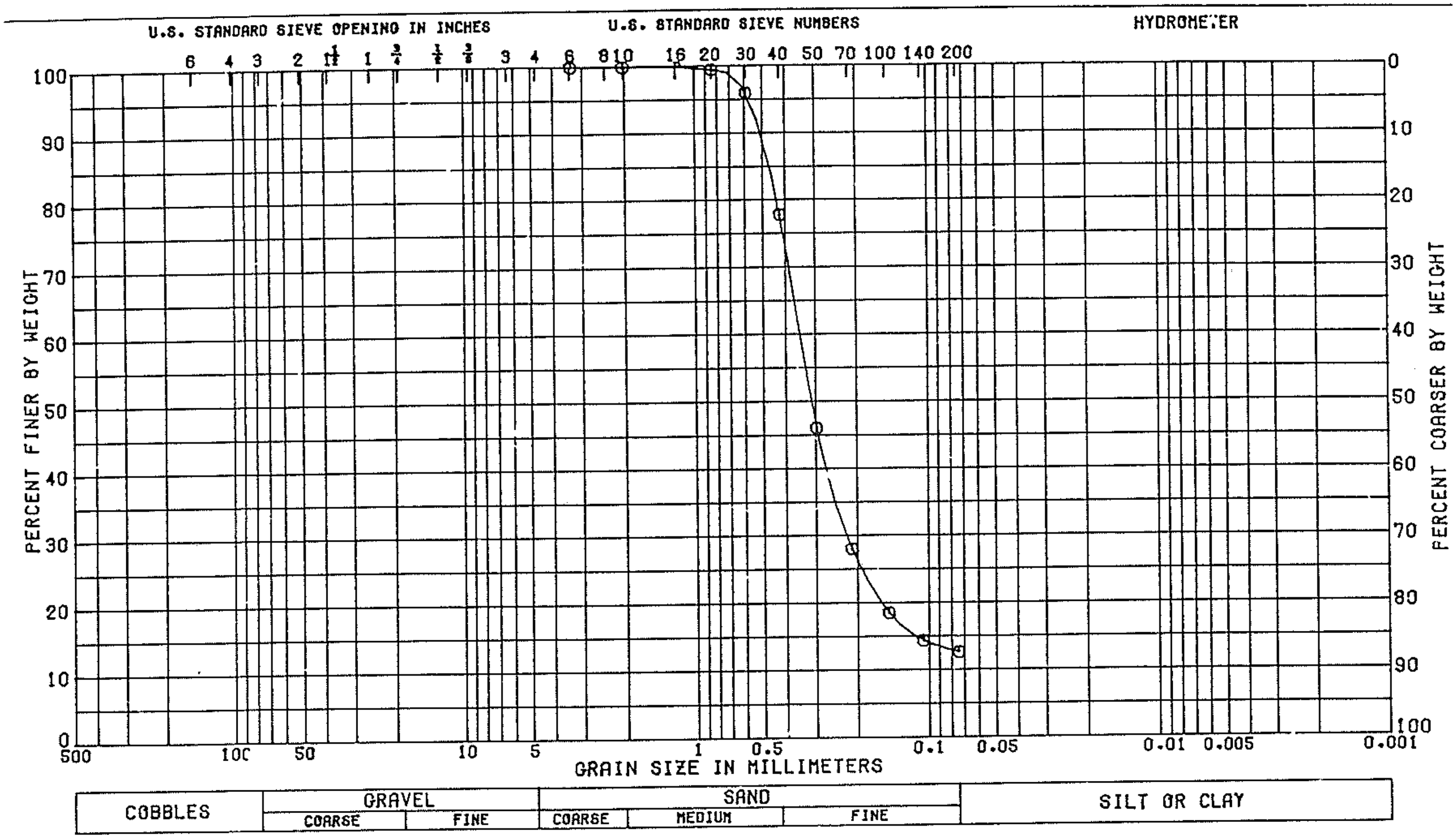

Figure 13. Grain-size distribution for the sand under the large-scale chemical grouting test area (Boring B2, depth 2.44 m).

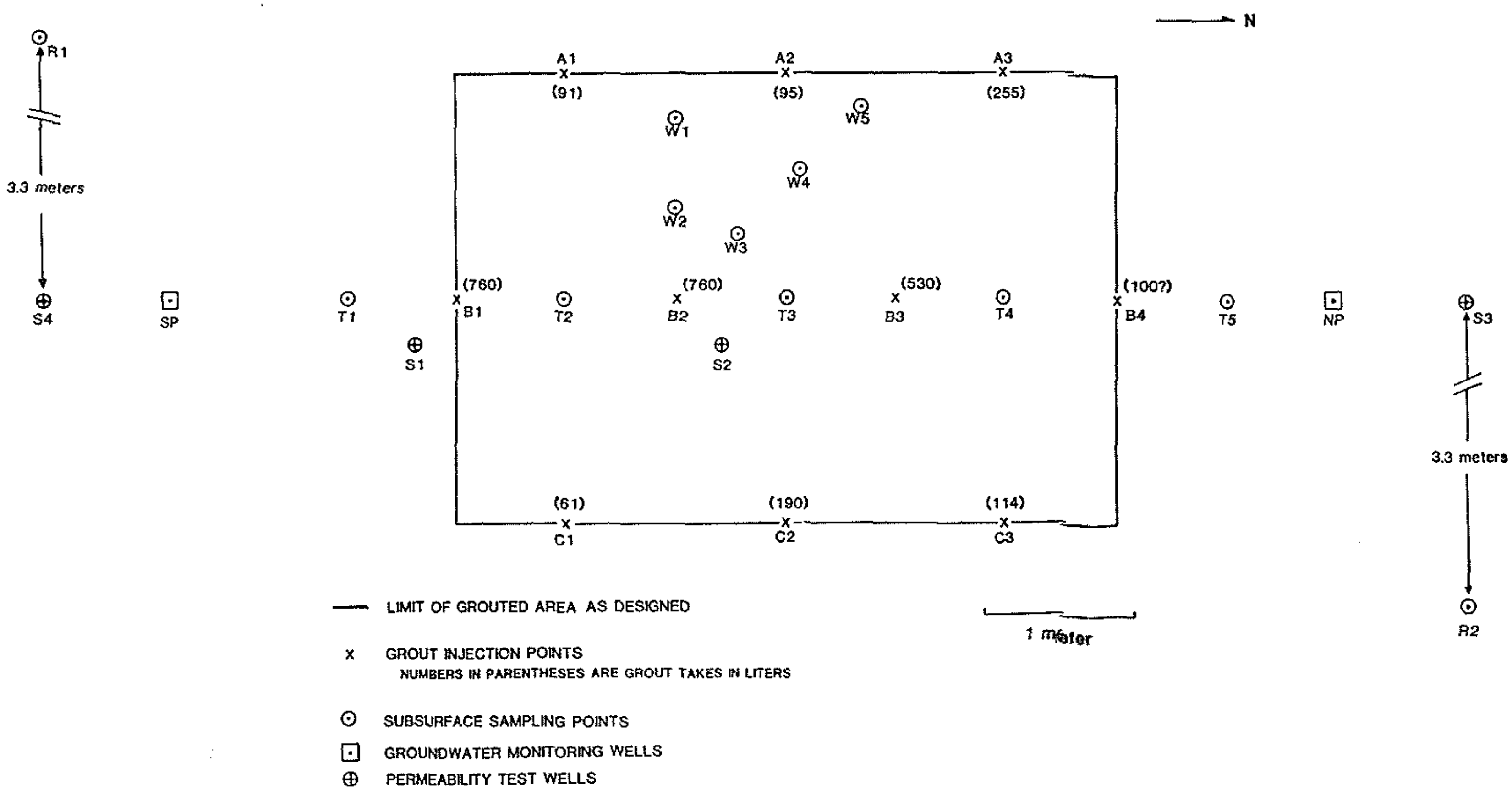

Figure 14. Layout of injection and test borings at the large-scale chemical grouting test area.

TABLE 9. PERMEABILITY MEASUREMENTS MADE AT THE LARGE-SCALE CHEMICAL GROUTING TEST AREA

Test Boring	Depth (meters)	Position in Grouted or Ungrouted Area	Coefficient of Permeability (cm/sec)
		In-Situ Measurements (Constant Head)	
S1	3.05	Grouted	1.92×10^{-3}
S2	3.05	Grouted	6.88×10^{-4}
S3	3.05	Not grouted	2.42×10^{-3}
S4	3.05	Not grouted	3.39×10^{-2}
		Core-Based Measurements	
T1	1.95-2.01	Grouted	5.00×10^{-4}
T2	2.44-2.59	Grouted*	3.88×10^{-4}
T3	2.44-2.59	Grouted*	6.61×10^{-4}
T4	2.44-2.59	Grouted*	3.01×10^{-4}
T5	2.44-2.59	Grouted*	9.32×10^{-4}
W1	2.44-2.59	Grouted*	6.65×10^{-4}
W2	2.74-2.90	Grouted	6.49×10^{-4}
W3	2.44-2.59	Grouted	6.74×10^{-4}
W4	2.44-2.59	Grouted*	5.48×10^{-4}
W5	2.44-2.59	Grouted*	4.47×10^{-4}
R1	2.44-2.59	Not grouted	6.06×10^{-4}
R2	3.05-3.20	Not grouted	6.76×10^{-4}

* Excavation of grouted sand mass indicates that these borings were in the grouted area but not in grouted sand.

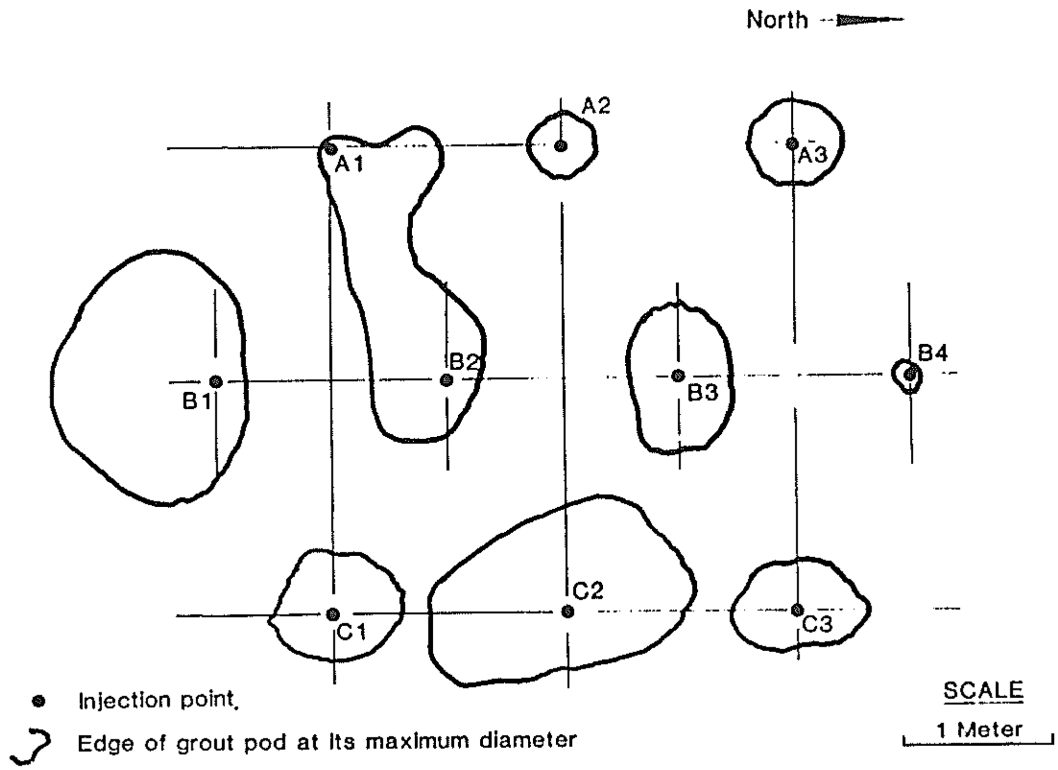

Figure 15. Distribution of grout bulbs over the large-scale chemical grouting test area.

less than two orders of magnitude. Other investigators using similar grouting approaches have noted that only a one to two orders of magnitude change in permeability could be obtained by grouting in the field while four to five orders of magnitude could be obtained in laboratory test materials. The lack of effectiveness of grouting in field tests as opposed to laboratory tests is often attributed to natural soil discontinuities or borehole effects (Perez, Davidson and Lacroix, 1982).

Several other problems related to field conditions were observed during excavation of the grouted sand bulbs:

a. The grouted sand masses were often highly asymmetrical. Only two grouted sand masses met (A1 and B2 in Figure 15). Large gaps existed between grout bulbs.

b. Voids larger than those between sand grains (root holes or rootlet holes) were not sealed with grout (Figures 16 and 17). The insides of the voids were usually coated with grout, but the holes were still open.

c. Coarse-grained filter sand used at the bottom of the injection hole was often completely uncemented with no evidence of grouting although the fine-grained sand around the filter sand was completely cemented

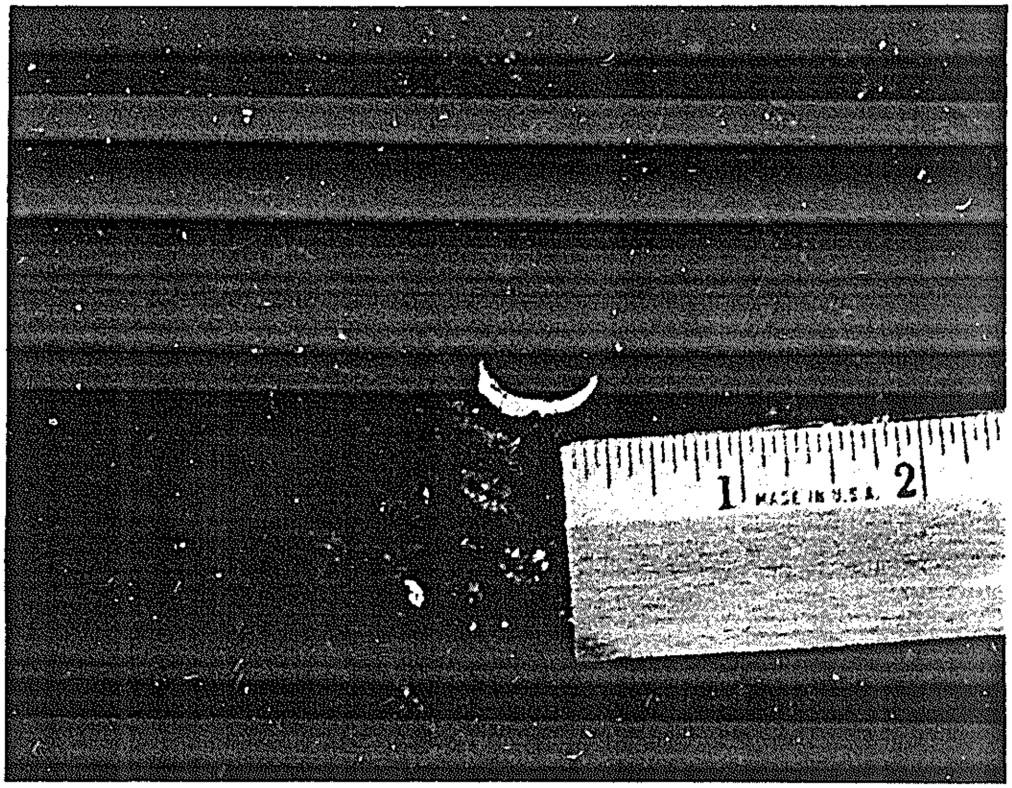

Figure 16. Root holes containing hardened grout. (The voids in the grouted sand were not sealed.)

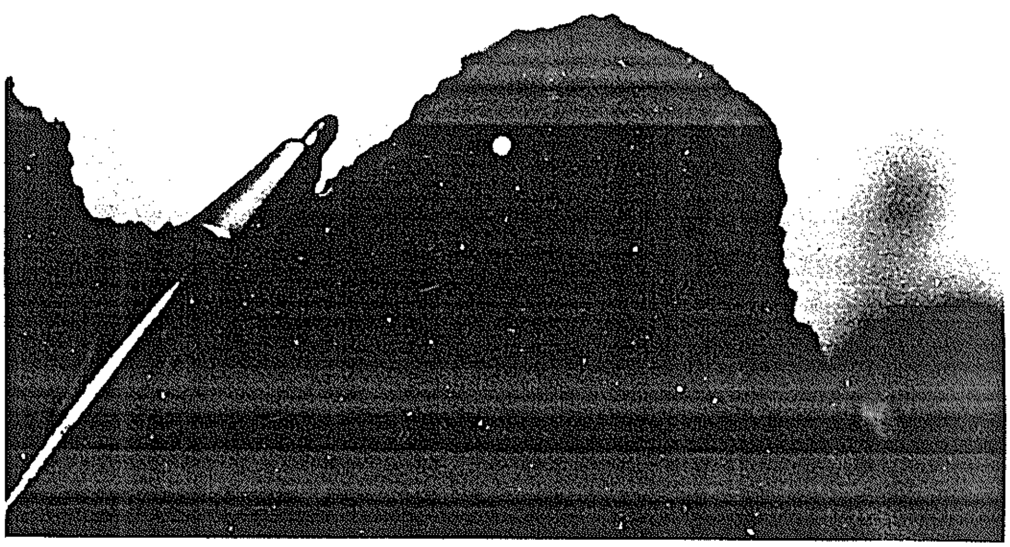

Figure 17. Rootlet hole present in solidly cemented sand.

(Figure 18). Any coarser-grained sand in a fine-grained subsurface soil may represent a zone that cannot be grouted.

The asymmetry of the grout pods is probably related to preferred flow paths in the subsurface caused by root holes. Root holes were noted as deep as three to four m (10 to 13 ft) below the surface and were up to 1- to 2-cm (0.4-0.8 in.) in diameter.

The problem with sealing large voids like root holes with silicate grout has been noted by other investigators (Littlejohn, 1985b). The silicate grout is a gel-like mass that can lose up to 70% of its volume (even with 60% silicates) as water is exuded from the grout. The shrinkage can begin within hours of grout injection and can continue for weeks.

The problem with grouting coarse and fine sand is also related to grout shrinkage. The bonding of the silicate to grain surfaces resists shrinkage

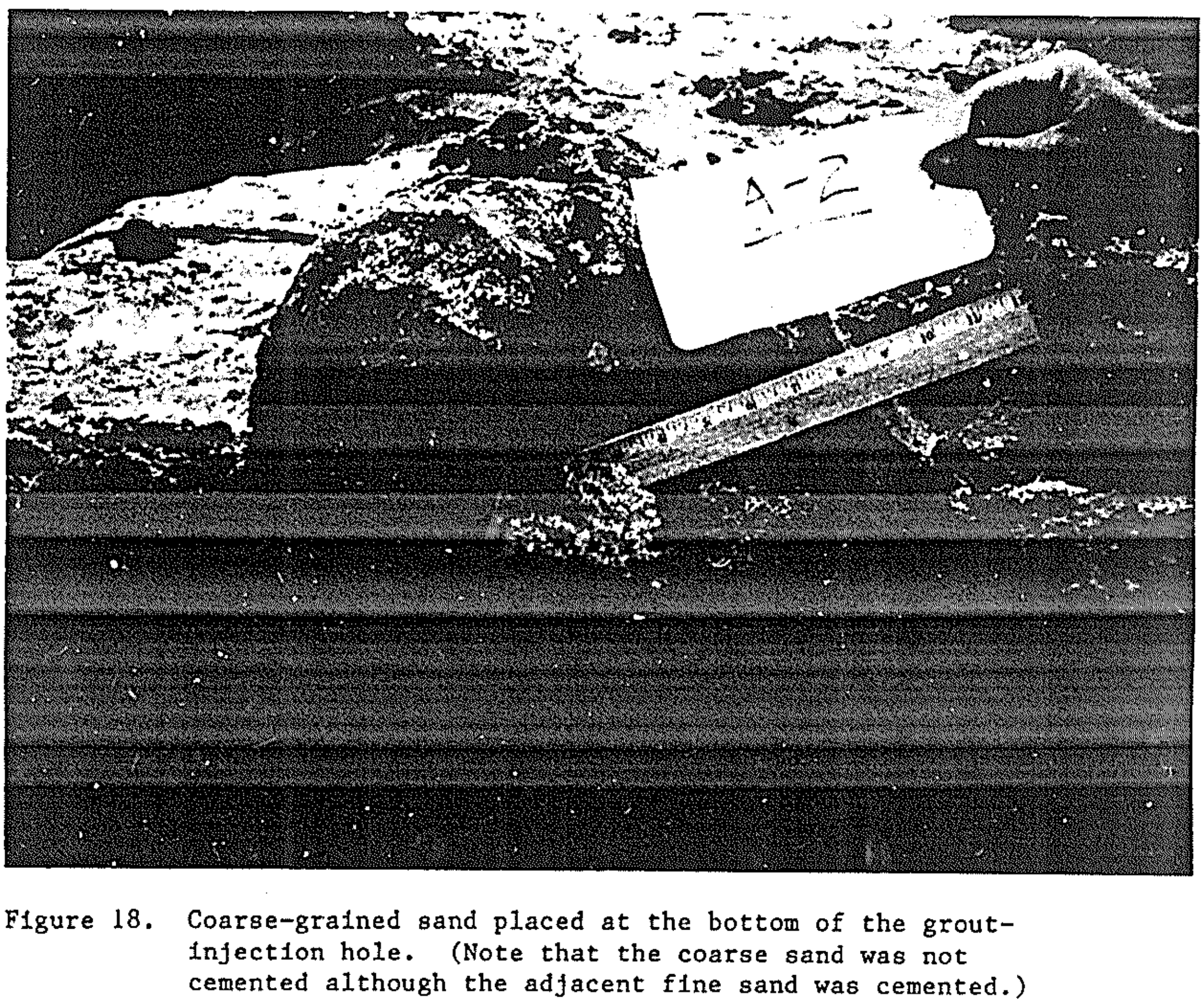

Figure 18. Coarse-grained sand placed at the bottom of the grout-injection hole. (Note that the coarse sand was not cemented although the adjacent fine sand was cemented.)

stress and reduces grout volume reduction. Grouts containing smaller concentrations of silicate (30 percent rather than 60 percent silicate) shrink so much they can only be used effectively in medium or fine sand. The viscosity of silicate grout increases as the silicate concentration increases (Littlejohn, 1985a). Therefore, a low-silicate grout is needed to penetrate fine sand; but, if coarse-grained sand is present in the fine-grained sand, syneresis will prevent the coarse sand from being sealed. Heterogenous sands or coarse-grained soils probably cannot be effectively sealed with ordinary silicate grout (Malone, May, Larson, 1983; May, Larson, Malone and Boa, 1985).

CHEMICAL GROUTING TEST RESULTS

Chemical grouting of geologic media to produce a barrier below a hazardous waste disposal site will require extensive planning and optimum site conditions and containment can not be guaranteed. These problems are in addition to those which may be caused by incompatibility of the grout with hazardous wastes. The experience obtained in the current testing program indicates:

a. The geologic medium must be homogeneous to assure that the grout moves out predictably into sand and produces a grouted sand bulb with reduced permeability.

b. Testing is required to assure that sufficient grout can be injected to produce a continuous mass of grout bulbs without gaps. No continuous mass was produced in this study.

c. The grout employed must not flow or be washed out of the medium after hardening.

d. Grout shrinkage can cause serious problems in increasing permeability if coarse-grained soil or voids are present in the area of the planned barrier.

e. Stringers or plugs of coarse-grained sediment in a fine-grained medium may require several different types of grout to control the permeability.

SECTION 6

JET GROUTING

TECHNIQUES FOR JETTING AND GROUT IMPLACEMENT

Jet grouting is a technique for excavating a cavity in the subsurface using a high-pressure fluid jet. The jetting fluid used can be water, water with entrained air or a water/bentonite suspension. The cavity made by the jet is held open with water pressure or air pressure maintained in the cavity. If a cavity is being cut in porous media such as sand or silt, bentonite is added to the cutting fluid to form a water- and gas-tight "mud cake" on the inside wall of the cavity. The bentonite suspension prevents the loss of fluid to the media and assists in the removal of cuttings. The pressure applied in a cavity is also used to remove the cuttings from the boring. After the cavity has been excavated, grout is introduced to fill the cavity and form an impermeable mass. Jet grouting has the advantage that a wide variety of grouts can be used, even particulate grouts, like bentonite or bentonite/cement.

MATERIALS AND METHODS

Jetting Equipment

The equipment and procedures in jetting used in this study are similar to those developed and described by Brunsing (1983). The jetting system (Figures 19 and 20) consisted of a high-pressure (1.65 MPa at 760 l/minute; 240 psi at 200 gal/min) positive displacement piston pump that delivers cutting fluid to a downhole jetting nozzle that can be directed from the surface. The pressure and volume of fluid are controlled by changing the speed of the pump and opening or closing a by-pass line on the pump outlet. The cutting jet is mounted horizontally on a vertical 5-cm (2-in.) pipe that fits down into a partly-cased hole through a gas-tight well cap (Figure 21). The vertical high pressure pipe extends below the well casing, so that the jet nozzle is directed against the uncased boring wall. A swivel on the high pressure line above the drill hole casing allows the pipe and nozzle to be rotated so that the jet can be directed against the wall on all sides of the borehole to cut a disk-like notch. The cutting fluid from the nozzle is removed from the hole through a low-pressure return line that extends down into a sump at the bottom of the bore hole. The plastic return pipe flexes enough to allow the jet to rotate 360 degrees. A compressor, regulator and air line are used to maintain approximately 35 kPa (5 psi) air pressure in the borehole and jetted cavity. The air pressure forces the jetting fluid and cuttings up the return line and into a settling tank and holding tank. The suction line from the high-pressure pump recirculates cutting fluid from the

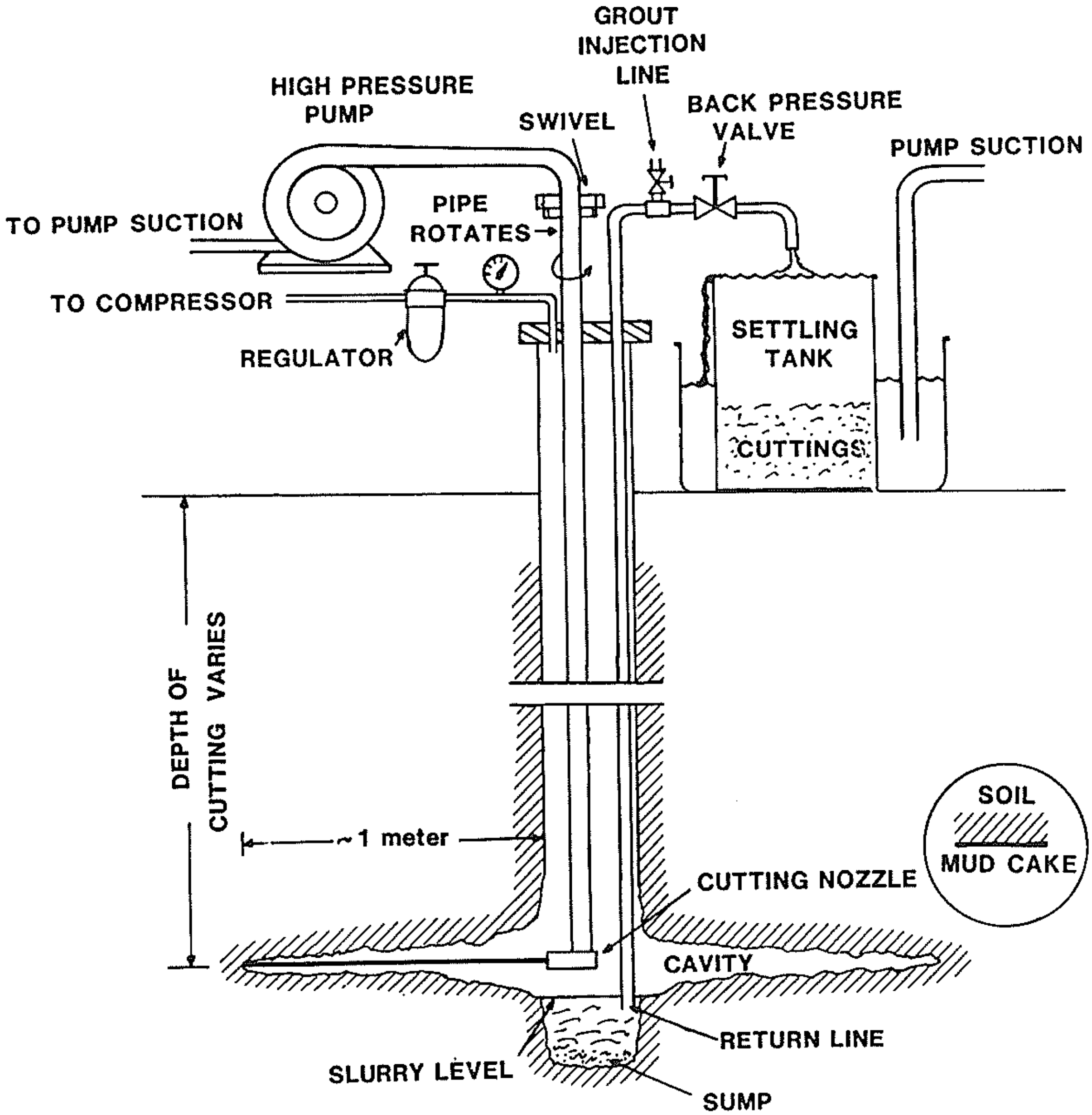

Figure 19. The jetting system used in this investigation.

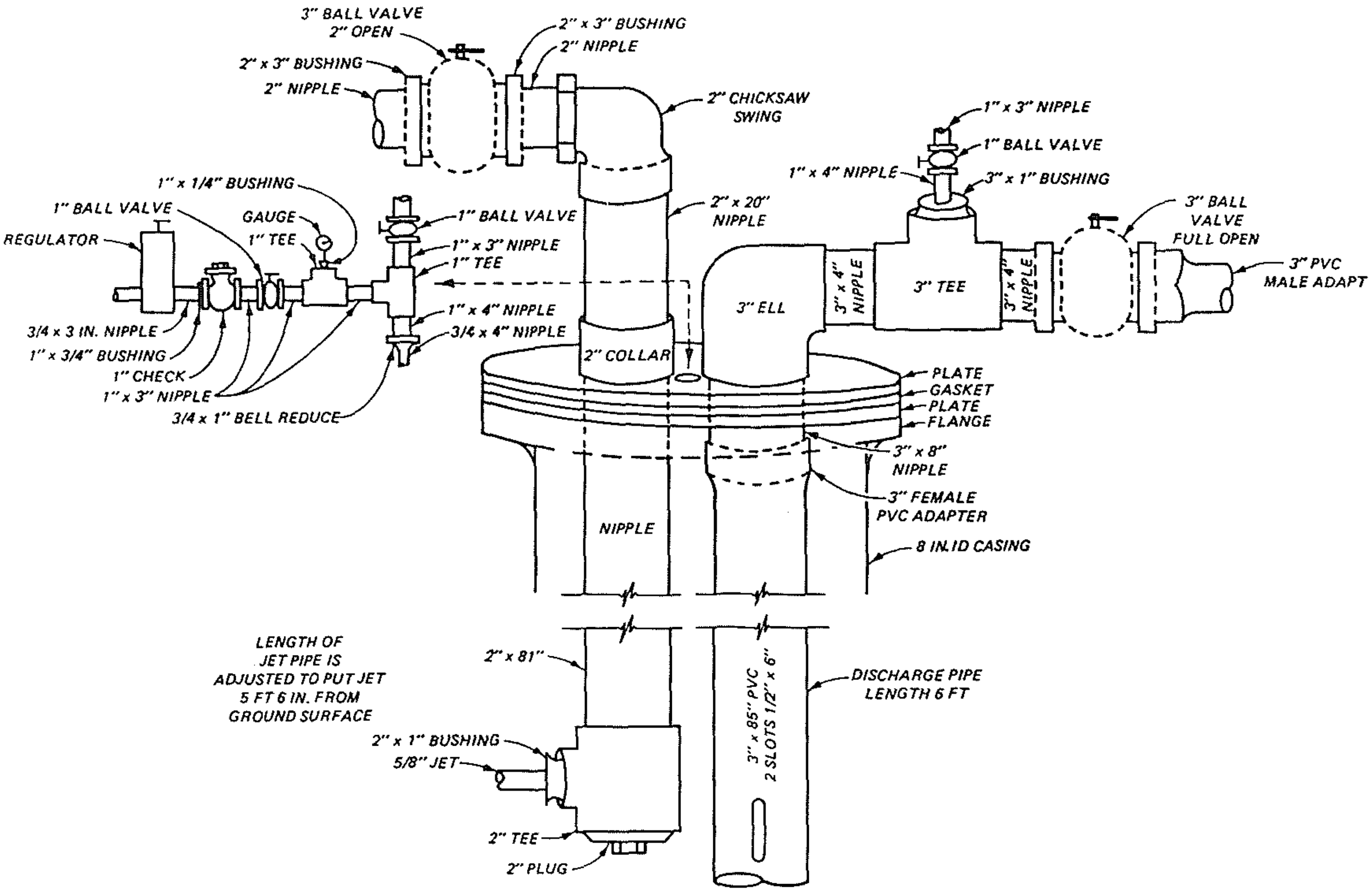

Figure 20. Piping diagram of connections for the wellhead and jetting nozzle.

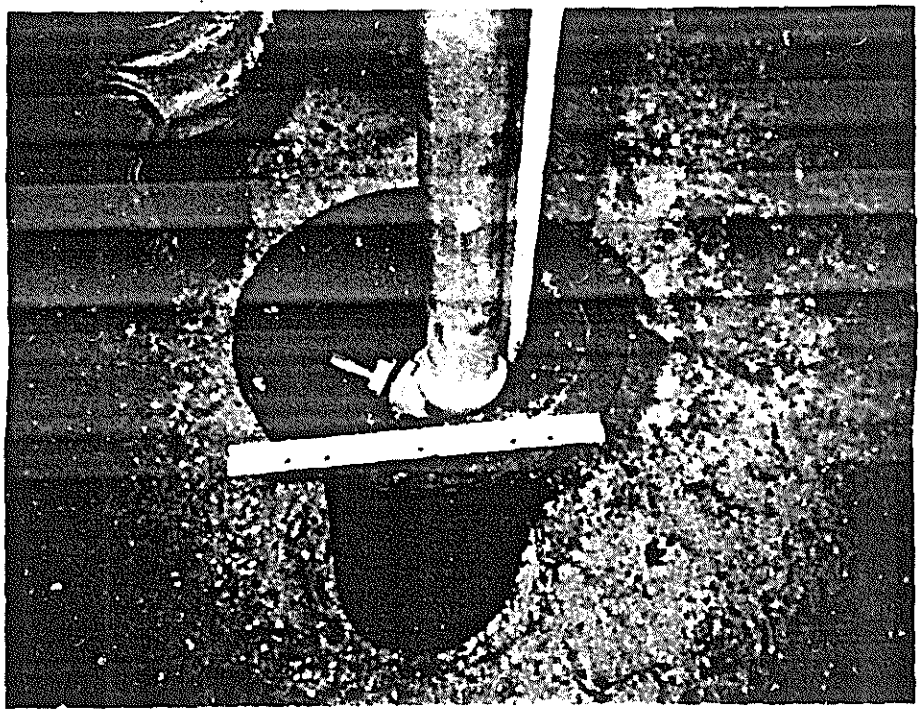

Figure 21. Jetting nozzle and return pipe being lowered into the boring casing.

holding tank. The air pressure also maintains sufficient pressure in the cavity to prevent collapse as the jet cuts an opening.

The cutting fluid used in this jetting was a 2- to 3-percent suspension of bentonite in water. The hydrated bentonite forms a mud cake on the sidewalls and prevents the loss of fluid through any porous material encountered during cutting. The cutting fluid makes it possible to jet in a sand where water without bentonite would normally be forced continually out of the cavity and into the sand. The cutting fluid also slows the settling of suspended cuttings so that they can be lifted out of the boring with compressed air.

Grout

The grout used to fill cavities was a conventional sand, bentonite and portland cement mix. The approximate amounts used per 0.23 cu m (8.0 cu ft) were 128 kg (282 lbs) of portland Type I cement, 186 kg (411 lbs) of mortar sand and 7.7 kg (17 lbs) of bentonite. The volume of water added was varied to adjust the consistency but averaged 136 liters (30 gal). In some grout batches a dye such as fluorocein, rhodamine or methylene blue was added to allow the grout to be identified after excavation. Samples of grout were taken as each injection was completed to assure that sufficient strength was obtained to allow for excavation. The 7-day unconfined compressive strengths were all above 9650 kPa (1400 psi). All grout pods were allowed to cure for 14 days prior to excavation.

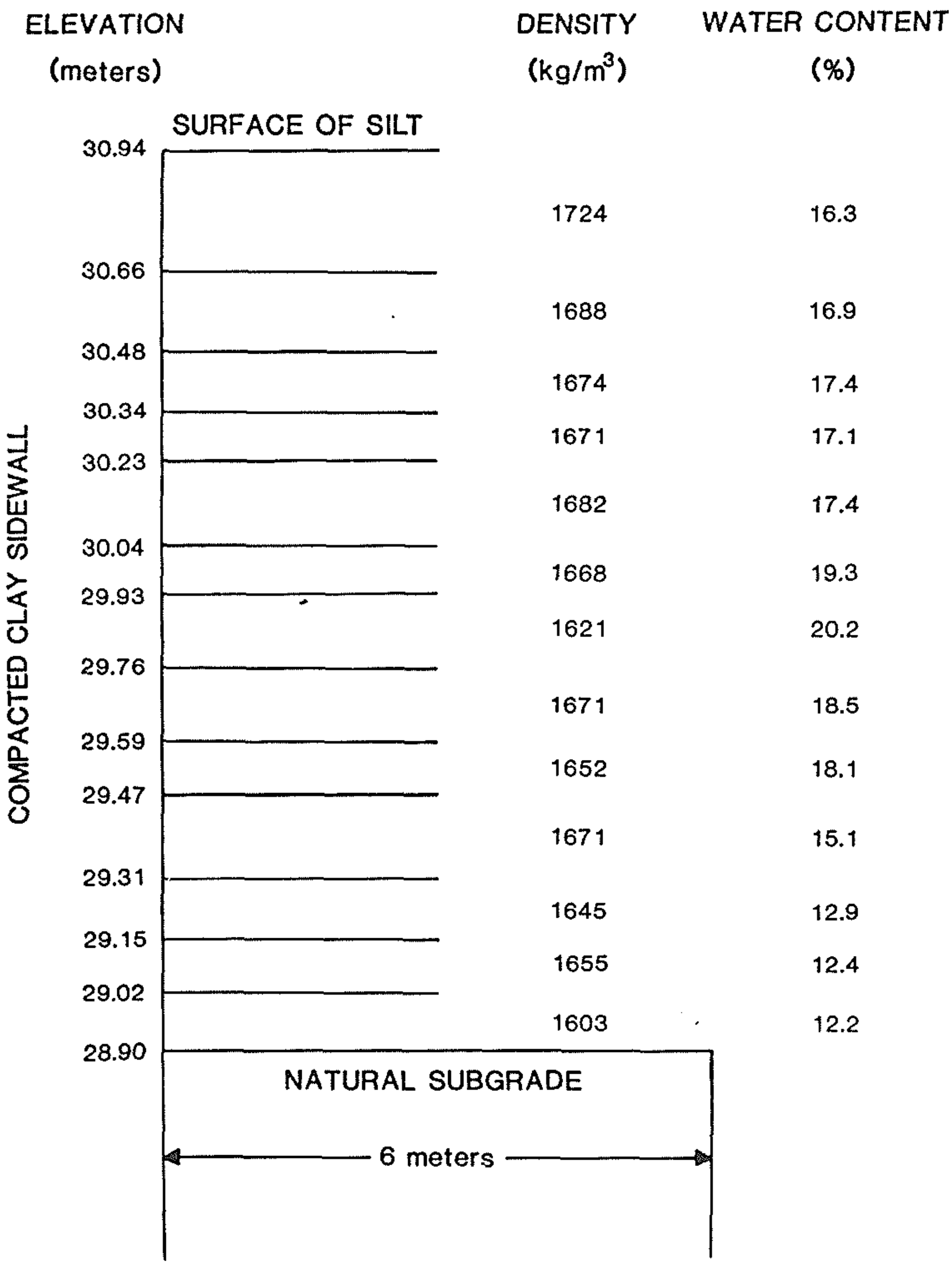

Figure 22. Thickness, wet density and water content of compacted silt placed in the jet grouting test pit.

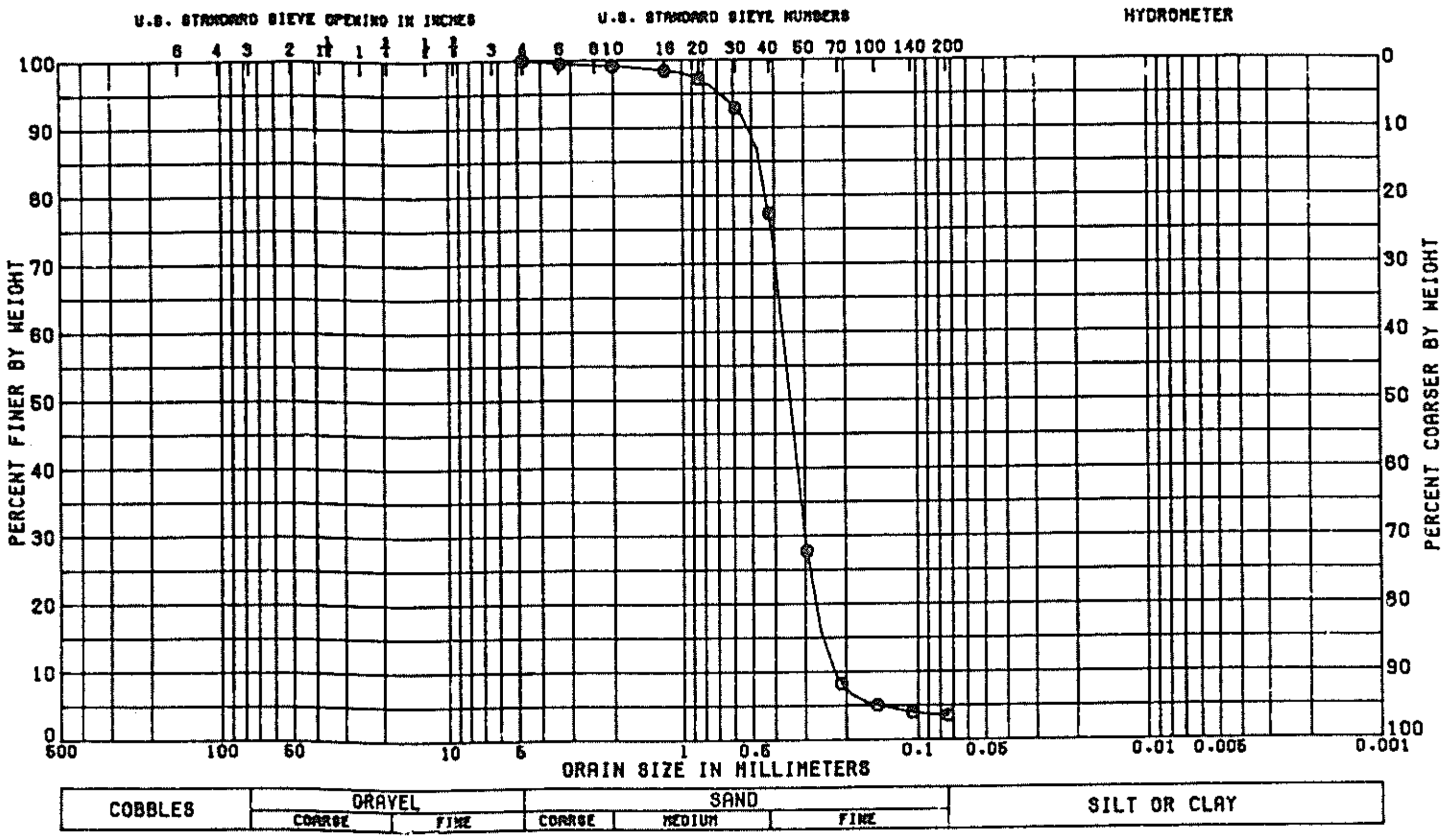

Figure 23. Grain-size distribution of sand placed in the jet grouting test pit.

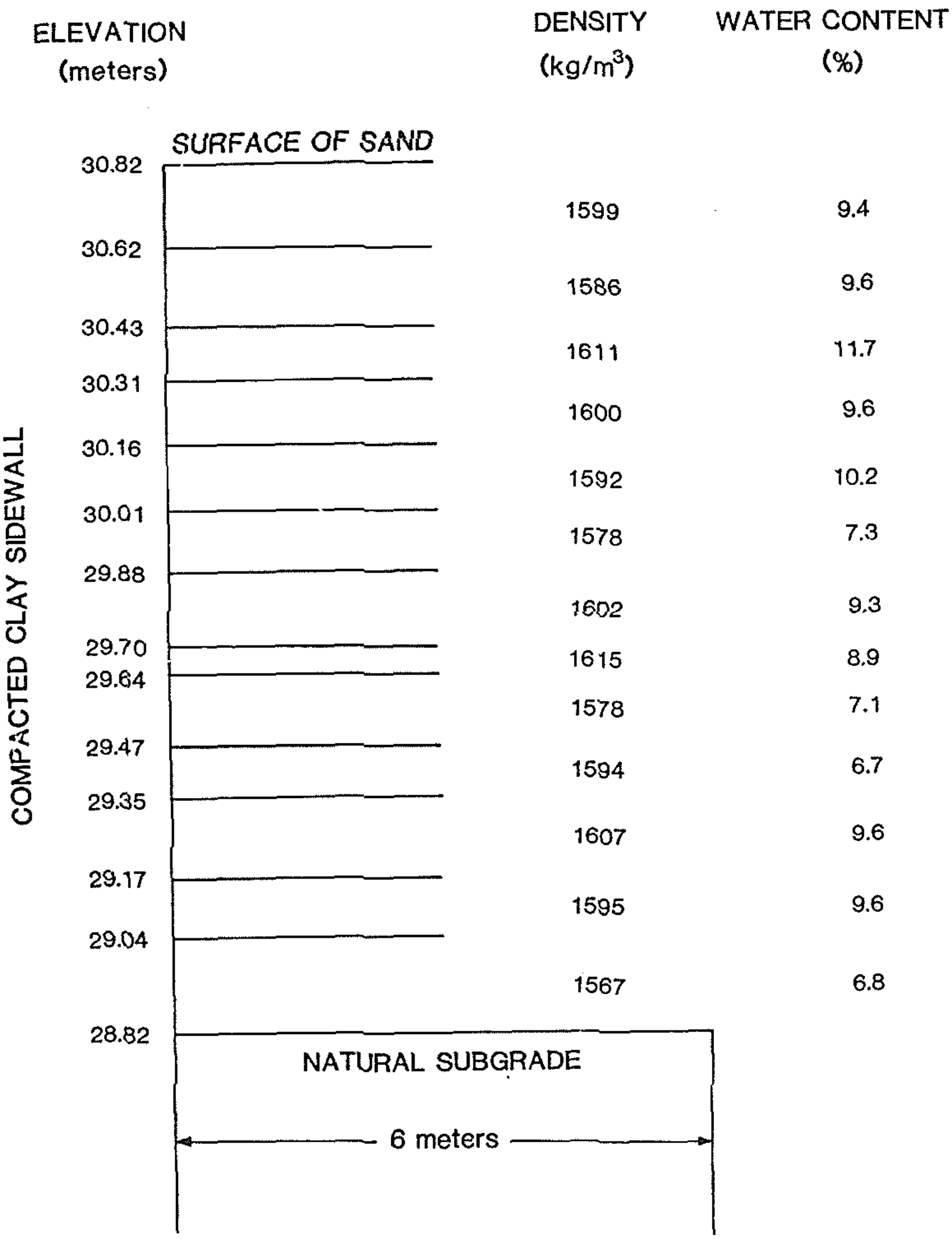

Figure 24. Thickness, wet density and water content of sand placed in the jet grouting test pit.

line and the return line that had been set into the well cap plate were lowered into the casing and the well cap plate was bolted through a gasket to the flange on the casing. The length of the high-pressure pipe had been set so that the nozzle would be 1.67 meters (5.5 ft) below the ground surface, 15 cm (6 inches) below the end of the casing. All of the hoses were connected to the high pressure and return side and the air line was connected and adjusted to maintain 35 kPa (5 psi). With the jet pump running and the return line open, jetting was continued until the elapsed time suggested the jet had probably penetrated approximately 76 cm (30 inches) horizontally. At selected injection points a small (5-cm) hand auger hole was bored down to a 2-meter (6 ft) depth, 0.76-m (30 in.) from the injection hole. The appearance of cutting fluid at that hole indicated that the nozzle had cut a cavity that would meet with or overlap jetted and grouted cavities from adjacent injection points. The time required to reach this point was noted and the small hand-augered hole was plugged. When the cavity was judged to be completed, the pump was shut down. The return line was kept open until the air pressure had driven the cuttings and jetting fluid out of the cavity. The air pressure was maintained while the line from the grouting pump was attached to a tee in the return line. The line to the grout pump was then opened and grout was forced down the return line into the cavity. A vent in the air line was opened to relieve pressure in the casing and cavity as the grout was pumped in. Grouting was discontinued when grout flowed out of the air line vent pipe, indicating all of the cavity and the drill casing was filled with grout.

RESULTS AND DISCUSSION

The jetting equipment performed well in creating a cavity in either silt or sand. However, it was not possible to determine the size or shape of the cavity prior to introduction of grout. The grout bulbs created were not always the size or shape needed to provide a barrier to movement of potential contaminant above the grouted layer. The grout bulbs that were obtained and the degree of sealing that occurred depended on the response of the sand, silt or loess to jetting. After the grout had cured each test area or test pit was excavated and the grout bulbs were measured and photographed.

Results Obtained in Loess

The sizes and shapes of the grout bulbs produced in jetting in loess are shown in Figures 25 and 26. Note that the pods varied in size and shape and did not overlap to produce a seal or barrier at the center of the cluster of borings. The smallest grout bulb was produced when jetting was performed on the basis of time. Smaller auger holes used at other borings had indicated that approximately twenty minutes of jetting should produce approximately 75-cm (30-in.) penetration in loess. This proved not to be the case, the maximum depth of jet penetration was approximately 20 cm (8 in.) for the smallest bulb in loess. The rate of cutting was so variable that elapsed time could not be depended on to provide any useful indication of the minimum cavity size. The other, larger cavities were jetted using 5-cm (2-in.) diam. auger holes spaced 30-cm from the injection points to indicate cavity size. This approach was also unreliable because of the very local nature of jetting in the loess. Fluid circulation to a small, augered hole was not a useful

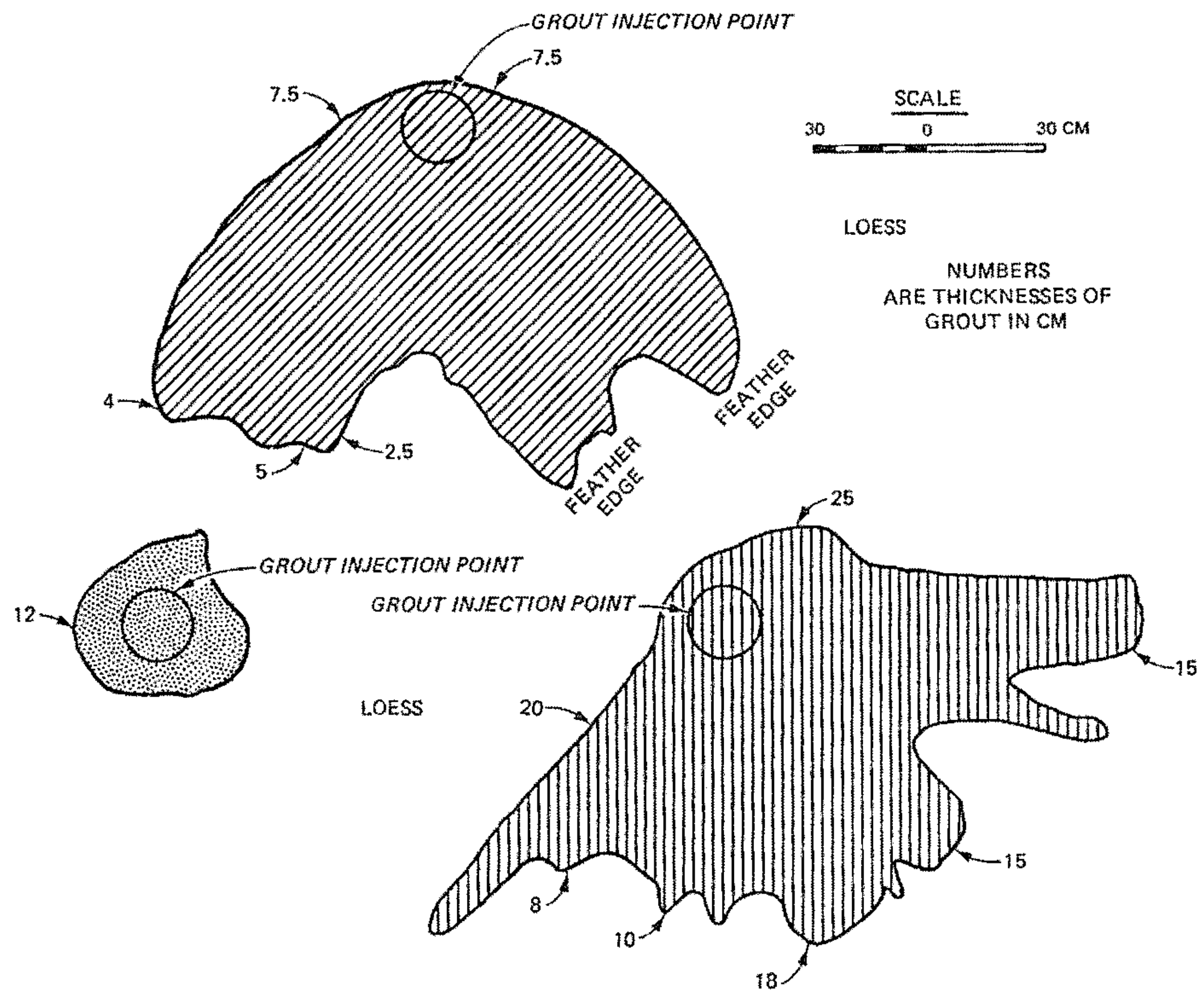

Figure 25. The shape and size of the grout bulbs produced by jetting and grouting in loess.

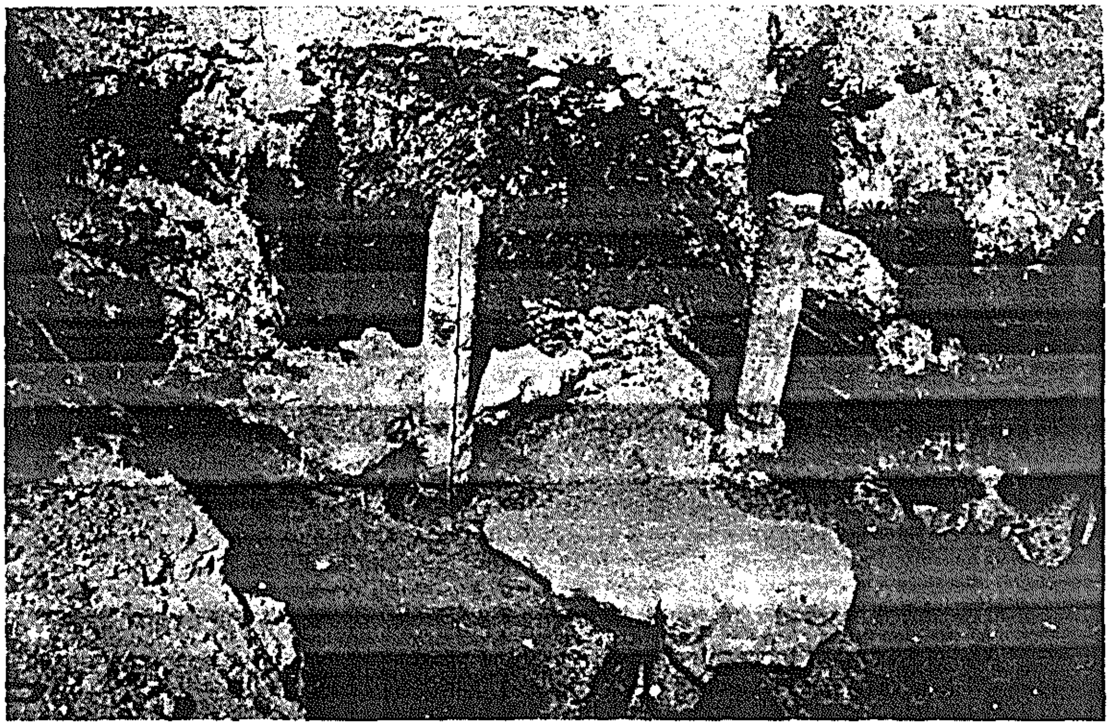

Figure 26. Grout bulbs formed by jetting and grouting in loess. (Note the finger-like projections produced by jetting.)

indicator of the progress in jetting the entire cavity because the cutting proceeded as finger-like projections not a disk-like cavity.

Results Obtained in Compacted Silt

Figures 27 and 28 show the results obtained in jetting and grouting in compacted silt. One small, hand-augered, hole was used at each injection point to verify that the jet had penetrated at least 76 cm (30 inches) from the injection point. The very local action of the jet in the silt made this technique ineffective.

In the process of jetting to produce the cavity shown in the lower left of Figure 27, the jetting fluid broke through to the boring on the lower right that had not yet been jetted. The shape of the grout bulb showed that the connection between the two borings was not a broad cavity but only a narrow finger-like hole.

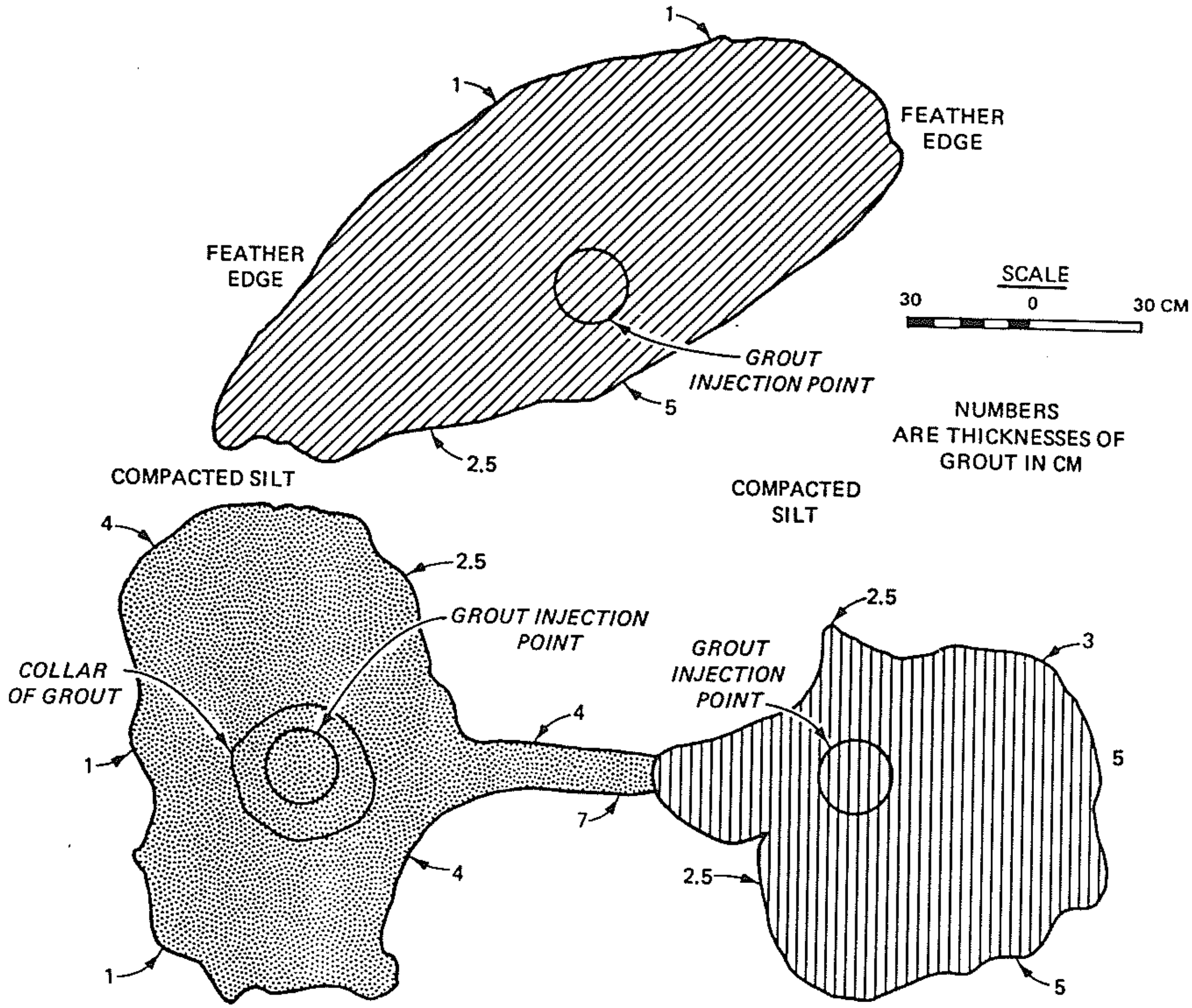

Figure 27. The shape and size of the grout bulbs produced by jetting and grouting in compacted silt.

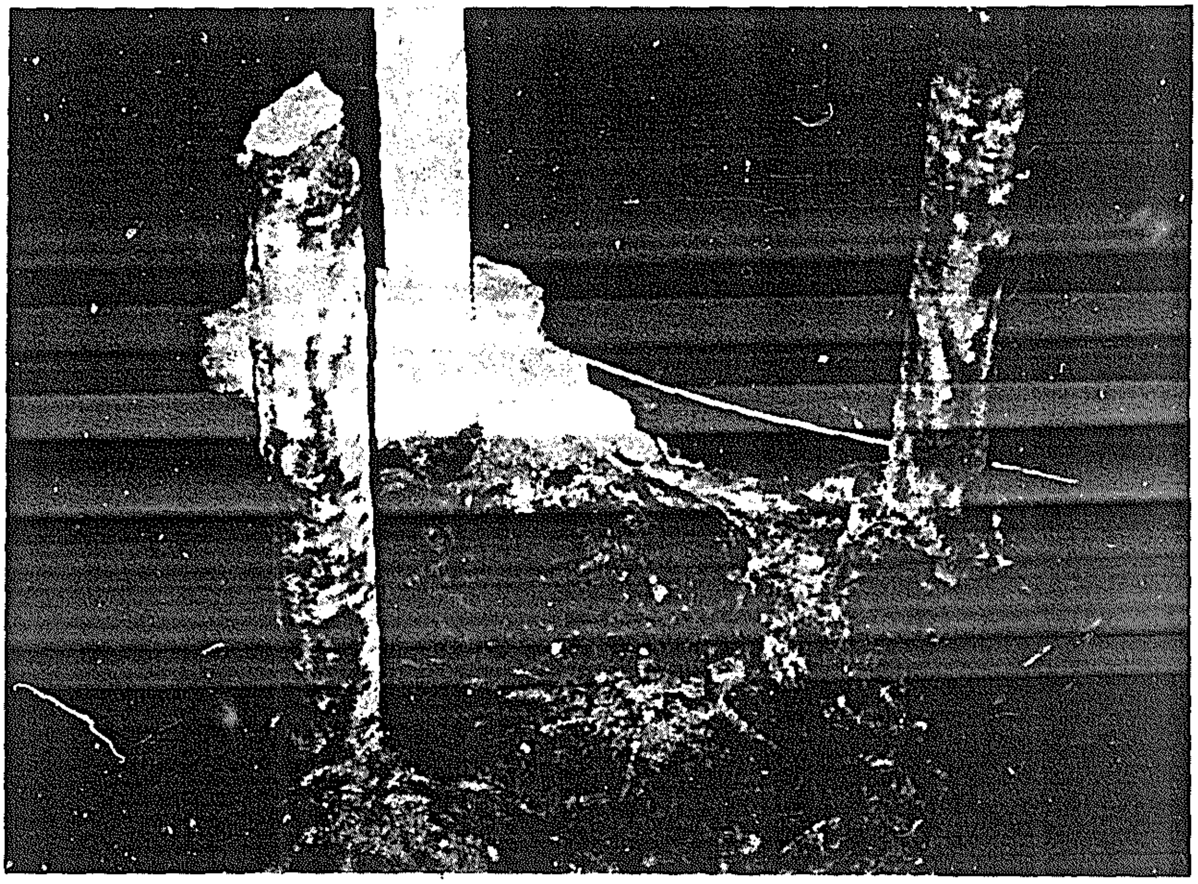

Figure 28. Grout bulbs formed by jetting and grouting in compacted silt. Note the channel between borings.

Cavities of useful sizes were produced in the compacted silt; but without a technique for determining the size and shape of the cavity, it is not possible to guarantee that a continuous grout layer will be formed. Developing communication between borings that are 1.5 meters (5 ft) apart demonstrates that the jet can produce penetration, but a system for directing the jet to produce a cavity of a desired uniform radius in silt is needed.

Results Obtained in Sand

Figures 29 and 30 show the sizes and shapes of the grout bulbs obtained when jetting and grouting in sand. The sand is noncohesive and washed out in more even disklike cavities with fewer finger-like projections than observed in the silt. The use of small, augered holes to determine the size of the cavity presented some problems in sand because of a tendency for the jetting fluid to wash out in the sand around any small boring. A thick column-like projection formed on the upper grout bulb in Figure 29 was directly under a small, augered, hole.

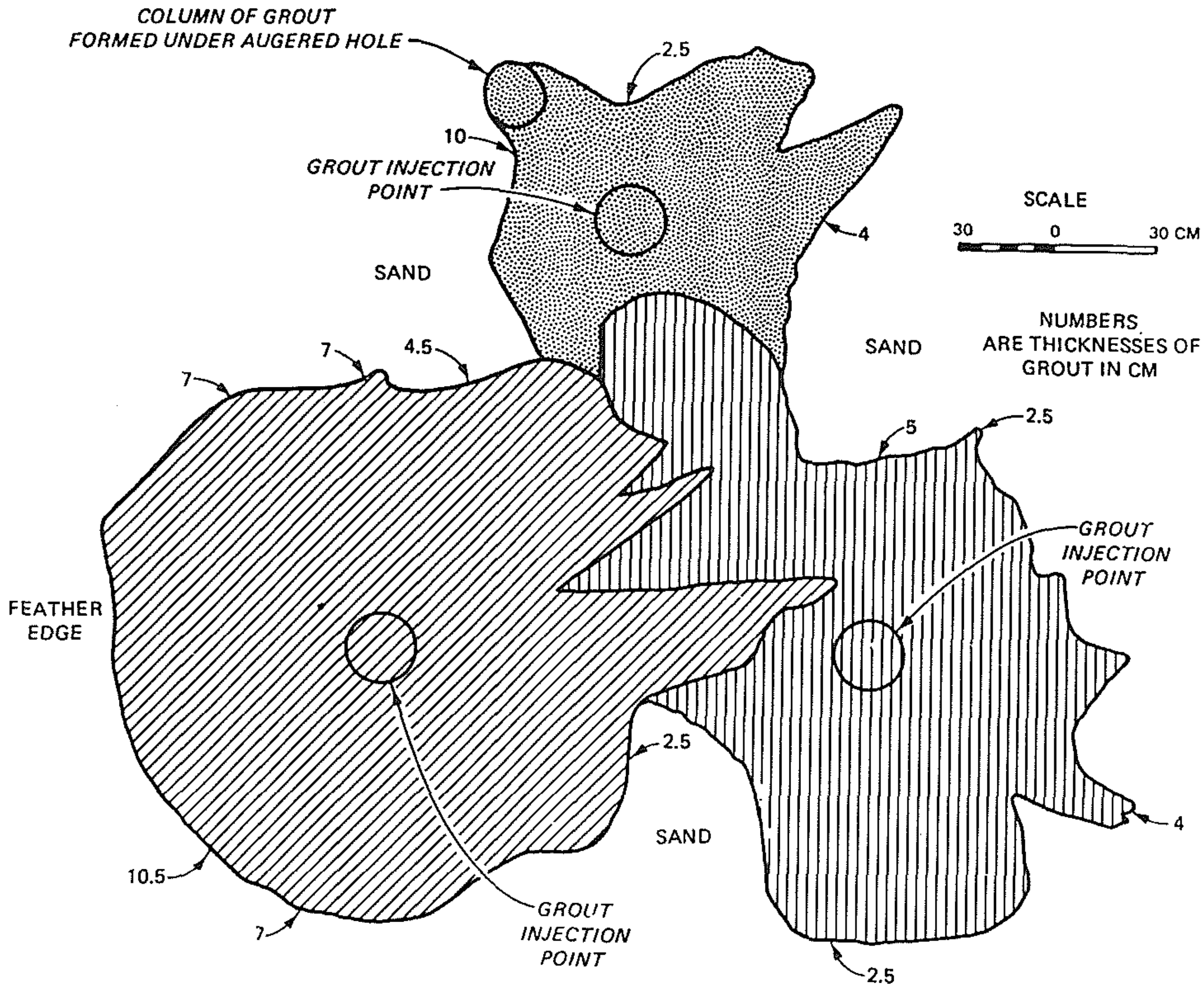

Figure 29. The shape and size of the grout bulbs produced by jetting and grouting in sand.

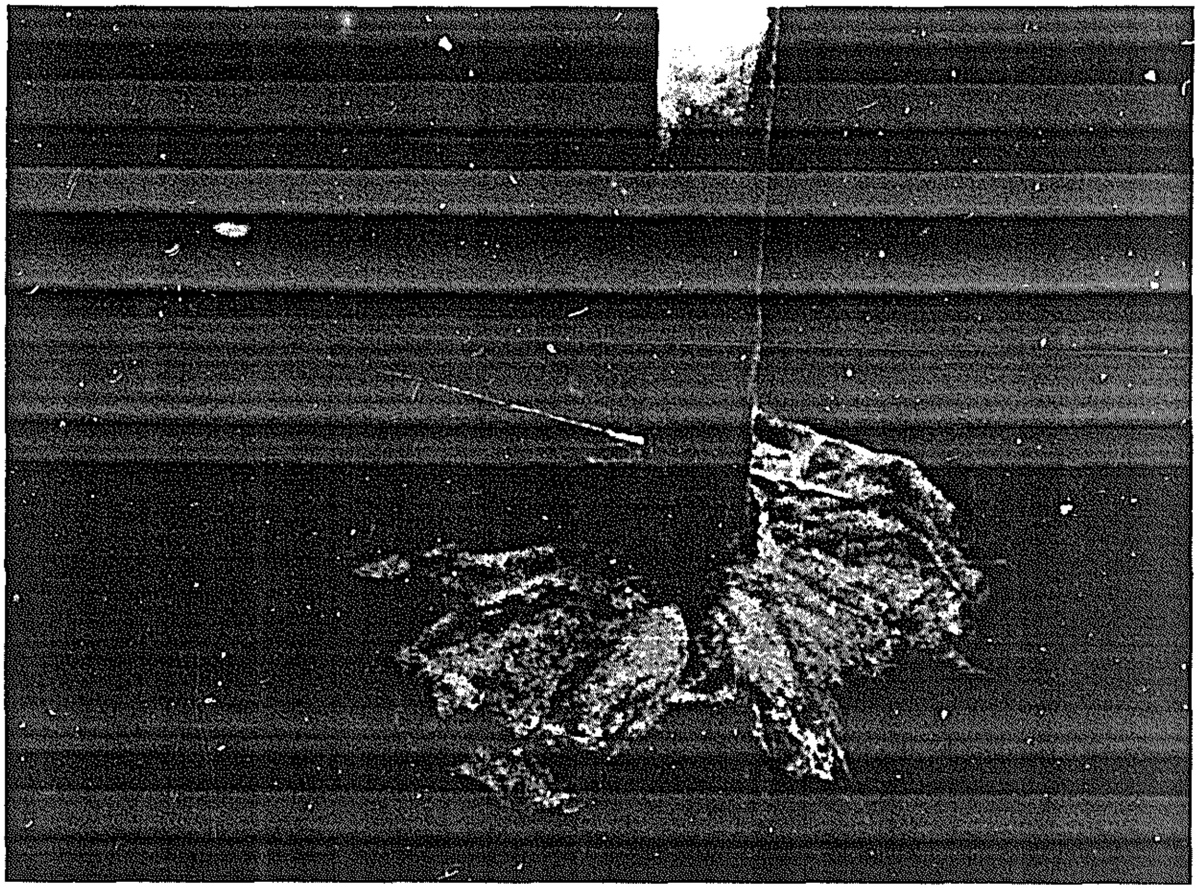

Figure 30. Grout bulbs formed by jetting and grouting in sand.

A continuous seal did form in the area inside the cluster of injection points. The minimum thickness in the central area where the disklike masses overlapped was 3.2 cm (1.25 inches). The jet grouting system was able to develop overlapping grout masses that would produce a useful seal in sand even without an adequate technique for monitoring cavity size and shape during jetting.

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