**US Army Corps
of Engineers**

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STATE-OF-THE-ART PROCEDURES FOR SEALING COASTAL STRUCTURES WITH GROUTS AND CONCRETES

by

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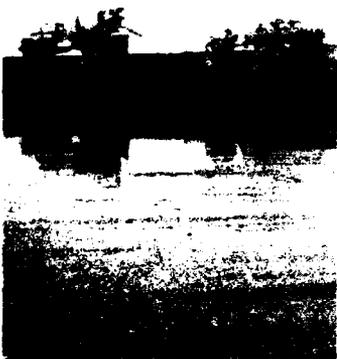
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GT	Geotechnical		EI	Environmental Impacts
HY	Hydraulics		OM	Operations Management
CO	Coastal			

COVER PHOTOS

TOP — Drilling sealant holes at Buhne Point, Humboldt Harbor, CA.

BOTTOM — Placing sealant at Buhne Point, Humboldt Harbor, CA.

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Many Corps rubble-mound breakwaters and jetties have become permeable to wave transmission and sand transport, conditions which result in increased Operation and Maintenance dredging costs, delays to navigation, and damages to recreational craft and marina facilities. A cost-effective alternative to traditional methods of rubble-structure rehabilitation (dismantling to rebuild core sections, chinking layers along surfaces, additional armoring layers, etc.) has been determined to be drilling and grouting (sealing) a vertical barrier curtain along the center line of the structure from the bottom to approximately mean higher high water.

Sealing of permeable structures (almost exclusively rubble-mound) by filling significantly large voids is a concept not routinely considered by coastal engineers. However, the basic underlying technology necessary for closing such large voids and for stabilizing sand within a structure has been developed previously in the grouting field
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for sealing cracks and fissures in rocks or dam foundations. Adaptation of this technology and promotion of the use of cementitious, chemical, and asphaltic products in coastal structures to reduce wave penetration and sand infiltration were initiated by WES in 1986, although specific guidance does not presently exist for sealing breakwaters and jetties by those means. Execution of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program Work Unit No. 32375, "Rehabilitation of Permeable Breakwaters and Jetties by Void Sealing," will develop and convey state-of-the-art knowledge in this area to appropriate Corps and other personnel charged with field application responsibility for performing such sealing measures.

Sealing permeable breakwaters or jetties should be approached from the standpoint of preventing wave or sand movement through the structure and not from the requirement of imparting structural stability or strength. In planning a sealing operation, a quantitative determination must be made of the wave energy or sand passing through the structure to ascertain economic benefits.

Grouting literature was reviewed for information pertinent to sealing voids in coastal rubble-mound structures. Field experience of sealing jetty voids and of grouting the interior of jetties was assimilated. While these operations have not been often performed, grouting technology and grouting material development are at an advanced state. Coastal applications comprise a special category of sealant emplacement, and the sealing materials must be specifically designed for those conditions.

Materials which have been used previously in void sealing of coastal structures include cementitious sealants (cements with admixtures for setting time acceleration), chemical sealants (sodium silicates with cements), and asphaltic sealants (cements and sands). Each of these materials have been utilized with a variety of reactants. Trial mixtures of portland-cement concrete at project sites in California have resulted in a somewhat standardized mix containing coarse aggregate, sand, clay, and accelerators which in turn result in a very stiff concrete for void sealing. Solutions of neat cement and sodium silicate have been used effectively to seal jetty voids. Although initially very thin, solution set time can be controlled to prevent loss due to erosion by currents or to dilution prior to gelling.

The most recent Corps experience in sealing voids existing in coastal structures occurred when the US Army Engineer District, Jacksonville, sealed the south jetty at Palm Beach Harbor, FL, in 1984, and the US Army Engineer District, San Francisco, sealed the Buhne Point groins at Humboldt Bay, CA, in 1985. Subsequent to that time, Broward County, FL, has sealed the south jetty to Port Everglades Harbor, FL, in 1988, and the US Army Engineer District, Detroit, has completed grouting and rehabilitating the north detached breakwater at Milwaukee Harbor, WI, in 1988. Asphaltic compounds were previously used successfully in Ashbury Park, NJ, in 1963, and a breakwater in the Dominican Republic was recently stabilized in 1983 using an asphaltic concrete. Portions of the north and middle jetties at Mission Bay, CA, were sealed with a cement-sand mixture in 1959 by the US Army Engineer District, Los Angeles. These projects have been summarized as a means of sharing on-the-job experiences in an area in which little guidance exists outside these specific Corps districts.

Planning a jetty sealing operation must be based on knowledge of field conditions, mixture characteristics, and equipment capabilities. Proper spacing of grout holes determines drilling costs and the radius of the grouted volume at each hole, and therefore the set time and quantity of the mixture. Contractor capability and/or experience are critical for accomplishing a successful void sealing job at a coastal rubble-mound structure. Having a competent construction inspector is also very important in light of changed field conditions which may dictate that operations be revised while the sealing project is under way.

PREFACE

Authority for this investigation was granted the US Army Engineer Waterways Experiment Station's (WES) Coastal Engineering Research Center (CERC) by the Headquarters, US Army Corps of Engineers (HQUSACE), under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program Work Unit No. 32375, "Rehabilitation of Permeable Breakwaters and Jetties by Void Sealing."

Assimilation of literature, reports, and field experience, which fulfills one milestone of this work unit, was accomplished under the general direction of Messrs. James C. Crews and Tony C. Liu, REMR Overview Committee, HQUSACE; Mr. Jesse A. Pfeiffer, Jr., Directorate of Research and Development, HQUSACE; Mr. John H. Lockhart, Coastal Technical Monitor, HQUSACE; and Mr. William F. McCleese, REMR Program Manager, WES. Mr. D. Donald Davidson, Chief, Wave Research Branch, Wave Dynamics Division, CERC, is the REMR Coastal Problem Area Leader, WES.

This report was prepared by Mr. David P. Simpson, Research Hydraulic Engineer, Coastal Processes Branch, Research Division, CERC, under the supervision of Dr. Steven H. Hughes, Chief, Coastal Processes Branch, CERC. General supervision was provided by Dr. James R. Houston, Chief, CERC; Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC; and Mr. H. Lee Butler, Chief, Research Division, CERC. Coprincipal Investigators of the work unit during this investigation and report preparation were Mr. Simpson and Ms. Joan Pope, Chief, Coastal Structures and Evaluation Branch, Engineering Division, CERC. Final editing of this report before publication was done by Ms. Gilda Miller, Editor, and Ms. Josephine Head, Editorial Assistant, Information Products Division, Information Technology Laboratory, WES.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831	cubic metres
cubic yards	0.7645549	cubic metres
cups	0.0002366	cubic metres
Fahrenheit degrees	5/9*	Celsius degrees or kelvins
feet	0.3048	metres
gallons (US liquid)	3.785	litres
inches	25.4	millimetres
ounces (US fluid)	0.00002975	cubic metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals
tons (mass)	907.184	kilograms
yards	0.9144	metres

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) temperature readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) temperature readings from Fahrenheit (F) temperature readings, use the following formula: $K = (5/9)(F - 32) + 273.15$.

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STATE-OF-THE-ART PROCEDURES FOR SEALING
COASTAL STRUCTURES WITH GROUTS AND CONCRETES

PART I: INTRODUCTION

Background

1. At the time when many coastal breakwaters and jetties were con-
structed, the structures' service was satisfactory if the inlet or entrance
was stabilized and wave energy was merely reduced in the harbor. Today, how-
ever, increasing ship drafts have pushed to the limit the practical ability to
maintain navigable depths. With increased competition world-wide among ports,
the need to provide reliable depths and to minimize operation and maintenance
costs has been accentuated. The permeability of some coastal structures to
the movement of shoal material and to the transmission of wave energy is se-
vere enough to have serious economic consequences.

2. The Corps of Engineers' annual Operation and Maintenance (O&M)
dredging budget is roughly a half-billion dollars. No estimate is available
of the amount of reduction in that figure that could be achieved by sealing
problem coastal structures to the through-flow of sand. It is certain, how-
ever, that savings could be realized by applying to coastal projects sealing
procedures developed in civil and mining engineering as a method of closing
voids and fractures.

3. Other economic losses resulting from permeabilities of coastal
breakwaters or jetties include decreased efficiency of ship operation, due to
light-loading for transiting a shoal area in a navigation channel, and limi-
tations on port development, due to insufficient reduction in wave energy by
such structures.

Purpose of the Investigation

4. Sealing of permeable structures (almost exclusively rubble-mound) by
filling significantly large voids is a concept not routinely considered by
coastal engineers. However, the basic underlying technology necessary for

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closing such large voids and for stabilizing sand within a structure has been developed previously in the grouting field for sealing cracks and fissures in rocks or dam foundations. While specific guidance does not presently exist for sealing breakwaters and jetties by those means, adaptation of this technology and promotion of the use of cementitious, chemical, and asphaltic products in coastal structures to reduce wave penetration and sand infiltration was initiated by the US Army Engineer Waterways Experiment Station (WES) in 1986. Execution of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program Work Unit No. 32375, "Rehabilitation of Permeable Breakwaters and Jetties by Void Sealing," will develop and convey state-of-the-art knowledge in this area to appropriate Corps and other personnel charged with field application responsibility for performing such sealing measures.

5. This report is the first milestone in a multiyear project to better understand cementitious, chemical, and bituminous materials and injection techniques applicable to Headquarters, US Army Corps of Engineers (HQUSACE), projects that are experiencing detrimental levels of sediment infiltration or wave energy transmission. Information on other methods of making jetties "sandtight" is contained in a separate WES Coastal Engineering Research Center (CERC) technical report, "Sand Sealing of Coastal Structures" (Thomas in preparation). That report organizes material gleaned from sealing experience of coastal field personnel. Following this report, other products of this research investigation will include results of laboratory tests based on proposed improvements in materials and techniques, field tests of recommendations resulting from those laboratory tests, and development of guidance for field use of cementitious, chemical, and bituminous sealants specifically directed toward coastal projects.

PART II: TYPES OF SEALANTS AND THEIR PROPERTIES

Terminology and Origin

6. Sealing voids in coastal structures and grouting are two operations that are closely related, but careful distinctions should be made between them. The term "grouting" implies the injection under pressure of a liquid or suspension into fractures in rock or in a structure or into interstices of smaller particles. The injected grout must eventually form either a gel or a solid within the treated voids, or the grouting process must result in the deposition of suspended solid within those voids.

7. Sealing products that have been applied to coastal structures, with one known exception (a sodium silicate solution), are not properly called grouts. Their viscosities cannot be measured with ordinary laboratory viscometers. According to Engineer Manual (EM) 1110-2-3506 (HQUSACE 1984), grout is usually defined as "a mixture of cementitious or noncementitious material, with or without additional aggregates, to which sufficient water or other fluid is added to produce a flowing consistency." Conventional terminology in the grouting field requires grout to be able, at least, to flow through a Marsh funnel. Materials used in most coastal applications are usually described by their slump and not by time of efflux from a funnel. Techniques for modeling grout flow, whether in physical scale models or by analytical procedures, are not applicable to coarse aggregate concrete, the material most often chosen to seal coastal structures.

8. The importance of terminology is emphasized because this research topic brings together two fields that have had relatively little interaction, those being coastal studies and geotechnical grouting. Use of the term "grout" is minimized or heavily qualified in this report when a sealant for large voids in a rubble-mound structure is intended. Many true grouters, upon hearing the term "grout" applied in this context, may develop an incorrect understanding of the problem and materials the coastal engineer deals with. The coastal engineer, likewise, must know how to communicate with grouters because the concept, basic materials, and some of the equipment are taken from the grouting industry.

9. A grout specimen is displayed in Figure 1. This specimen hardened from a thin solution of water, cement, and admixtures. The purpose of such a mixture is to impart structural strength. Figure 2 shows a jetty void sealant. During hardening, this sealant maintained the shape it had as it was extruded from the grout tube. Figure 3 shows the type of voids in which the material is expected to form a barrier curtain. The purpose for sealing voids in rubble-mound coastal breakwaters and jetties is to create a vertical barrier that is impervious to the movement of shoal material or wave energy.

10. As an alternative to the term "grout," it is proposed to establish the term "sealant" as a generic descriptor of the very viscous materials pumped into the interiors of coastal structures to achieve a purpose similar to that of cavity filling in other environments. Sealant is intended to imply that the injected material may be thick or quick-setting to avoid loss through dilution or dispersion by dynamic forces, and to prevent uncontrolled gravity flow as in special preparations of cementitious or asphaltic concrete. The term also includes a true grout that may be used to stabilize sands occupying voids within a rubble structure, an example being sodium silicate gel.

Figure 1. Specimen of cementitious grout which hardened from a thin solution of cement, water, and admixtures
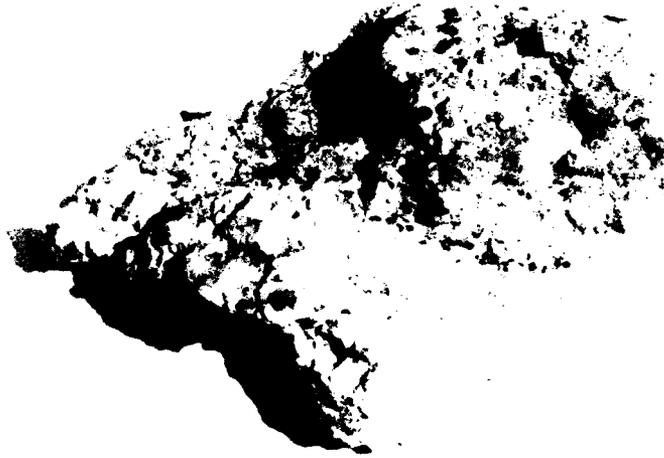
Figure 2.   Specimen of jetty void sealant which
maintained its extruded shape during hardening

Figure 3.   Representative example of size of void in rubble-mound
breakwater or jetty to be closed with sealant

11. It is important, nevertheless, for those undertaking a sealing operation to develop a historical perspective of grouting. The technology for emplacing sealants in coastal structures was refined over many years by grouters, and the basic ingredients used, though modified for coastal work, were developed by grouters.

12. The first modern application of grouting was in the marine environment. French engineer Charles Bérigny grouted the masonry walls in the Port of Dieppe, France, in 1802 with a suspension of clay and lime. The repair was necessary because mortar had been scoured away (Glossop 1961). In the mid-1800's injection processes appeared in English engineering practice. W. R. Kinipple's work with cement grouting is noteworthy. In 1882 he sealed leaks in a dock at Greenock, Great Britain. After experimental work at Abberdeen, Scotland, in 1883, and at St. Helier, Jersey, in 1884, he used cement grouting on a large scale where, as a consulting engineer, he was responsible for lengthening the Hermitage Breakwater at St. Helier (Glossop 1961). Grouting of shingle (gravel) to form a foundation was carried out in depths as great as 60 ft[*] below the level of high spring tides.

13. Grout development and grouting technology have made great advances in the fields of geotechnical and structural engineering. The main purposes have been to stabilize or impart strength to soils or other geologic materials for tunneling or foundation work, termed structural grouting. Equally important to advances in grouting have been efforts to block the flow of water, as in cases of leakage into an excavation area or out of a containment area, and to minimize seepage and uplift pressures under hydraulic structures, a procedure termed waterproof grouting.

Types of Sealant Materials

14. There are many sealant materials in existence, with the basic types being suspensions, solutions, and emulsions. Other taxonomic classifications have been attempted, but distinctions become difficult when various constituents are added to obtain particular properties. At the beginning of this

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[*] A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

century, cement-based sealants were viewed separately from sodium silicate-based (chemical) sealants. Grouping sealants by modes of network formation (such as interlocking crystals for portland cement), neutralization of surface charges (such as in bentonites), and others may be useful. Categorizing chemical sealants by their viscosity is a practice in Europe. Sealants with viscosities close to that of water are termed resins, and those with higher viscosities are termed gels.

15. Examples of the suspension type of sealants are portland cement in association with water and clays in water (i.e., some or all of the ingredients do not dissolve in water). Suspensions may be normal, such as cement-clay mixtures or thixotropic, such as bentonite. A solution type of sealant is one in which all ingredients go into solution. Colloidal solutions have the solute present in the colloidal state (i.e., in suspension). Chemical sealants may be applied as a "one-shot" solution (e.g., sodium silicate and a coagulant) or a "two-shot" solution (e.g., successive injections of sodium silicate and an electrolyte). Emulsions are two-phase systems in which the dispersive phase comprises minute drops of liquid (e.g., bitumen and water).

16. In coastal engineering practice, a pure portland-cement sealant would rarely, if ever, be used. Admixtures are needed to accelerate the setting time for minimizing dilution or erosion by water. Because the mixture has such a low water-to-cement ratio, it is more properly called "concrete" than a sealant. Therefore, this report discusses sealants according to chemical, cementitious, and asphaltic types, and groups coastal structure sealants as concretes (both cementitious and asphaltic) or gels (e.g., sodium silicate, a true grout).

Properties of Sealants

17. Desirable properties of sealants for coastal work include suitable rheological characteristics with appropriate viscosity, correct setting time, minimum shrinkage, stability, and durability. Viscosity and other rheological properties are important not only for pumping and injection into the structure, but also for penetration into the spaces to be sealed.

18. The effective rates of injection of sealants in typical coastal applications are determined by permeability of the material being sealed,

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injection pressure, and viscosity of the sealant. (Where soils are sealed, the soil shear strength is another determining factor.) Permeability is the measure of fluid flow through voids between solid particles. In cases where sealant is injected into spaces in such a way that the flow is laminar (Reynolds number less than 5), Darcy's law states the velocity, V , is linearly related to the hydraulic gradient, dh/ds , by the coefficient of permeability, k .

$$V = k\frac{dh}{ds} \tag{1}$$

where

    h — head drop across the section, ft

    s — length of section, ft

19. There are only slight deviations from Darcy's law at Reynolds numbers less than 200 (Bowen 1975). Reynolds numbers express the ratio of inertial forces to viscous forces. The permeability coefficient is a function of the shape and degree of packing of the solids, the square of a characteristic particle diameter, and viscosity of the fluid (Ippen 1966).

20. At higher Reynolds numbers (turbulent flow) in fully saturated media of grain size more than 1.00 mm, Darcy's law is stated as:

$$V = k\left(\frac{dh}{ds}\right)^{\phi} \tag{2}$$

where ϕ is the exponent of turbulence, shown by experimental results to be between 0.65 and 1.00 (Tuma and Abdel-Hady 1973).

21. Viscosity is the proportionality constant between shear stress and rate of shear in ideal viscous deformation. An ideally viscous body is called a Newtonian liquid. It has no shear strength, and strain is proportional to time elapsed (Dennis 1972). The velocity gradient of shearing deformation is linearly related to shear stress in the ideal fluid. However, only approximations to Newtonian conditions are encountered in nature. For example, the plotted relation of shearing stress versus gradient of velocity for shearing deformation of clay solutions is upwardly concave (Figure 4). Viscosity of a grout depends on the rate of shearing because of its non-Newtonian nature. Water and chemical grouts prior to setting are examples of viscous liquids.

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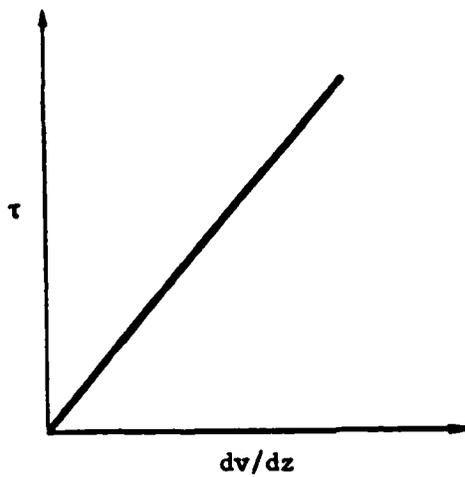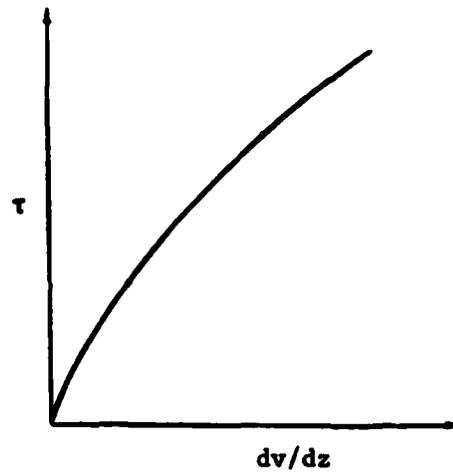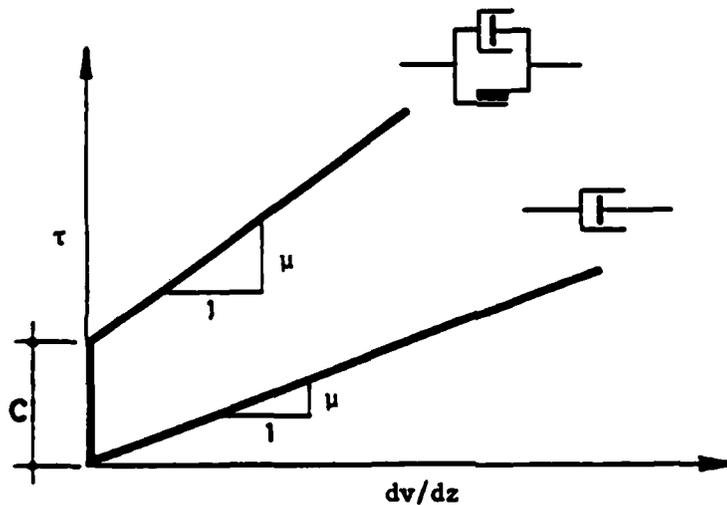
(a) Behavior of a Newtonian fluid possessing a viscosity μ which is defined by the slope of the line so that the equation of this line will be $\tau = \mu(dv/dz)$ (where dv/dz = vertical gradient of velocity of shearing deformation, τ = shearing stress).

(b) Behavior of a non-Newtonian fluid, the viscosity of which depends upon the rate at which it is sheared (dv/dz = vertical gradient of velocity of shearing deformation, τ = shearing stress).

(c) Behavior of a Bingham fluid is characterized by both viscosity and cohesion (C). Cohesion must be exceeded by applied shear stress before flow occurs.

Figure 4. Schematic rheological description
of (a) Newtonian, (b) non-Newtonian, and (c)
Bingham fluids

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22. Stable cement and bentonite-based sealants are examples of visco-plastic liquids, called Bingham fluids. They have properties of both viscosity and cohesion. Cohesion of the mixture is its yield stress, that stress which the applied shear stress must exceed before flow occurs (Figure 4c). Analysis is possible only of stable mixtures, which by this definition are mixtures having less than 5 percent sedimentation in 2 hr; i.e., less than 50 ml of water standing at the top of a 1,000-ml cylinder filled with the mixture (Lombardi 1985). Percentage of sedimentation of cement-based sealants can be greatly reduced by addition of small amounts (2 to 4 percent) of bentonite. The bentonite is particularly effective for thinner sealants (Deere 1982). The effect of stabilizing a sealant mixture is to increase both the viscosity and cohesion, but especially the cohesion (Deere and Lombardi 1985). Deere and Lombardi (1985) showed that viscosity is a factor in the rate at which a sealant flows under pressure, and cohesion is a factor limiting the distance of sealant travel, and therefore, the volume of sealant required to fill a cavity or fissure.

23. The size of particles in a grout suspension is an important factor in the effectiveness and ability to seal fractures and granular material. For all the foregone reasons, it is necessary to develop empirical relations in estimating the ability to seal certain materials. Groutability Ratios (GR) have been developed for the successful treatment of soils and rock strata, as:

$$(GR)_{soil} = \frac{(D_{15})_{soil}}{(D_{85})_{grout}} > 25 \tag{3}$$

$$(GR)_{rock} = \frac{(D_{max})_{fissure}}{(D_{max})_{grout}} > 3 \tag{4}$$

In the preceding, D_{15} and D_{85} are the particle sizes such that 15 percent and 85 percent, respectively, of the mixtures are finer in size. Figure 5 shows the limiting grain sizes of materials that can be successfully sealed by various types of sealants. Experience with chemical sealants has resulted in a delineation by size ranges of soils according to groutability (Figure 6).

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Figure 5. Groutability limits of materials using various grouts, EM 1110-2-3506 (after HQUSACE 1984)

Figure 6. Grain size ranges for chemically groutable soils, EM 1110-2-3506 (after HQUSACE 1984)

24. After injection, grout will spread a radial distance, r:

$$r = 0.62\left(\frac{Rgt}{n}\right)^{1/3} \tag{5}$$

where

R = ratio of viscosity of water to viscosity of grout, dimensionless

g = rate of grout intake, g/sec

t = gel time, sec

n = soil porosity, ratio of volume of voids to total volume, dimensionless

25. Rheological properties of sealant suspensions are important because they determine the minimum pumping pressure required to inject a sealant into a material with specified void dimensions. Thixotropy is a rheological property of some gels and clays, defined such that gels and clays behave as liquids when agitated and set when quiescent. This is a desirable behavior of sealants being pumped, and not impacted by dynamic loading after injection. Conversely, in some applications, it has been found advantageous for a sealant to mobilize shear strength to resist wave forces, yet deform slowly to accommodate settling.

Correct setting time

26. Setting time of sealants placed in the coastal environment must be controlled. Sealants tested for resistance to erosion in a flume showed the most important factor was a fast set time (Walley 1976). Admixtures control gel times and set times of sealants over a wide range. Care must be taken so that the sealant does not set in the injecting equipment, or in voids in such a way that blockage to other voids occurs and ineffective grouting results.

Minimum shrinkage

27. Volume change of a sealant during setting or curing in typical coastal applications is not as important as in waterproof sealing. The barrier being created does not have to be watertight in order to be successful. Shrinkage would be important if it were so extreme as to not effectively reduce sand or energy transmission through the structure, or prevent bonding of particles being grouted.

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Stability

28. Permanence of the chemical state of a sealant is important to the success of a coastal sealing project because, unlike some geotechnical applications, creating an impermeable barrier is the structural objective. Should the sealant fail to meet this objective, the investment represented by the total contract cost would be lost. The sealing material should resist deterioration by chemicals, organisms, sunlight, and air.

Durability

29. Not all sealants are intended to be permanent, however, but sealing jetties and breakwaters to block the movement of sand and wave energy does require the material to have a long service life. In contact with sediment-transporting water, the sealant must not be easily eroded or dissolved. It must also not be sensitive to cycles of wetting and drying or freezing and thawing. In one application for which documentation exists, the cost of the sealing materials was only 20 percent of the project, the rest being mobilization and demobilization, drilling sealant holes, placing sealant, and other costs. It is important, therefore, that the durability of the sealant be considered as significant in economic analyses and specification writing.

30. Durability tests have been designed to determine how various sealant materials will perform under actual long-term environmental field conditions. Test specimens of selected cementitious and chemical sealants have been placed at three field evaluation sites and are presently undergoing environmental exposure to waves, currents, freezing and thawing cycles, wetting and drying cycles, abrasion, biological influences, temperature effects, and chemical reactions to determine the effects of these factors on material durability properties. Forty samples of four different cementitious and chemical sealants for nondestructive testing and 350 samples of asphalt-cement sealants for destructive testing have been placed at the field test sites (Treat Island, ME; Duck, NC; and Miami, FL) to evaluate essentially the entire range of environmental factors. Physical parameters of each sealant specimen being evaluated include, but are not limited to, compressive strength, ultrasonic pulse velocity, resonant frequency, dynamic modulus of elasticity, Marshall stability, resilient modulus, and indirect tensile strength. Such structural characteristics which vary under different exposure conditions over long periods of time cannot be scaled in the laboratory by accelerating time; hence,

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it is necessary to periodically sample and evaluate specimen characteristics after long periods of real-time exposure to environmental factors.

Cementitious Sealants

31. To the present time, cementitious mixtures have been the most often used method of sealing voids in coastal structures. The chemical and physical properties of these suspensions should be understood by anyone desiring to utilize a cement-based sealant. For that purpose, a review of pertinent sealing literature follows.

Portland-cement sealants

32. Portland cements are the most common hydraulic cements. Portland cements are categorized into three types, depending upon their ability to (a) resist sulfate attack, (b) develop early strengths, and (c) generate heat during hydration. Engineer Manual 1110-2-3506 (HQUSACE 1984) provides a complete discussion of these types.

33. Pozzolan is a siliceous or siliceous with aluminous material added to portland cement to react with calcium hydroxide in the presence of water to form compounds having cementitious properties. There exist three classes of pozzolans, with fly ash (finely divided residue of coal combustion) being the most commonly used pozzolan for sealants. Fly ash may be used as a filler or as an admixture to improve pumpability. The maximum amount of fly ash to be used in sealant mixtures generally is around 30 percent by weight of the cement before strength levels of the sealants are adversely impacted.

34. An admixture is any material other than water, fine aggregate, and hydraulic cement added to sealants immediately before or during its mixing to alter its chemical or physical properties to a desired characteristic during its fluid or unhardened state. Admixtures are principally accelerators, retarders, water reducers, fluidifiers, and expansion producing materials (e.g., aluminum powder).

35. Accelerators provide for early stiffening and setting of sealant mixtures, and the most widely used is calcium chloride (CaCl). Calcium chloride may be safely used in amounts up to 2 percent by weight of the cement and, in some specific cases, could be used in amounts larger than 2 percent. Dissolving calcium chloride in the mix water is a recommended way to add it to

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the cementitious mixture. This accelerator may aggravate sulphate attack, alkali-silica reaction, and in high concentrations it acts as a retarder. It should not be used when the sealant is in contact with steel. Other accelerators include certain soluble carbonates, silicates, and triethanolamine.

36. Retarders are used to offset the undesirable accelerating effects of high placement temperatures and to prolong sealant injection or placement time. A retarder may be required for temperatures above 70° F. The most commonly used retarders are lignosulfanic acid salts, hydroxylated carboxylic acid salts, and other organic chemicals.

37. Water reducers may be used to increase the pumpability of cementitious mixtures by increasing their fluidity or to increase their strengths by allowing a reduction in the water content of the mixtures while at the same time maintaining the same degree of fluidity.

38. Aluminum powder is sometimes used in portland-cement mixtures to produce shrinkage compensation, or a slight-to-moderate amount of controlled expansion prior to the final setting of the mixture. The amount and rate of the expansion are largely dependent on the temperature of the mixture, the alkali content of the cement, and the type, fineness, and particle shape of powder per sack of cement. Laboratory or field trial mixtures, using mixing water which will be used onsite, are mandatory prior to the use of aluminum powder in project work. Aluminum powder as a shrinkage-compensating agent in sealants is feasible only when a very thick sealant is used. Thinner sealants allow escape of the hydrogen bubbles prior to set. Also, fineness and particle shape affect the time of onset and duration of reaction. All of these parameters must be optimized for this type of sealant. Additionally, mixing the powder with dry cement will help blend the two materials without cutting into the time available to mix and apply the sealant.

39. Fluidifiers in cementitious mixtures inhibit early stiffening, hold fine particles in suspension, produce a controlled amount of expansion prior to initial setting, and improve pumpability. The principal ingredients are usually a gas-generating additive, a retarder, and a dispersing agent. Fluidifiers such as rock flour, pumicites, diatomites, and bentonites usually require an increase in amount of mixture water.

40. Fillers, or extenders, are various types of materials used in cementitious mixtures to replace various amounts of cement for economic

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reasons and will probably be limited to sealing very large voids. Where sand has infiltrated into rubble or where graded materials exist as a core within larger stone, void size will probably not allow filler material. It should be noted that use of fillers tends to increase the setting time of the mixtures. In the case of high water content mixtures containing fillers, excess mixture water may result in ingredients coming out of suspension before hardening occurs, causing shrinkage and strength loss, particularly if silts and clays containing organic materials are used. Accelerators and water-reducing admixtures should be considered when fillers are used.

41. Fine mineral fillers include rock flour, clay, fly ash, silt, diatomite, pumice, barite, and others. Bentonite is a montmorillonite sodium base clay often called gel. Its utilization has increased in recent years, as it improves the pumpability of mixtures and tends to maintain ingredients in suspension until hardening. Bentonite also acts to reduce shrinkage and prevent bleeding but, if it is used as a filler, it increases mixture water demand and decreases strength. Kaolin is another type of clay used in sealants to improve pumpability, injectivity, and economy but does not exhibit gel-swelling properties. Attapulgite is a third type used in a seawater environment because of its satisfactory performance in high saline conditions.

42. Deere and Lombardi (1985) summarized some effects of additives on properties of sealant slurries. They reported,

> ...(a) decreasing the water-to-cement ratio increases both the viscosity and the cohesion, but increases the cohesion proportionately more, (b) adding bentonite increases both the viscosity and cohesion, but increases the cohesion proportionately more, (c) adding a fluidifier (Interplast, Intracrete, or Rheobuild) decreases the viscosity and, probably to a lesser extent, the cohesion, and (d) for the same Marsh flow value, a sealant with a fluidifier will be denser and have a greater 28-day compressive strength than one with bentonite. Bentonite should, therefore, be used only to increase the cohesion and limit the travel distance (its action is contrary to that of a lubricant).... .

43. Caution must be used when mixing bentonite, cement, and water to prevent phase change of sodium bentonite to calcium bentonite. It is necessary to fully hydrate the bentonite before allowing it to come in contact with cement or even a cement-contaminated mixer (Albritton, Jackson, and Bangert 1984). Deere (1982) recommended that the bentonite be premixed with water and aged for at least 2 hr before adding it to the slurry. The amount of premixed

water is assumed to be around 15 percent of the total mixture water.

44. Ordinary sand is the most common coarse sealant filler and is usually screened to a desired gradation. Two parts of sand to one part of cement by weight is the practical upper limit of sand content in a sealant mixture, unless mineral fillers or admixtures are used. Sand containing as much as 25 percent of fines passing the No. 100 sieve can be pumped success- fully at 1-to-3 ratios of cement-to-sand by volume or weight. Many other coarse fillers are available for cases where sealant strength is not a consideration.

45. Mixing-water should be free from large concentrations of impurities such as dissolved sodium or potassium salts, alkalies, organic matter, mineral acid, sugars or sugar derivatives, and silts. Water obtained from natural sources "onsite" must be tested according to American Society for Testing and Materials (ASTM) specifications using standardized procedures of WES (1949) Handbook for Concrete and Cement, Method CRD-C 400 and approved, if suspected of containing impurities. Water acceptable for drinking is generally accept- able for use as the mixture water for sealants. Seawater can also be used if the level of dissolved sodium salts in seawater is not unacceptably high.

46. The water-to-cement ratio in sealant mixtures influences strength and workability as well as pumpability, viscosity, penetration, grout intake, setting time, and pumping pressures, all of which influence the effectiveness and economics of the sealing job. The volume basis for cement sealants is commonly used in the field for convenience because it eliminates batch weigh- ings when precision weighing of constituents is not essential.

47. The volume of fluid sealant actually produced by any combination of properly proportioned materials is equal to the absolute volume of cement plus the sum of the absolute volume of filler material, significant amounts of ad- mixtures, and volume of water. The absolute volume of one 94-lb sack of cement is considered to be 1.0 cu ft. (Actually, the absolute volume is 0.956 cu ft for cement having a specific gravity of 3.15.)

48. Mixtures with a high degree of fluidity, usually containing no sand and only cement, water, and small amounts of modifiers that do not appreciably alter the fluidity characteristics of the mixtures, are referred to as slur- ries. They may also be referred to as self-leveling, level-seeking, thin cement, neat cement, or highly fluid sealants.

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Ultrafine cement sealants

49. Ultrafine-ground cement is a constituent of a commercially available sealing material which has promising characteristics for coastal engineering applications. Microfine Cement, a company which markets ultrafine cement, claims the product can penetrate fine sand, and is strong and durable with a 4- to 5-hr set time. Fifty percent of Microfine Cement's particles are less than 4 microns. This compares with 10, 15, and 22 microns for colloidal, high early, and ordinary portland cement, respectively (Clarke 1984). As with ordinary portland cement, ultrafine cement may be combined with sodium silicate to give 1- to 3-min gel times. Ratios of particle size of an ultrafine cement and ordinary portland cement were examined by Karol (1985), who concluded that the average penetration difference between ordinary portland cement and ultrafine-ground cement may not be as great as previously indicated.

50. A literature review of the subject of sealant injection under conditions of flowing ground water (Walley 1976) yielded the consensus that short gel times and set times, no matter whether the sealant is a suspension or solution type, are all important for a successful sealant application in a region of flowing water. Walley (1976) tested freshly injected sealants of 35 different mixtures for resistance to erosion and dilution by flowing water in a flume. He concluded that the most significant properties of sealants (i.e., low viscosities, high fluidity, pumpability, and ease of placement) are factors that work against sealant retention in flowing-water environments. The study indicated that the most efficacious sealants in flowing water are those that either develop a comparatively high viscosity soon after deposition or already possess this property when deposited. After being subjected to flowing water in the flume for 1 hr, two grouts that maintained 60 percent or more of their original volume were those with Chemcomp Cement (a proprietary, shrinkage-compensating cement) and Reg Set Cement (a proprietary, extremely fast-setting, hydraulic cement) as the main cementing agents.

Chemical Sealants

51. Chemical sealing technology has expanded greatly in the last few decades in response to specialized needs for high penetrability, high strength, and precisely controlled set times. Many chemical sealants exist,

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although they may be grouped into the two specific categories: (a) precipitated sealants, and (b) polymerized sealants. The only chemical sealant which appears to be suitable for stabilizing sand within jetty voids is sodium silicate, one of the precipitated grouts. Other sealants have been considered, such as acrylamides, lignins, and resins, but appear undesirable from toxicity and economic standpoints. Some of the very exotic sealants may be useful, however, in special applications. For example, the petroleum-based TACSS-type sealant which reacts with water as a catalyst might be useful in limited amounts (due to expense) where water velocities are a problem. The following paragraphs include pertinent information regarding chemical sealants other than sodium silicate sealants for completeness and for providing background knowledge for the coastal engineer who will deal contractually with members of the grouting and sealant industry.

Precipitated sealants

52. Sodium silicate is the basic chemical for a variety of silicate sealing processes. In the coastal environment such chemical sealants may be used when a design specifies that sand which fills voids within a structure be stabilized. In the presence of appropriate reactants, sodium silicate sealants form a gel that fills voids and binds particles of the material being sealed. A variety of grades of sodium silicate and any of several reactants can be used. The choice is determined by the gel time, strength, and permanence desired of the sealant. The strength and permanence of sodium silicate-cement sealant and sand sealed with sodium silicate are presently being evaluated by a series of long-term durability field tests. Test specimens have been placed at three field evaluation sites. These specimens are undergoing environmental exposure to waves, currents, freezing and thawing cycles, wetting and drying cycles, abrasion, biological influences, temperature effects, and chemical reactions to determine the effect and extent of seawater on sodium silicate sealants.

53. The various sodium silicate sealing systems form colloidal silica when the alkaline silicate solution is mixed with an acid or a salt of an acid. The colloids form a gel if the concentration of silica in the silicate solution is greater than 1 to 2 percent by volume. Reactants include chlorine ammonium salts, bisulfates, bicarbonates, sulfur dioxide, and sodium silicofluoride. Sodium silicate also reacts with salts of some metals, such as

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calcium, magnesium, aluminum, zinc, lead, titanium, and copper. Sodium silicate may be injected either with the reactants in a single-solution process, or separately as part of a two-solution process.

54. The silicate solution concentration that may be used in sealing can vary from 10 to 70 percent by volume, and in systems using amide (a metallic derivative of ammonia in which the $-NH_2$ group is retained, e.g., potassium amide, KNH_2) as a reactant, the amide concentration may vary from less than 1 to greater then 20 percent by volume. A low concentration of silicate in a one-solution system causes the sealant mixture to have a low viscosity. With increases in concentration above 60 percent, the increase in viscosity may be significantly greater. Sealants containing 35 percent or more silicate by volume are resistant to deterioration by freezing and thawing, and by wetting and drying. Sealants containing less than 30 percent silicate by volume should be used only where the sealed material will be in continuous contact with water, or for temporary stabilization.

55. The one-solution process permits better control of the radius and completeness of sealant penetration because of the controlled gel time. In the one-solution process, the reactant solution is diluted with water and mixed thoroughly, then introduced into the sodium silicate solution. Reactants commonly used include sodium bicarbonate, formamide, sodium aluminate, calcium chloride, dilute hydrochloric acid, and copper sulfate. Combinations of two or more reactants are sometimes used in the one-solution process. Often formamide is the principal reactant causing gelation, and sodium aluminate is an accelerator which speeds up the reaction. At temperatures below 100° F, the effect of the accelerator becomes increasingly important.

56. The two-solution process involves the injection of one solution containing sodium silicate followed by a separate injection of one solution containing reactants. The second solution can be introduced through the injection line used for the sodium silicate solution, or it can be introduced through a separate injection line and hole simultaneously with or following the injection of the sodium silicate solution. The most commonly employed reactant for the two-solution process is calcium chloride. Other reactants are magnesium chloride, aluminum sulfate, and gel-forming gases such as carbon dioxide. The reaction between the silicate and reactant solution or gas is almost instantaneous.

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57. Since it is expected that sealing in coastal engineering practice will involve drilling through stone or concrete to reach a rubble interior, a major disadvantage of the two-solution system is the additional drilling and labor involved in separate injections, since drill holes are not normally large enough to accommodate two physically separated supply pipes. Pumping the second solution through the same hole after injection of the first solution will almost certainly ensure that the two solutions will not become mixed. Other disadvantages include the limited radius of sealing that might be obtained since the reaction is so rapid, and the possibility of forming partially grouted pockets as the mixing of the chemicals cannot be controlled below the surface. Regardless of the process used, the sealing radius depends upon pumping rates, permeability of materials being sealed, and concentration of chemicals.

58. Common silicate sealant systems consist of sodium silicate as the gel-forming material, formamide as the reactant, and one of the following as accelerators: (a) calcium chloride, (b) sodium aluminate, or (c) sodium bicarbonate. Since formamide has the potential of being a health hazard, diacetin (glycerol diacetate) may be substituted for this chemical. Excessive amounts of accelerators may result in undesirable flocculation or formation of local gelation, producing variations in both the gel and setting times that may tend to plug injection equipment or restrict penetration, thereby resulting in a poorly sealed area. The accelerator is usually dissolved in water at the desired concentration before the addition of other reactants, and the subsequent combination of this mixture with the silicate solution forms the liquid sealant. Sealants formed using the chloride or aluminate accelerators tend to be more permanent than sealants containing bicarbonate.

59. A silicate sealant system which has successfully sealed jetty voids consists of sodium silicate (17-percent solution by volume) in water combined in a 1-to-1 ratio with a 14-percent solution of portland cement and water (using the absolute volume measure of cement). The set time of this sealant is on the order of a few minutes. Increasing the cement volume shortens the set time significantly.

60. The Malmberg System is based on the production of a silicate acid gel by the mixing of a solution of sodium silicate with a solution of the salt of a weak acid. Based on a precipitant, this system differs from other

similar two-solution systems, and it differs from other acid reaction systems by maintaining an alkaline pH.

61.   Reactants used in this system include acid, alkali, or ammonium salts of weak acids such as sulfurous, boric, carbonic, and oxalic acid. Specific salts include sodium bisulfate, sodium tetraborate, sodium bicarbonate, potassium-hydrogen oxalate, potassium tetraoxalate, and sodium aluminate. The proportioning of the sodium silicate to the total volume of sealant in the Malmberg System can vary from 10 to 75 percent by volume, with most work being done in the 20- to 50-percent range. The liquid silicate may be used as a diluted stock solution, or mixed with water during the reaction with the acid salt stock solution.

62.   This system has a small corrosive effect on light metals such as aluminum; however, the effect is not strong enough to warrant anything other than conventional equipment in mixing and pumping.

63.   A two-pump proportioning system is desirable when working with a fast gel time. For gel times longer than 20 min, batch mixing can be employed. Compressed air bubble mixing or violent mixing that introduces air should not be used because of the reaction between the solutions and carbon dioxide. Gel time can be accelerated by either (a) decreased sodium silicate concentration, (b) increased acid salt concentration, (c) increased temperature, (d) acidity of the materials being sealed, or (e) presence of soluble salts such as chlorides, sulfates, and phosphates in the material being sealed.

Polymerized sealants

64.   It is doubtful that polymerized sealants will be used in coastal applications for reasons of toxicity and economics, especially in rubble-mound void sealing operations. Nevertheless, the following is presented for completeness, and to acquaint the coastal engineer with these specialty products.

65.   **Acrylamides.** The most widely used acrylamide chemical sealant consists of acrylamide and methylene bisacrylamide mixed in proportions that produce stiff gels from dilute water solutions when properly reacted. Several reactants and mixtures of reactants may be used, but commonly a system of beta-dimethylaminopropionitrile (DMAPN), ammonium persulfate (AP), and potassium ferricyanide (KFe) is employed. DMAPN is the activator for the reaction. KFe acts as an inhibitor and is used to control the reaction. Injection is by a one-solution process with the AP solution being added to the solution

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containing the other chemicals just before the injection. Gel time can be controlled from a few seconds to several hours by proper proportioning of all ingredients. The viscosity of the solution approaches that of water, and the solution retains its low viscosity for approximately 95 percent of its fluid life. The gel is stable under nondehydrating conditions, but will lose water and shrink if allowed to dry. If the gel is allowed to dry, it will (within limits) slowly swell again to its original volume upon sustained contact with water and exhibit its original physical properties. Excessive drying will destroy the gel.

66. Acrylamide sealants have been found to penetrate materials having 90 percent of their particles larger than 0.01 mm, and have been used for waterproof sealing in fissured rock and in channels up to 4 to 6 in. wide. The gel is translucent and stiff at a concentration of 4 percent or more acrylamide. It is insoluble and may swell slightly in water, depending on the concentration of the acrylamide, the type and concentration of the other reactants, and variations in hydrostatic pressure.

67. Freezing and thawing cycles and cycles of complete wetting and drying will cause eventual deterioration of the gel in granular material due to rupture of gel particle bonds and not to gel deterioration. The gels are resistant to attack by fungi, dilute acids, alkalies, and salts and gases normally found in the ground and, presumably, in the coastal environment.

68. **Lignins.** Lignin, a by-product of the sulfite process of making paper, when combined with a commercial grade chromium compound such as sodium dichromate, forms an insoluble gel. Viscosities and gel times are controllable over a range that makes the lignins capable of being injected into materials as small as fine sand. One- and two-component systems of lignosulfonates are commercially available. The reactants are premixed in the lignin-base material in the one-solution system. Gel times of these precatalyzed lignosulfonate systems are easily adjusted by changing the quantity of water. Closer control of gel time is possible with the two-component systems. Reactants are mixed separately as with a proportioning system, and the total chemical sealant is not combined until immediately prior to injection. Lignin sealants thicken rapidly during the gel-forming period so that its pumping life is approximately one-third the total time required for complete gelation in typical applications. When injected into saturated materials, lignin

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sealants can be expected to take longer to set.

69. The chrome-lignin process combines a lignin liquor with hexavalent chromium salts. Chrome-lignin sealants can be prepared and pumped using conventional cement sealing equipment. Chrome-lignin sealants penetrate smaller voids in sands than those penetrated by cements or other suspension-type sealants. The acidity of the system prevents precipitants from forming.

70. The gel probably forms a matrix rather than creating a bond in the soil particles. The sealant is stable under conditions of continuous immersion. However, the strength diminishes with each cycle of wetting and drying.

71. Various reactants used with lignin-based sealants include sodium bichromate, potassium bichromate, ferric chloride, sulfuric acid, aluminum sulfate (alum), aluminum chloride, ammonium persulfate, and copper sulfate. The bichromates have been the most widely used and, apparently, are the most satisfactory. Acidity affects gel time, and field tests are recommended to determine the suitability of lignin sealants before large quantities are placed. The precatalyzed lignosulfonate is incompatible with portland cement, and should never be used as an admixture in cement sealant or vice versa.

72. While metallic chromium is not poisonous, it is toxic in the hexavalent chromium compounds such as dichromate; therefore, extreme caution is advised. It is more dangerous when inhaled than when swallowed. Hexavalent chromium is an irritant to the mucous membrane of the nose and to sensitive skin. Respirators and gloves should be used in all operations involving this material. Also, under some conditions, water in contact with certain chrome-lignin gels will leach highly toxic hexavalent chromium from the gel, and the indiscriminate and uncontrolled use of chrome-lignin sealant could contaminate water and make it unsuitable for drinking purposes. The US Public Health Service permits a maximum of only 0.05 ppm of hexavalent chromium in drinking water. The amount of the hexavalent chromium leached from soils stabilized with chrome-lignin is influenced by the chrome-to-lignin ratio, the acidity, and the curing time. A chrome-to-lignin ratio of 1-to-10 produced no appreciable toxic effects after 7 days curing in toxicity tests (EM 1110-2-3504).

73. **Resins.** Resin sealants are normally two-component systems made up of solutions of resin-forming chemicals and a catalyst or hardener that combines to form a hard plastic. Injection is by the one-solution process. The principal resins used as sealants are epoxy and polyester resins. The

viscosities of resins are generally higher than those of other sealants, although they can be formulated to have low viscosities. They retain their initial viscosity throughout the greater part of their fluid life, and pass through a gel stage just before complete hardening. A large amount of heat is generally given off by resins during curing. The length of time from mixing to hardened stage can be adjusted by varying the amount of the hardening reactant, by adding or deleting filler material, and by controlling the initial temperature.

a. **Epoxy resins.** A flexible stabilizer is sometimes incorporated into one of the components of epoxy resins to increase the ability of the hardened sealant to accommodate movement. A filled system is one in which another ingredient, generally an inert material such as sand, has been added. An unfilled system refers to the original system. For both filled and unfilled systems, tensile strengths generally range in excess of 4,000 psi, elongation may be as much as 15 percent, and flexural strength in both filled and unfilled systems is generally in excess of 6,000 psi. Considerably higher strengths have been reported in some instances with filled systems. Compressive strengths greater than 10,000 psi are attainable. In general, epoxy resins (a) are resistant to acids, alkalies, and organic chemicals, (b) can be cured without volatile by-products, therefore no bubbles or voids are formed, (c) have the ability to cure without the application of external heat, (d) are thermosetting resins (once they have hardened they will not again liquefy even when heated), (e) accept various thixotropic or thickening agents such as special silicas, bentonite, mica, and short fibers such as asbestos or chopped glass fiber, and (f) can be used in combination with various fillers to yield desired properties both in the hardened and unhardened states. Fillers reduce heat evolution, decrease curing shrinkage, reduce thermal coefficient of expansion, and increase viscosity. They also reduce cost by reducing resin content. Examples of extenders are aluminum silicate, barium sulfate, calcium carbonate, calcium sulfate, and kaolin clay. Graphite filler aids in lubricating the mixture. The tensile strength, elongation, and compressive strength are adversely affected by the addition of granular fillers.

b. **Polyester resins.** Factors influencing the rate of curing include resin volume, ambient temperature, catalyst selection, and heat dissipation. Viscosity can also be controlled through choice of catalyst. Promoters are sometimes used to accelerate the setting of polyester resins. Shrinkage occurring during hardening may range up to 10 percent. Compressive, tensile, and flexural strengths are appropriate for structural sealing, and far exceed strengths needed for sealing coastal structures. A polyester resin used in dry fractured rock gels in 15 to 20 min, and becomes solid in about 90 min at ambient

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temperatures ranging from 60 to 80° F. Moisture lessens the adhesiveness of the resin and inhibits its curing. Other resins are available and may occur in the form of aqueous solutions of resin-forming chemicals, or water-base resins. Particular chemicals or mineralogy present in the sealed material are known to affect the set time of some of these commercially available sealants. For example, one water-base resin has an affinity for siliceous surfaces and attains a hard set, but will not set properly in calcareous materials. Other chemical grouts include a cationic organic-emulsion which utilizes diesel oil as a carrier, a resorcinol formaldehyde, an epoxy-bitumen system, a calcium acrylate and aniline-furfural, an aluminum oxalate compound, a urea formaldehyde, and a polyphenolic polymer system.

Asphaltic Sealants

74. Bitumen is the binding material in asphaltic mixtures. It forms a physical bonding with the aggregate or with the sealed material, and is chemically inert. Binding to cold, humid aggregate (termed cold mixture) is possible only with chemical additives. Bituminous mixtures are categorized by the amount of bitumen relative to the interstitial spaces of the coarse material with which it is mixed. Most experience with asphaltic sealants has been in Western Europe, and particularly in The Netherlands.

75. Examples of over-filled mixtures are mastic asphalt and over-filled stone asphalt. The firmoviscous properties of bitumen dominate. In exactly filled mixtures, the volume of bitumen is approximately the same as the volume of voids. Asphalt concrete is an example of an exactly filled mixture, and must be compacted when placed. In under-filled mixtures, such as lean sand asphalt and Fixtone, the properties of the aggregate dominate. Under-filled mixtures are permeable to water.

76. Mastic asphalts are poured hot, and used as a solid impervious layer or as a penetration mixture. The reach of penetration is proportional to the fourth power of a characteristic diameter of the voids being filled, and is a function of velocity of injection and rate of cooling. Penetration depth is controlled by varying the ratio of particle size in the mixture to the particle size of stones being penetrated. For underwater sealing, van Garderen and Mulders (1983) suggested maintaining a ratio $(D_{15})_{stone}/(D_{85})_{mixture}$ of 10 to 20, where D_{15} and D_{85} are the particle sizes at which 15 percent and

85 percent, respectively, of the material are finer. For above-water placement, the ratio should be 5 to 10. Such ratios will yield a penetration depth of a two-stone thickness.

77. In using asphalt concrete, much attention must be paid to the amount of compaction. The steeper the slope, the less energy for compaction can be supplied. Although the obtainable stability of the mixture may permit a steeper slope, the maximum slope on which asphalt concrete is applied in The Netherlands is about 1-to-1.7 (vertical-to-horizontal) because of the soil-mechanical stability limitations of the subsoil.

78. Stone asphalt, another of the exactly filled types, was developed in constructing the breakwater at Ijmuiden, the outer harbor of Amsterdam. An impervious 6-ft-thick layer was laid on a slope of 1-to-2 above water without artificial compaction. To avoid experiencing creep, a mixture employing two stages was developed. A mastic asphalt was first produced, then mixed with predried rock weighing 20 to 150 lb (8- to 17-in.-diam stone). Special mixing equipment had to be used because standard equipment processes aggregate only up to 2- to 2.5-in.-diam stone.

79. The procedure in the preceding paragraph is the basis of development of the under-filled mixture called Fixstone. This mastic asphalt is made (by weight) from approximately 60 percent sand, 20 percent filler, and 20 percent bitumen. This mixture is then combined at a ratio of 4-to-1 with crushed stone or gravel.

80. Lean sand asphalt, an under-filled mixture, can be made from dredged sand mixed with 2- to 6-percent bitumen by weight. The grains are coated with a thin film, which is susceptible to breakdown by ultraviolet radiation and oxidation. Lean sand asphalt is usually not artificially compacted. The void ratio remains 35 to 40 percent, so the permeability is about the same as that of sand alone.

81. After cooling, sand asphalt behaves like soft sandstone under short-duration loadings, and like loose sand under long-duration loadings. It withstands erosion by currents exceeding 9 ft per sec (Mulders et al. 1981). Experience has shown it to be chemically stable for at least 30 years, which is the extent of field experience. Since petroleum residues represent a food source for some biota, the material is not entirely resistant to biologic agents; however, that material untouched by biological activity remains

chemically stable. The extent of degradation by ultraviolet radiation and oxidation of rich asphalt and sand mixtures is presently being determined by long-term durability tests at the Miami, FL, exposure station.

82. Suklje (1969) modified the widely used Burger Model for sand asphalt when he developed a rheological model for bitumen consisting of a Hooke body in series with a Kelvin body. Sand asphalt was considered to possess a viscoplastic behavior and was modeled by adding a Bingham body (Figure 7). The viscoplastic component is dominant for sheer strains greater than 4 percent, and is presented by Mulders et al. (1981) as:

$$\tau = \tau_i(\sigma_o, \varepsilon) + \eta\frac{d\varepsilon}{dt} \tag{6}$$

where

τ – shear stress, lb/ft^2

τ_i – internal shear resistance, lb/ft^2

σ_o – isotropic stress, lb/ft^2

ε – total shear strain, dimensionless

η – apparent coefficient of viscosity, $lb\text{-}sec/ft^2$

t – time, sec

83. When sand asphalt is isotropically (perpendicularly) loaded, the coating is first squeezed from between the grains. Under deviatoric (distortion) loading, bitumen shears between particles before being squeezed out. This results in a gradual buildup of internal resistance due to increasing amount of grain-to-grain contact (Figure 8). At shear strains in the range of 9 to 16 percent, the internal resistance approaches that of sand.

84. According to Equation 6, high strain rates do not lead to failure as much as would be expected from considering only the low angle of friction, but they mobilize increased viscous resistance. The term $d\varepsilon/dt$ is important to the rheology of sand asphalt, and is displayed as a function of time in Figure 9. Values for internal shear resistance, the failure limit, apparent coefficient of viscosity, and the dependence of strain on shear were obtained from test results using a type of triaxial cell termed a Dutch Cell (Mulders et al. 1981). Creep, $\Delta\varepsilon$, is defined by the formula:

$$\Delta\varepsilon = (\tau - \tau_i)\frac{\Delta t}{\eta} \tag{7}$$

Hooke   Kelvin

Elastic   Firmo-   Visco-
               viscous   plastic

Viscous character   Viscoplastic behavior,
of sand asphalt   dominant for shear strains
                           greater than 4 percent
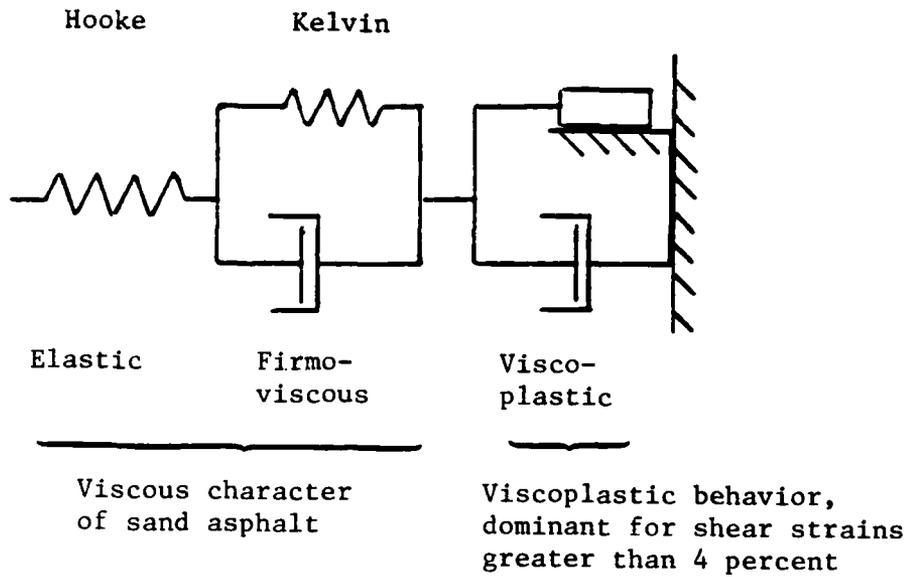
Figure 7. Adopted rheological model for sand
           asphalt (after Mulders et al. 1981)

Strain (percent)
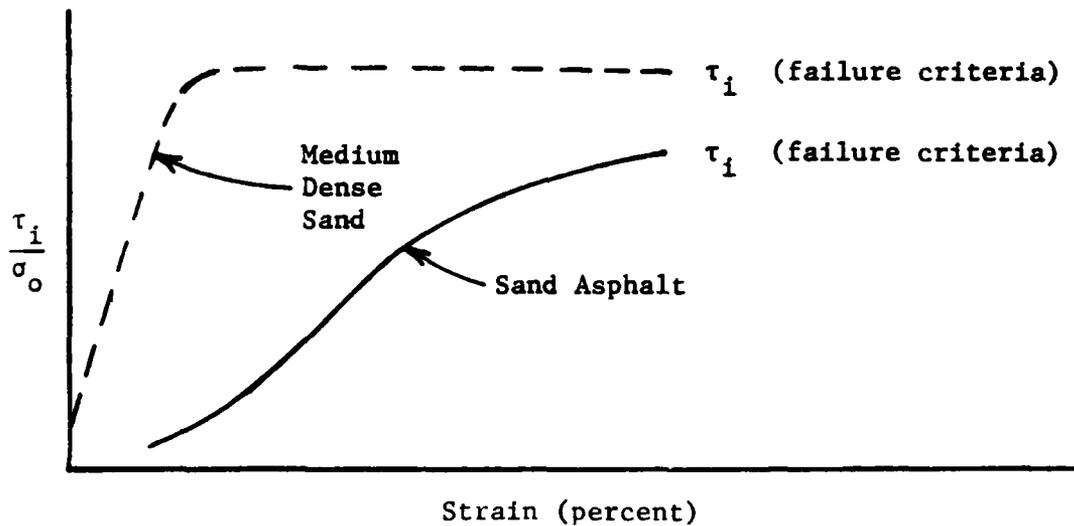
Figure 8. Stress-strain relationship for sand
           asphalt (after Mulders et al. 1981)

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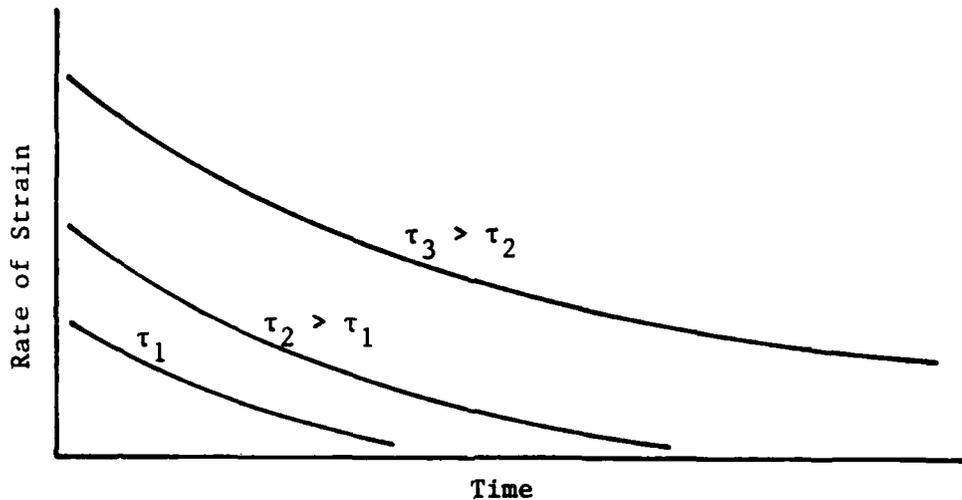
Figure 9. Schematic rate of strain as a
function of shear stress for sand asphalt
(after Mulders et al. 1981)

The symbols have been previously defined. Using experimentally determined
values for the pertinent parameters, calculations for a particular sand as-
phalt yielded the time-dependent shear-strain relation shown in Figure 10.

85. All mixtures to be used should have a record of successful prior
applications under conditions similar to those of the proposed project, or
should be tested either in a laboratory or in a test section in the field.
This entails using the actual materials in the test evaluations which will be
used in the field prototype application.
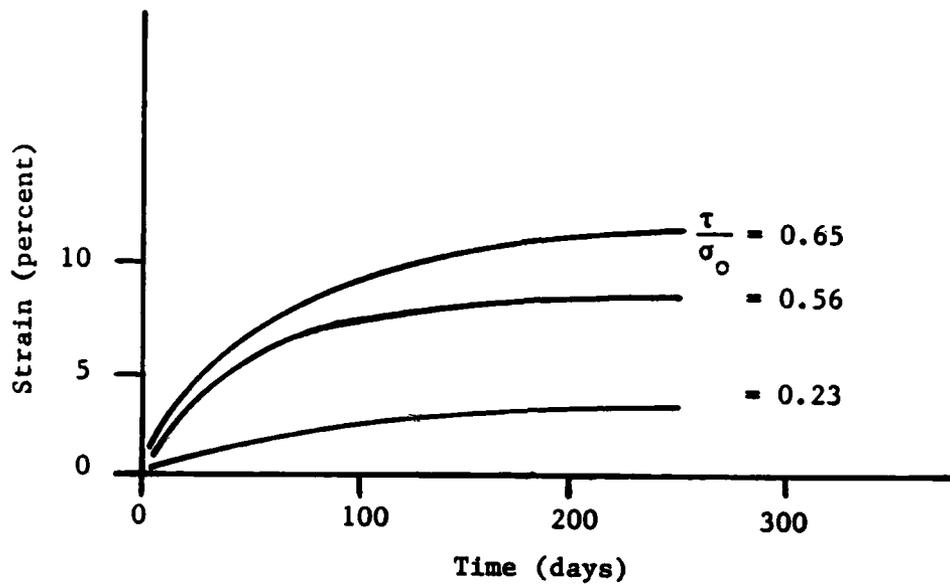
Figure 10. Computer simulations of strain-time relationship at different shear levels for sand asphalt (after Mulders et al. 1981)

PART III: SEALING TECHNIQUES

Historical Perspective

86. The first recorded use of grout material appears in the Biblical scriptures, Genesis 11:2-3, as an account of the construction of the ill-fated Tower of Babel, where bricks and bitumen were used as mortar. The injection process was later invented by Charles Bérigny and was used by him in the repair of the "scouring sluice" at Dieppe, France, in 1802. The drive for developing sealants and sealing techniques has come principally from the efforts to strengthen foundations under buildings and dams, to sink shafts and drive tunnels, and to cut off water seepage through fractured rock or soil under dams. A summary of significant events in the development of sealants and sealing techniques (Glossop 1960, 1961) provides perspective to the engineer and field inspector faced with the task of planning and executing a sealing task in the coastal environment.

  a. 1802. Bérigny invented a pump for placing grout, "pompe à percussion" during the grouting of a weir at the Port of Dieppe, France. The device consisted of a wooden pump barrel having an inside diameter of 8 cm, with a 3-cm-diam nozzle at one end. When in use the pump barrel was filled with clay. A removable wooden piston was then inserted and driven down with a heavy mallet after the nozzle had been injected into holes bored into the surface of the foundation raft. The injection pressure developed was capable of lifting timbers from the raft.

  b. 1837. Raynal published a paper describing his use of an injection process and its first application in the repair of damaged masonry. Here he made the prophecy regarding the grout pump, "...The utility of this invention is unquestionable today; and we do not doubt that with time, one will increase the number of possible applications a great deal...."

  c. 1838. Marc Isambard Brunel was first to use portland cement, during construction of the Thames Tunnel.

  d. 1869. J. H. Greathead invented the grout pan with an implement for injecting the grout by a syringe.

  e. 1876. Thomas Hawksley first used cement grout to seal fissures in the rock beneath an earth dam at the Tunstall reservoir.

  f. 1882. Reumaux introduced the injection process to mining when he sealed a water-bearing fissure by injecting cement into it under gravity head.

g. **1882-1890.** C. Colson performed cement grouting of rock fissures while constructing a dock at Malta.

h. **1884.** W. R. Kinipple used cement grout in stabilizing shingle to form the foundation of the extension to the Hermitage breakwater at St. Helier, Jersey. Throughout his long career he tried, without a great deal of success, to convince others of the "...feasibility of cementing shingle together in foundations of great depths, grouting up fissures, and repairing structural works undermined or wasted away by the action of the sea or scour...." (Glossop 1961).

i. **1886.** Greathead patented an improved grout pan which employed compressed air for grout injection.

j. **1887.** Jeziorsky invented a two-shot process for chemical grout, consisting of the injection of sodium silicate and a coagulant in two different holes.

k. **1890.** Camere first used direct air pressure in injection of cement grout in sealing joints between caissons while forming walls of a lock at Port Villez on the Seine.

l. **1893.** Cement grout was first used systematically and on a large scale to seal fissures and strengthen rock beneath the foundations of a dam on the New Croton project in New York.

m. **1894.** First use of power operated pump for injecting grout, was applied to shaft sinking.

n. **1905.** *Portier observed that forcing cement grout into fine* sand would cause cement to be filtered out at the point of injection.

o. **1908.** H. P. Hill put into practice an original idea of using a very dilute grout to block the finer fissures as a remedial measure to cut off water leaking from reservoirs. This was a valuable contribution to grouting practice. The grout was a 20-to-1 water-to-cement ratio mixture, changing to a 10-to-1 ratio as grouting proceeded.

p. **1909.** Lamaire and Dumont patented a single-shot process of chemical grouting using premixed solutions of dilute acid and dilute silicate.

q. **1919.** G. W. Christians invented a method of injecting asphalt grout into openings through a pipe heated by steam or electricity ("hot wire"). It was used with some measure of success on the Hales Bar Dam, Tennessee, 1919-1920. In 1936, while constructing the Chickamauga Project Lock on the Tennessee River, experiments were carried out using the same method in which standard roofing asphalt was pumped into a 3-in.-diam hole into which sizes 00 or 000 iron wire had been placed for the purpose of providing heat by way of electrical resistance. Cores were recovered after grouting and showed distribution of the asphalt was spotty. Shrinkage was 15 to 20 percent (US Army Engineer District, Nashville 1937).

r. 1922. M. Durnerin discussed the problem of the filtering
    effect of sand on the cement particles injected as grout into
    fine sand in a publication on alluvial grouting. He gave ex-
    cellent theoretical reasons why a low-viscosity grout which
    produces a gelatinous precipitate would not work.

s. 1925. H. J. Joosten invented an in situ chemical grout injec-
    tion process using a low-viscosity grout which gives a gelat-
    inous precipitant. Use of his process continues almost un-
    changed to this day. It was the first thoroughly reliable
    method of treating alluvium of size down to the fine sand
    range. It consisted of successive injections of a concentrat-
    ed solution of sodium silicate and a strong electrolytic
    saline solution through a pointed pipe perforated at its lower
    end.

t. 1927. E. Ischy invented the "tube á manchette" which permits
    grouts of differing properties to be injected into the ground
    in any order and at any interval of time from the same bore-
    hole. This permits the easy grouting of coarse media with
    cement first, followed by less viscous grouts to treat the
    finer media. It is said to be probably the most important
    single invention in the development of alluvial grouting.
    This tool made more effective the technique of systematically
    controlling injection pressures and varying the type of grout
    used according to the degree of acceptance which is observed as
    the work proceeds. The success of the technique has been due
    to a fruitful collaboration between such public bodies as
    Service des Grands Travaux d'Algerie, Electricite de France,
    and the Laboratorie du Batiment et des Travaux Publics,
    together with a small number of specialist contractors.

87. The following observations of Glossop (1961) are pertinent to any
endeavor to expand the application of a sealing process:

> ...Thus it would seem that although the rock grouting method in-
> vented by Hawksley was first developed by French mining engineers
> for use in shaft sinking, its use in the treatment of dam founda-
> tions developed in the United States. It was first used systemat-
> ically in France at the Barrage du Chavannon (Haute Dordogne) in
> 1924. Having once realized the value of this process, French engi-
> neers concentrated on details of injection techniques rather than
> on elaboration of a standard practice and, in particular, on the
> interpretation of what is happening below ground, based on contin-
> uous records of pumping pressures and of grout acceptance. They
> soon realized the value of self-recording manometers, as had been
> used by Saclier, since the start of strata uplift is at once evi-
> dent from them. This approach was more flexible than that follow-
> ed in the United States, and together with research on grouts other
> than those of cement, it led directly to success in the treatment
> of alluvial deposits....
>
> Although Bérigny and Kinipple grouted coarse gravel and shingle,
> the treatment of a wide range of alluvial material was the last

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type of injection process to be perfected, and seems likely to prove the most important in civil engineering practice.... .

88. Prior to the mid-1900's dam construction expanded, and larger and higher dams were made. Deeper grout holes had to be used and hence light-weight diamond drills were designed. The necessarily higher pressures needed for injection promoted the development of positive displacement pumps suit-able for efficient cement sealant handling. Later, other pump types were de-signed.

89. Since the mid-1900's great advances have been made in developing chemical sealants with specialized characteristics of injectability, exactly controlled set times, compressive strengths, impermeability, and others.

Sealing Methods

90. In the typical coastal structure sealing operation (excluding some asphaltic applications), drilling is necessary and expensive. Because of the linear aspect of the usual sealant placement in coastal applications, the drill hole pattern is normally a single line. The split spacing method should be employed for greater economy. By that method a series of primary holes are drilled, with center-to-center distances greater than that estimated for the final hole pattern. Sealant is injected into the primary holes and the grout intake (volume of sealant placed) per vertical foot rise of the injector noz-zle is determined. The occurrence of sealant loss from the sides of the structure, as well as any appearance of sealant in any adjacent ungrouted hole, should be ascertained. A 10-ft spacing has been used previously in sealing a jetty to prevent sand passage, and was found to be an acceptable spacing for the primary holes. Because hole spacing is dependent on project conditions, a test program should be undertaken before writing large contracts (Part V). The next series of holes, the secondary holes, are centered on the same line as the primary holes, but are spaced midway between the first holes. The secondary holes are sealed, then the decision must be made as to whether drilling and sealing a third set of holes is required. On one Corps sealing project, a final 2.5-ft hole spacing was required to seal the structure.

91. The order in which holes should be filled depends on field condi-tions. If the sealant intake into a hole seems excessive, or if it is obvious

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that sealant is being lost to areas not intended to be filled, consideration should be given to decreasing the sealant's set time or advancing to the adjacent hole and filling the lower part of the hole. After that, the next level of the first hole would be filled and so forth. In such an operation, the field engineer must balance the increased labor costs with the savings in sealant. The prime objective, however, is to achieve adequate closure of the voids.

92. In a typical civil or mining engineering sealing application, the medium to be grouted is either soil or rock. However, in coastal engineering applications, the usual case is that sand must be stabilized, and voids in the rubble-mound structure must be closed from the same bore hole. Therefore, methods for treating soils as well as rock will be included. The types of sealant treatment known as barrier curtain creation, cavity filling, soil sealing, and riprap sealing are described from a coastal engineering frame of reference.

93. Barrier curtain sealing was developed to control seepage under dams or other structures. It often consists of multiple lines of sealed holes. To prevent sand from flowing through a coastal structure, theoretically a two-dimensional, vertical barrier is all that is required, and a single line of sealed holes in communication with each other should accomplish that. Minimum acceptable depths and maximum spacings should be specified. However, specifications should be flexible enough to add additional lines of sealant holes at any location or alter depth and spacing of holes as determined necessary in the field. Final depths or heights should not be based on precedent alone, but on the elevations at which sand could be expected to move under design conditions.

94. Cavity filling is one of the least standardized types of grouting (i.e., sealing abandoned coal mines). Air- or water-filled cavities of large, open joints can successfully be sealed with concrete. The extent of a cavity is not known after the penetration of a single sealant hole, but an accurate rule of thumb is that the void space is 30 percent of the rock size in old, well-settled structures. When a cavity is encountered in drilling, the hole should be sealed before continuing into the structure. A coarse aggregate concrete may be used for cavity filling and for economy and effectiveness in achieving the desired dimensions of the injected mass.

95. Soil sealing methods were first developed to stabilize, to reduce settlement of, and to arrest water movement through unconsolidated granular materials ranging from sand-size particles to, and including, fine gravels. Beach sands are the typical "soil" materials encountered in sealing coastal structures, and injectability of the sealant mix into the local material should receive much attention. With the proper sealant and proportions determined, methods for soil sealing are summarized (HQUSACE 1970) as:

a. <u>Casing.</u> A casing may be drilled, jetted, or pushed to the full depth to be treated and then withdrawn as sealant is pumped into the soil. The escape of sealant up the contact surface of the casing and the soil may be a problem. This method is used extensively in chemical sealing at shallow depths.

b. <u>Sealant sheath.</u> In this method, a flush-joint sealant pipe is sealed in place, using a special brittle sealant that prevents leakage up the outside of the pipe. The sealant pipe is withdrawn a short distance, leaving a brittle sealant sleeve below the pipe. Sealant is pumped into the soil through cracks produced by the pressure of the sealant in the brittle sealant sleeve below the end of the sealant pipe.

c. <u>Pierced casing.</u> A patented soil sealing method has been developed in which the casing is sealed in the drill hole, using a special sealant. The casing can be pierced at any selected point by firing an explosive-impelled projectile from a device lowered into the casing.

d. <u>Tubes á manchette.</u> In this method, a perforated pipe is sealed into the hole with a special sleeve sealant. The perforations are covered with short sections of a rubber sleeve (manchettes) on the outside of the pipe that act as one-way valves. Perforated sections of the pipe are placed opposite injection locations. A double packer is used to control the treatment location. The pressure on the sealant pumped into the hole between the confining packers causes it to push past the small rubber sleeves covering the perforations, rupture the sleeve sealant, and enter the soil. This device is suitable for injecting cement, clay, or chemical sealants. The same holes and the same rubber-sleeved vents have been used in some cases for the injection of each of these sealants separately, and in rotation, into a soil. This permits economical treatment of soil containing large voids with an expensive chemical sealant by first filling the large voids with less costly cement sealants.

e. <u>Riprap sealing.</u> Stability of unconsolidated riprap may be improved by sealing. Riprap sealing may be accomplished above and below water in providing slope protection for revetments, shoreline stabilization, levee facing, and similar projects. Riprap sealing applications normally consist of the gravity or pump placement of sanded cement sealants into the voids existing in riprap. The mixtures may contain up to three to four

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parts as much sand by weight as cement. For steeper slopes, more viscous sealant is required. The sealant is usually filled to approximately one half to three fourths of the depth of the voids and, where possible, topped out by brooming and curing by conventional methods.

Sealing Equipment

Drill rigs

96. In the selection of a drill rig, site considerations and job drilling and sealing requirements dictate the type and size drill rig to be used. Drilling from the crest of a jetty is usually best accomplished using a crawler or wheel unit. Hole diameter should be kept as small as necessary to inject sealant, for reason of economy, yet large enough that a reasonably straight hole can be drilled. The two basic types of drills are percussion drills and rotary drills.

97. **Percussion drills.** Percussion drills are used for drilling in solid rock. Percussion drills are operated by air- or hydraulic-driven hammers. The best known types are the jackhammer, the drifter, and the wagon drill. Jackhammer drills are only suitable for shallow work and, due to their light weight, are usually held in position by hand. Drifter-type drills are designed for tripod, bar mounts, or jumbo attachments. The commercially available wagon drill is composed of a drill head mounted in leads that are supported on a track, wheel-mounted, or skid-mounted chassis.

98. The drill proper consists of a hollow steel rod which is fitted with a fixed or detachable bit on one end and a shank on the other. Most percussion drills both rotate and reciprocate in normal drilling action. The shank fits loosely into the chuck at the forward end of the machine, where it is struck by a hammerlike piston actuated by compressed air or hydraulic fluid. The bit remains in close contact with the rock at all times during drilling except during the slight rebound caused by impact of the hammer. Cuttings or sludge materials are removed from the hole by air or water that passes through the machine and down the hollow steel drill rod to the bottom of the hole. This material then rises up the hole to the surface.

99. **Rotary drills.** Rotary drills can accept a variety of bit types and are capable of retrieving cores. The hole is made by advancing a drilling bit

attached to a rotating column of hollow drill pipe. The drill pipe is turned by a motor at speeds ranging from approximately 200 to 3,000 rpm or greater. Pressure on the bit is applied hydraulically or mechanically. Water is forced through the drill pipe to wash cuttings out of the hole. Drill rigs vary in size from small, lightweight machines capable of drilling holes only a few hundred feet deep to large rigs that can drill holes miles in depth. The small rigs would be used on coastal structures because only shallow holes are needed and portability is important. Rotary drills are practical only for retrieving cores, usually after sealing has been effected, and for examining sealing completeness.

Drill bits

100. The major types of bits used in rotary drilling are diamond bits and hard metal bits. Diamond bits may be core- or plug-type. Both types employ a diamond-studded bit to cut the rock. The bit is cooled and the hole is continuously cleaned by water or compressed air pumped through the drill rods. The core-type bit consists of a hollow steel cylinder, the end of which is studded with diamonds. The bit is fitted to the lower end of a hollow steel chamber (core barrel) that is rotated rapidly while the bit is held firmly against the rock so that the diamonds cut an annular channel in the rock. The rock that lies within the channel and projects into the barrel constitutes the core.

101. The plug-type bit is available in two varieties. One is the concave type, the head of which is depressed toward the center, and the other is a pilot type, which has a protruding cylindrical element that is smaller in diameter than the main bit head. Noncoring diamond bits have a wide range of usefulness in foundation sealing. However, plug bits are more costly than coring bits for drilling in extremely hard foundations and in badly fractured rock because of greater diamond cost. Since plug bits produce only cuttings, part of the rock encountered is removed as core. The loss of one or two diamonds from the center of a noncoring bit occasionally occurs when shattered rock is drilled, and thus renders the bit useless for further cutting. A commercially available bit utilizing polycrystalline diamond blanks has proven very effective. Penetration rates reportedly have been obtained that are two and three times greater than tungsten carbide and surface set diamond drill bits.

102. The sizes of diamond bits are standard and are generally known by the code letters EW, AW, BW, and NW. Most diamond-drilled sealant hole sizes are EW or AW in typical civil engineering applications. The dimensions of each size are:

	Size, inches		Size, mm	
Code	Hole	Core	Hole	Core
EW	1-31/64	27/32	37.7	21.5
AW	1-57/64	1-3/16	48.0	30.1
BW	2-23/64	1-21/32	60.0	42.0
NW	2-63/64	2-5/32	75.7	54.7

Diamond Bit Sizes

103. Wire line bits are another type of bit, but would not be used in production drilling for coastal structure grouting. Wire line bits were developed for efficient retrieval of cores, which may be needed for checking the continuity of the barrier sealant curtain.

104. Hard metal bits are made of hardened steel notched to resemble the teeth of a saw, and are placed on the core barrel to substitute for a diamond bit. In some soft rocks this type bit drills a hole much faster, is not easily blocked, and is much cheaper than a diamond bit. The teeth of such bits are often faced with one of the alloys of tungsten carbide, or replaceable inserts of hard alloy are welded into holes cut into the bit blank. The hard alloys can also be used to make a noncoring bit.

105. Roller rock bits are also attached to the bottom of a hollow drill pipe column. The bit is made of toothed rollers or cones, and each one turns or rolls on the rock as the bit rotates with the drill pipe. Cuttings and sludge are washed out of the hole by circulating water or drilling mud through the drill pipe and back to the surface between the drill pipe and the walls of the hole. The roller rock bit is not extensively used for sealant hole drilling because the smallest available size is approximately the same as that of an NW diamond bit.

106. Drag and fishtail bits are suitable for rock and soil. The cutters, or cutting edges of the blades of the bits, are made of hardened steel or are covered with hard alloys and curve away from the direction of rotation.

107. Drill bit types, and the materials in which they are generally used, include:

Drill Bit Type	Principal Use	Not Suited For
Diamond core	Rock and concrete	Unconsolidated soils
Plug	Rock	Extremely hard rock, extremely soft rock, unconsolidated soils, and shattered or fractured rock
Hard metal	Soft rock, hard clay, and cemented soils	Hard rock and unconsolidated soils
Roller rock	Rock	Unconsolidated soils and very hard rock
Drag and fishtail	Soft rock and soil	Hard rock
Percussion	Rock and concrete	Unconsolidated soils

Sealant pumps

108. A great variety of sealant pumps of various makes and sizes are available for the placement of sealant. They may be air, gasoline, diesel, or electrically powered. They may be constant- or variable-speed pumps. Sealant pumps should be carefully selected to ensure a built-in flexibility that provides close control of pumping pressures and variable rates of injection. The pumps should be a type that can be easily and quickly serviced during sealing operations. Pumps for most sealing projects should be of the nonsurging or minimum surging type, which reduces or eliminates the pulsating effect transmitted to a hose, pipeline, drill stem, or sealant hole. Spare pumps and spare parts should be available during all sealing operations. Types of sealant pumps include line-type slush pumps, sidepot-type sump pumps, divided fluid-cylinder valvepot-type pumps, progressive cavity pumps, and centrifugal pumps. More detailed information on such pumps is contained in EM 1110-2-3506 (HQUSACE 1984).

Concrete pumps

109. Concrete pumps are occasionally used to pump sanded and unsanded cement sealants in cases where the consistencies of such mixtures are near minimum fluidity. These mixtures have a standard slump cone consistency ranging between 4 and 8 in. Concrete pumps can easily handle aggregate to a

maximum size of 1-in. diam, and are also capable of pumping sealants contain-
ing steel fibers. These units are composed of reciprocating pistons housed at
the bottom of a stowing-type hopper. The piston delivers the mixture directly
into 4-in.-diam or larger steel pipelines through a swedged head-type cou-
pling. The pumps are normally truck- or trailer-mounted and gasoline-powered.
They are not used in sealing applications that require close pressure con-
trols, but they are mainly used in filling large cavities and, at times, are
used to deliver concrete to tremies.

Sealant mixtures

110. The first consideration in the selection of a sealant mixer is
ensuring that it has the desired capacity and that it will produce a homoge-
neous mixture in a desired period of time. Types of sealant mixers available
include vertical tub mixers, horizontal drum mixers, high-speed collodial mix-
ers (which are required for mixing ultrafine grout cement), transit mixers,
skip-loaded concrete mixers, jet mixing units, and compressed-air tank mixers.
EM 1110-2-3506 (HQUSACE 1984) provides details of such mixers.

Agitator holding tanks

111. To provide a high volume and continuous injection of sealant, two
mixers are usually set up to alternately discharge into an agitator holding
tank. This agitator holding tank has a capacity at least two, and preferably
up to three, times the capacity of the mixing system. Tub- or horizontal-type
mixers operated at slow speeds are frequently used for agitating holding
tanks. Agitator holding tanks may be similar in design to certain tub-type
mixers having paddle blades mounted on a vertical spindle and arranged in
pitch to force sealant to the discharge end of the tub.

Sealant lines

112. Two primary arrangements of sealant piping are used to supply
sealant from the pump to the hole for typical noncoastal applications. The
circulating system is compiled of a double line, and one of the lines serves
as a return line from the header to the sealant pump. That system is designed
for sealing media under pressure, which is not the case for rubble-mound
coastal jetties and breakwaters. The single-line system is the simpler of the
two arrangements, and is the only one appropriate to coastal rubble-mound
structures. The system consists of a pipe, hose, or combination of both ex-
tending from the pump discharge to the header at the hole collar. The pump

speed alone controls the pressure and rate of sealant injection. Hose lines are usually made of reinforced rubber or plastic. The inside diameter of these hoses for most sealant applications ranges from 1 to 2 in.

Valves

113. Valves for sealant lines should be quick-opening, easily regulated, and resistant to corrosion and abrasion. They should be capable of accurately controlling pressures in all positions. When in the full open position, valves should not present a restriction to the flow of sealant. Diaphragm-type valves have proven to be quite effective. Pressure relief valves should be installed in sealant lines as an added precaution against the creation of excessive pressures which might rupture lines or other equipment.

Asphalt sealing equipment

114. Portable asphalt heating kettles commonly used by contractors for pavement crack sealing, roofing coatings, and similar applications have served well in heating asphalt for many sealing purposes. Hot asphalt heating should be maintained below the flash point of the asphalt. Reciprocating pumps with ball valves, 1-in.-diam boiler-fed piston pumps, or gear pumps have been used to pump hot asphalt through 1- to 2-in.-diam black iron pipes. Conventional-type cement sealing equipment can be used for asphalt emulsions. Bituminous structures are different concepts for the use of asphalt. Mastic asphalt is produced at a large-scale plant, mixed with stone weighing 20 to 150 lb, trucked to the site, and then placed with a crane-operated bucket.

Chemical sealing equipment

115. Sealing equipment has been generally developed by the chemical manufacturers to mix and place particular chemical sealant systems. Conventional sealing equipment may also be used for a number of processes, especially when single batching will meet the job requirements. Closely controlled proportioning systems are frequently recommended for handling two or more components of a given formulated sealant. Details of chemical sealing equipment are contained in EM 1110-2-3504 (HQUSACE 1973).

Casing

116. Casing commonly used on sealing work is steel or plastic tubing. The tubing is lowered into a borehole to prevent collapse of the hole or entry of loose rock, and to prevent loss of circulation fluid into permeable zones. Perforated casing is used to isolate zones to be sealed.

Meters

117. An accurate and expeditious method of controlling sealant water content is by using volume-measuring water meters. These meters can be obtained with graduated measurements in either gallons or cubic feet, and can usually be read to the nearest one-fourth gallon or one-tenth cubic foot. A meter should be checked for accuracy before it is used and, if necessary, should be calibrated. Meters for measuring quantity of sealant placements may consist of something as simple as a vertically graduated scale or rod gage placed in mixers or agitator trucks, or they may use calibrated spindles placed in the sealant line and geared to counters or strip recorders. These meters may be designed to measure barrels, cubic feet, gallons, or any specified fraction of these units.

Pressure gages

118. Pressure gages are essential in virtually all types of sealant and pressure testing, and they must be extremely reliable. Emplacing some sealants in coastal structures is accomplished with a concrete pump operating at low pressure. Pressure gages are not critical pieces of equipment in such operations. In sealing at high pressures, however, malfunctioning gages have resulted in damage to structures and equipment as a result of excessive pressures. Gages should be tested for accuracy prior to use and periodically checked during the course of the work. The moving parts of the gage should be protected from dust and grit, and from direct contact with the sealant. Diaphragm systems, such as glycerin-filled gage savers, provide an additional degree of protection.

Monitoring Equipment

119. In sealing coastal structures, the specialized monitoring equipment developed in other fields of cementitious, chemical, and asphalt sealing is not absolutely required. However, this does not discount the need for monitoring sealant travel and solidification. The simplest probe can indicate travel of sealant from a filled hole to an adjacent untreated hole. Observation can reveal leakage of the mixture from the sides of a structure into the channel or ocean water. Pressure gages on the sealing equipment can be very effective monitoring equipment when utilized by an experienced observer.

Flow cone

120. The flow cone measurement may be used both in the laboratory and in the field for determining the flow of sealant mixtures. This is done by measuring the time of efflux of a specified volume of sealant from a standard cone. This test is used to ascertain the fluidity of sealant mixtures. The ASTM procedure for testing is provided in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 611. The usual mixtures used for jetty void sealing are thick, contain coarse rock aggregate, and do not flow from a flow cone.

Slurry scales

121. The unit weight of mixtures may be determined by using either the standard American Petroleum Institute (API) approved mud scale balance or by a precisely calibrated unit weight container that ranges in volume from 0.25 to 1.0 cu ft. The calibrated unit weight container has a set of scales graduated to 1/10 lb, with a weighing capacity of at least 250 lb.

Slump cone

122. The consistency of very thick mixtures may be determined by measuring the slump. The cone is a metal frustum that has a base diameter of 8 in., a top diameter of 4 in., and a vertical height of 12 in. The mixture is placed in the cone in three equal layers, and each layer is rodded 25 times. The cone is removed vertically, and the slump of the mixture is measured in inches from the tip of the slump cone to the top of the sealant. This ASTM procedure for testing slump is further described in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 5.

Air content measurement

123. There are five fundamental methods that may be used for determining the air content of portland cement sealant mixtures: (a) gravimetric, (b) high pressure, (c) micrometric, (d) pressure, and (e) volumetric. These ASTM procedures are described in the Handbook for Concrete and Cement (WES 1949), Methods CRD-C 7, CRD-C 83, CRD-C 42, CRD-C 41, and CRD-C 8, respectively. Methods CRD-C 7, CRD-C 41, and CRD-C 8 apply to the measurement of air in freshly mixed sealant, whereas Methods CRD-C 83 and CRD-C 42 describe the measurement of hardened sealant air content, which is usually determined in the laboratory.

Time-of-setting apparatus

124. The initial and final sets of portland cement sealants are determined by the use of a mechanical device known as the Vicat apparatus. The instrument is designed to measure with time the depth of penetration (or no penetration) of a blunt needle into a small cuplike receptacle containing a sample of the sealant. This test can be conducted in the laboratory or in the field. The ASTM procedure for testing is described in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 614.

PART IV: PLANNING AND DESIGN FOR SEALING COASTAL STRUCTURES

Determining Need for Structure Sealing

125. Establishing clear, quantitative objectives of the sealing program early in the planning process is essential to success. In the case of suspected sand movement through a rubble-mound structure, it must be shown that deposition results from sand actually passing through, and not around or over, the structure. The speed at which dye released in the water on one side of the structure appears on the other side gives an indication of the ease of sediment through-flow. If the dye appears in less than 1 min through a rubble-mound jetty or breakwater, it may be assumed the structure can facilitate an abundant amount of sediment flow. Hydrographic surveys, strategically scheduled around dredging and meteorological occurrences, will reveal the location, size, and rate of growth of a shoal attributable to transport through a structure. Even though accretionary offsets indicate coastal sediments move predominately in one direction, it is possible for the problem shoal to result from sediment moving locally in the opposite direction because of local hydrography or a longshore current that has even minor reversals. The existence of topographically depressed areas adjacent to the structure indicates sediment is moving from that location through the structure.

126. The quantity of material moving through the structure which contributes to the shoal must be of such a magnitude that the cost of its elimination is offset by the savings in mobilization, demobilization, and dredging which would otherwise be attributed to it. In instances where a designated disposal area for such material is nearing its capacity, a high priority would be placed on minimizing shoaling material which passes through the structure, thus reducing material which would need to be placed in the disposal area. Alternately, if the shoal built from sediments moving through the structure does not impair navigation significantly between times when a dredge is ordinarily in the area, the cost-effectiveness of sealing would be questionable. If the service life of the structure is near an end, sealing may not be feasible. Instead, designing for sediment cut-off in the rehabilitation would be more reasonable. Benefits claimed from any sealing efforts undertaken in a deteriorating structure may detrimentally affect the economic justification of

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a rehabilitation effort planned for the near future.

127. Another factor affecting the determination of need for sealing is the engineering feasibility of accomplishing the job (Baker 1982). If it is inordinately difficult to mobilize drilling equipment, sealing equipment, and supplies to the site, those facts should be recognized early in the planning process. If exposing the equipment to high risks due to, for example, high wave occurrence on a low-elevation structure, those potential costs resulting from such risks should likewise be recognized early.

Determining Extent of Injected Barrier

128. Design conditions must be established for which the barrier sealant curtain is intended to provide protection. Sealing to reduce wave transmission depends on some described excessive wave climate propagating through the structure. Sealing to reduce sediment flow may not be designed to a high wave event but to the present and final configurations of the accreted sand on one side of the structure and to the channel on the other side.

129. If the structure is being sealed to prevent sand transmission only, the existing sand layer should be stabilized first. After sand stabilization, the top elevation to which the barrier will be constructed should exceed the height to which sediment presently moves, or in the future probably will move, against the structure by currents or waves (Figure 11a). The sand layer should also be stabilized to a bottom elevation sufficient to block the flow of sediments moving through the structure from the down-flow side. Grouting probably will not extend below the bottom elevation of the structure unless stabilizing the foundation is an objective. If both sand and wave energy transmission are problems at a site, then void sealing should extend from the top of the stabilized sand layer to approximatley mean high water elevation (Figure 11b).

130. The length of the barrier of sealant should bracket the locations of sediment permeation or wave transmission. Additionally, the barrier curtain should traverse all locations that may become problem areas due to any changes in bottom elevation or breaker angle resulting from the changed hydraulic characteristics of the sealed structure (Figure 11c). A final equilibrium shoreline must not flank a sealed section of jetty.

Figure 11. Sealing rubble-mound structure where problem may be either (a) sand transmission only, or (b) both sand and wave energy transmission

Crest of Structure

Mean High Water Line

(Voids in this region not sealed)

Probable Sand Fillet Formation

Existing Sand Fillet

Natural Ground Line
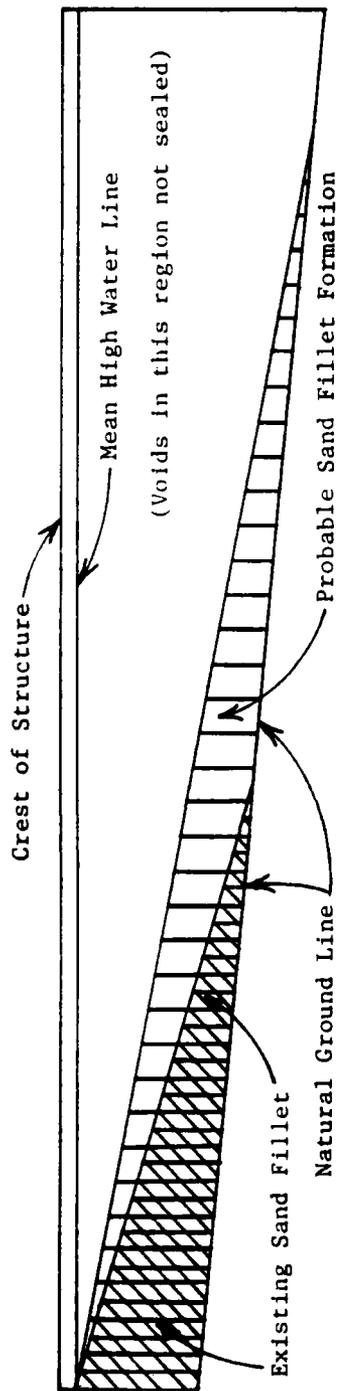
(a). Sealing structure where sand transmission is dominant problem (existing sand fillet stabilized and voids sealed in probable sand fillet region)

Crest of Structure

Mean High Water Line

Probable Sand Fillet Formation

Existing Sand Fillet

Natural Ground Line
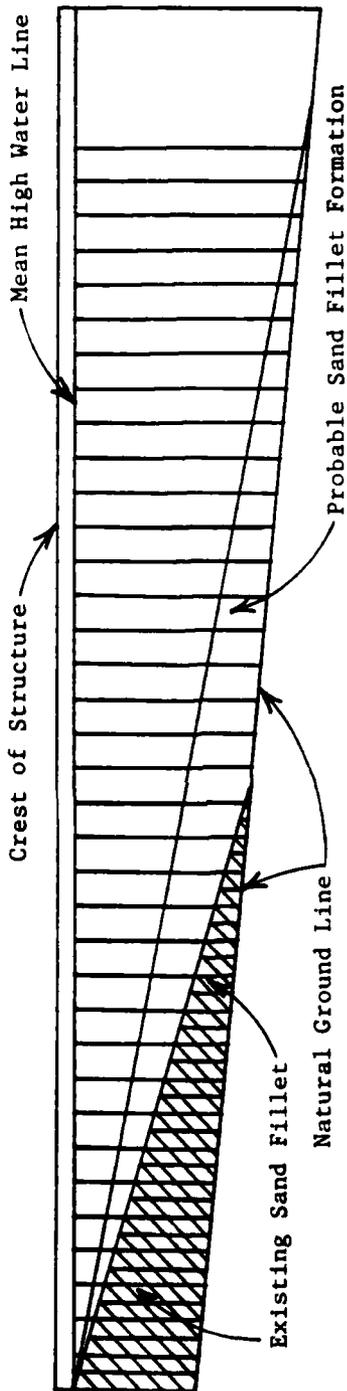
(b). Sealing structure where sand and wave transmission are dominant problems (existing sand fillet stabilized and voids sealed above existing sand fillet)

Top of Structure

Probable Sand Fillet Formation

Existing Sand Fillet
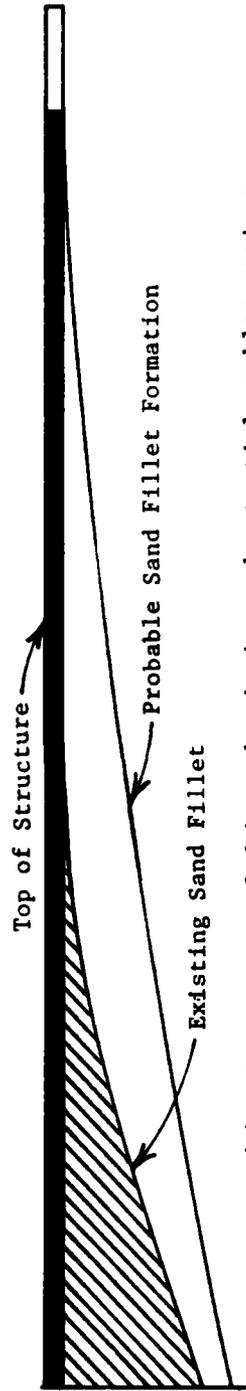
(c). Structure sealed beyond existing and potential problem regions

Preliminary Field Investigations

131. Field conditions of primary importance are rock size and type in the rubble-mound structure section to be sealed. These characteristics offer information about void size and degree of communication with other voids, percent of voids filled with sand, and voids filled only with water or air. The rate of water movement through the area to be sealed, pH, salinity, and temperature of the water saturating the media also infer ramifications regarding the groutability of the structure.

132. These factors can be evaluated through results of an experimental contract, in which some selected holes are drilled and investigated. Such work will indicate future ease of drilling, which is not often known because rock type and random surface orientation at depth may present difficulties. Knowledge regarding surface elevation and porosity of sand within the structure are necessary for computing not only volume of sealant but also are required for determining the flow characteristics and set time to specify for the sealant. Whether or not to specify flushing of the hole before sealing in situ sand can be decided in the exploratory program. Estimating the size of between-rock voids may be possible only from the drilling logs, recognizing the limitations of one-dimensional measurements. Data gathered must be correlated and analyzed to be beneficial. Information presented in this document is intended to serve as guidelines only, and cannot replace experience of qualified engineers, technicians, and contractors.

133. Factors of pH, salinity, and temperature of the water in which the sealant will be placed, as well as the mix water, are known to affect the stability and durability of the mixture. Knowledge of these factors will lead to a more efficient field testing of mixtures. Preliminary testing should also include the pumpability, groutability, and set time of mixtures. There exists no substitute for field testing a mix before specifications are written for the main sealing job.

Sealant Design

134. The main factors affecting a sealant mix designed for filling rubble-mound breakwater or jetty voids include (a) the potential for dilution

and dispersion by water movement through the structure during emplacement, (b) the consistency of the sealant and structure materials, (c) size of the voids needed to be filled, (d) elevation of the sealant application, and (e) permanence of the grout mass. Taken together, these factors constrain the sealant mixture to be highly viscous after emplacement, yet fluid enough under low pumping pressure to be placed at a rate much greater than the water flow rate through the cavity, have a fast set time, be durable and stable under conditions of cyclic wetting and drying, and be economical. Because of the many variables of cement and admixture properties, laboratory tests are recommended to determine the characteristics of sedimentation, slurry density, Marsh funnel viscosity, and Vicat needle setting time (Deere 1982).

135. Deere (1982) also notes that a specific procedure must be followed in determining the apparent viscosity using a Marsh funnel, and that funnels of different dimensions yield different values. Funnel viscosities of certain sealants have been determined for the most commonly used funnels. Actually, Marsh cone values reflect a combination of rheological properties of the sealant mixture and the boundary roughness of the cone (Lombardi 1985). Actual sealant viscosity can be easily obtained from funnel viscosity if cohesion is known. Lombardi (1985) designed a simple method for determining cohesion and, thereby, viscosity. It consists of a roughened steel plate of known weight and dimensions which is dipped into the sealant (of known unit weight), and then weighed. This yields the thickness of sealant layer on both sides of the plate and, thus, the cohesion per unit weight.

136. Sealants injected to stabilize sand must have the ability to penetrate the sand mass a distance of a few feet at low pressure. They must have a set time which permits injection, yet minimizes loss by dispersion, and are stable in their chemical environment.

137. As part of the present research investigation, guidelines will be developed for designing sealant mixtures, and recommendations regarding yield properties of such sealants for coastal applications will be made.

Injection Process Planning

138. The thickness of the injected barrier curtain theoretically is of little concern. A two-dimensional barrier curtain of finite small thickness

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should be just as effective as a barrier of large thickness. Sealant injection, however, results in a three-dimensional sealed space. Optimizing the sealant hole spacing based on drilling costs, sealant intake, subsurface conditions, and material costs is crucial to the economic planning of a sealing program. Development of an optimization diagram of the type shown in Figure 12 for each sealant mixture design would be useful during planning of a sealing project.

139. Diagrams for selection of sealant hole spacing should be used only as guidance. Experience has proven the split spacing technique to be the best staggered arrangement of placement. Limited field experience with sealing rubble-mound jetties and breakwaters has shown that good results can be obtained by spacing primary grout holes on 10-ft centers in a single, straight line on the structure crest. After filling primary holes, secondary holes are drilled and grouted in the same alignment on 5-ft centers. Sealant intake should reduce considerably with each set of holes. Instances where actual field construction has utilized hole spacing less than 2.5 ft are not known.

140. The contractor should be able to quickly assess and modify the mixture viscosity as it is being injected but, because of the amount of
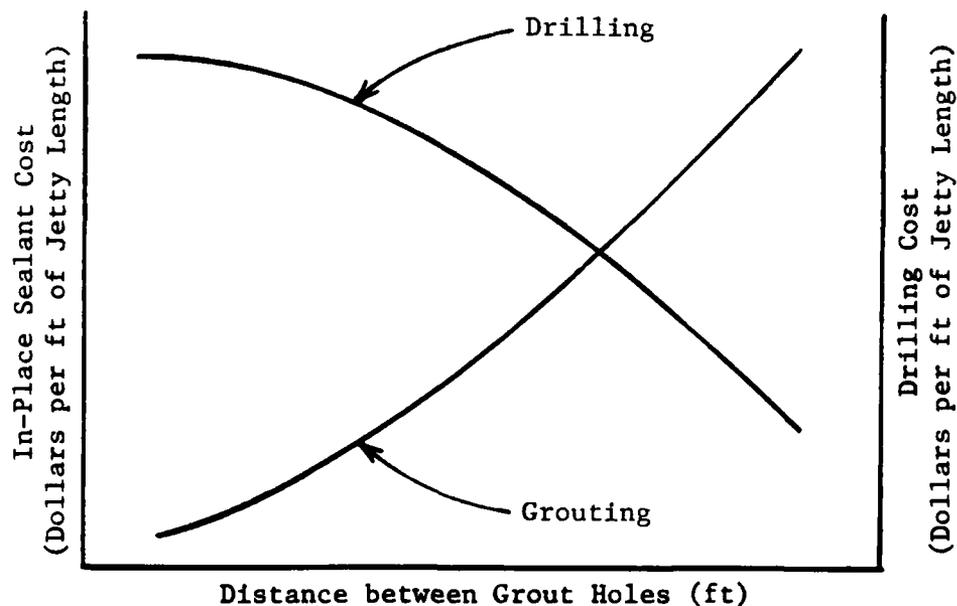
Figure 12. Optimization for most economical sealant hole spacing

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communication of voids with each other, it may not be expedient to fill one hole to the top before pulling out and filling the next hole. Maximum economy may be achieved by staging the filling of adjacent holes.

141. If the sand filling the area to be grouted is clean and well-sorted and the groutability is adequate, sealing of the sand in the structure may be preferred instead of flushing the sand from the cavity. Otherwise, the sand must be flushed out and replaced with a sealant. Sanded concretes should be used for the sake of economy to fill large voids. The larger voids should be filled first, usually with a cement-sand mixture, then the sands that are to remain should be sealed as a secondary effort.

142. Much work remains to be performed in the area of developing ways of estimating the quantity of mixture needed. In one field application, the net quantity for sealing a rubble-mound jetty was very close to the estimated amount. This occurred when the estimate was based on a theoretical volume 6 ft wide at the design length and height of the sealant barrier curtain, plus a 30 percent factor for voids. The in-place cost should be used in comparing the costs of different sealants. This includes costs for not only all actual sealant materials, but also drilling, pumping, equipment, labor, and super-vision. Delays and loss of mixture due to lack of control of viscosity or set time will also affect the final cost. For these reasons, the tendency to con-sider colloidal solution sealants exceedingly expensive and suspended-solids sealants less costly may not always be correct.

Field Procedures

143. Field procedures are affected greatly by the way specifications are written. In some cases specifications may be written with the intention of leaving procedural decisions to the field sealing supervisor. That could be an advantage in those cases where it is known which organization will be designated for field supervision, and the field sealing supervisor in that or-ganizational element is known to be sufficiently experienced. The Corps em-phasizes the need for the sealing procedure to be closely supervised by a Corps inspector who is experienced in sealing methodology. A disadvantage of this approach is that some of the design responsibility is removed from the designer and given to the sealing supervisor, who must therefore know at what

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point his field decisions should involve input from the designer.

144. In other cases specifications may give clear and detailed guidance regarding sealant hole layout, design of slurry, pumping of slurry, etc. The design drawings and the specifications must then precisely show the hole location, mixing design of the ingredients, and every succeeding step through the criteria for determining the adequacy of the sealant spread and continuity. This approach demands that the designer have considerable field experience, since a great deal of the sealing process is as much an art as a science.

145. Once the slurry mixing has begun in the field, the mixture must be checked periodically. It is recommended that the mixture be sampled hourly and that three tests be done on the specimens, including (a) temperature of the slurry, (b) density of the slurry using the mud balance, and (c) Marsh funnel viscosity. An in-line nuclear density gage is also available which can give density values and, by means of correlation, indicates water-to-cement ratio, viscosity, and cohesion. The values will indicate adjustments which might be required in the quality and proportions of the ingredients, and in the mixing procedure.

146. If bentonite is used in the sealant, the bentonite should be pre-mixed with about 15 percent water by weight and aged for at least 2 hr before adding to the sealant slurry. That procedure is necessary to prevent a phase change of sodium bentonite to calcium bentonite. When seawater is used as the mix water, attapulgite is recommended over bentonite if clay is to be an ingredient.

147. The most important part of the entire sealing operation is retaining a contractor who is competent in this type work, and who is conscientious enough to understand the indications of what is occurring below the surface and make necessary adjustments. The flow of sealant to adjacent holes or out the sides of a structure must be monitored to adjust the mix or injection procedure.

PART V: ESTIMATES AND SPECIFICATIONS FOR SEALING COASTAL RUBBLE-MOUND STRUCTURES

148. In recent jetty sealing efforts, the Corps has not experienced the degree of inaccuracy in estimating the amount of drilling and grouting which is common for dam foundation sealing. Inaccuracies with the latter have resulted in contractual disputes based on claimed differing site conditions. However, coastal engineers are not totally insured against such difficulties just by the fact that their sealing jobs are in more homogeneous media (rubble masses).

149. Practices recommended to minimize contract problems in foundation sealing are utilized for estimating quantities and writing contract language for coastal structure sealing. One recommendation in a report by George Washington University (1985) is to increase use of Corps drilling and sealing capabilities, particularly for repair work but especially for predesign investigations. A second recommendation is to perform more thorough site investigations on which to base estimates. A third recommendation is to develop better methods of estimating amounts of drilling and mixture quantities, but especially mixture quantities. The fourth recommendation concerns the major area which requires improvement, contractural procedures. In actuality, all four recommendations should be implemented in combination.

Test Program

Evaluation of exploration borings

150. The evaluation of the cores of test borings from the exploration program is fundamental in the initial stages of preparing an estimate of mixture quantities.

Test injections

151. For medium and large projects, probably the most reliable method for estimating sealant intake is to conduct an experimental prototype test program on a specific reach of the structure. The area of the structure chosen for testing should be representative of conditions for the entire project and should be extensive enough to allow adequate estimation of the effectiveness of the sealing program.

"Unit take" estimates

152. A method frequently used during preparation of detailed estimates for rock drilling and sealing programs is called the "unit take" method. In adapting this method to a coastal application, the area to be sealed is divided into horizontal reaches and vertical zones, each having different permeabilities, based on rock size and whether the voids are filled with sand or unfilled. Estimates are made of the number of primary and split-spaced holes required to complete each area and zone. Sealant intake in cubic feet per foot of hole is estimated, as well as the reduction in sealant intake for each split and zone. The amount of sealant intake in each series of split-spaced holes normally should be less than the preceding set of holes, and if multiple lines are used, intake in each line should be less than a previously treated line. Each zone of each hole is assigned an estimated intake in cubic feet of mixture per foot of hole. A typical estimate using this method may resemble the following:

Reach "A"
Sealant Intake, cubic feet per foot of Structure

		Depth	Primary	Secondary	Tertiary
Line A:	Zone 1	0-10	5.0	2.0	0.5
	Zone 2	10-20	3.0	1.5	0.5
	Zone 3	20-35	1.0	1.0	0.5

Note: The above figures are for illustration only and should not be used for purposes of estimating, as criteria for split spacing, or for completion of grouting.

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153. Results of different methods of estimating should be compared and critically evaluated for estimating sealant mixture quantities by personnel experienced in this type of sealing methodology.

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Final Contract

Contracting procedures

154. The contract types and provisions used in Corps coastal sealing projects should promote quality work firstly because of the assumption of risk by the Corps, and timely completion with appropriate economy secondly. Different approaches to payment and incentives for quality work are available.

155. Albritton, Jackson, and Bangert (1984), after reviewing dam foundation sealing practices Corps-wide, recommended that service-type contracts rather than construction contracts be considered for sealing dams. Performance specifications, though possessing the potential for saving Government funds in some types of construction, seem not well suited to subsurface sealing where performance cannot normally be precisely ascertained. Only a complete understanding of the methods used ensure quality of the work. Use of disclaimers with the traditional contracting method is discouraged, the reason being that the language used probably would not be accepted by a board or court for overriding the mandated differing site conditions clause or other pertinent contract clauses. Use of a more detailed procedural specification seems impractical because detailed knowledge of subsurface conditions is not available. The sealing supervisor should be free to make field decisions.

156. Two-step formal advertising could be advantageous where time allows, and where state-of-the-art techniques are involved. The steps are: (a) evaluation of technical proposals from prospective contractors, and (b) selection of a contractor based on price competition among those submitting satisfactory technical proposals. Prequalification of potential contractors could also be beneficial if the sealant is separately contracted, and if the job is sufficiently complex.

157. Based on the above, the traditional specifications seem to serve the Corps best. Options include paying for contractor effort, paying for quantities of sealant materials, or paying for some combination of these two elements. By paying for some measure of effort (as time spent in pumping mixture) the Corps may maintain close supervision over the contractor's methods, the contractor will be assured a reasonable profit, and reimbursement terms are clearly defined. Although the project cost may not be minimized, the contractor loses the incentive to move off holes that take mixture slowly, or to

claim differing site conditions when the average sealant intake is not as represented in the contract documents.

158. If a sealing program is to be performed along with other rehabilitation or construction work, the sealing work may be part of a general construction contract, or may be accomplished under separate individual contracts. Both methods have advantages and disadvantages.

159. Performing the sealing under a general contract eliminates contractual difficulties that might arise from interference between sealing work and other activities. Economy of use of resources is also realized by the contractor if men and equipment can be used on other activities when not pumping sealing mixtures. If the general contractor sublets the sealing work, the contracting officer's representative (COR) is contractually removed from the subcontractor, and it is more difficult to administer and maintain control of the operation.

160. Accomplishing a sealing program under a separate contract allows the sealing specialist to be the prime contractor, but this could lead to interference of one contractor with the operations of another. The sequence of operations must be well planned, and coordination among contractors fully maintained.

Contract specifications

161. Because of the risk of unforeseen site conditions, design changes often become necessary. Causes for disputes between Government and contractor should be minimized. The message in decisions of the Corps of Engineers Board of Appeals seems to be to promptly acknowledge a differing site condition (ideally at the field level) when there is an overrun or underrun, negotiate a changed unit price with the contractor, and avoid a costly claim (George Washington University 1985).

162. The Differing Site Conditions clause is often a cause of claims by foundation sealing contractors. In attempting to mitigate the problem, the Corps (a) has included language to indicate that the amount of drilling and sealing which will be required is unknown and will be governed by conditions encountered and (b) has used subdivided items to provide for variations in quantities (this method provides for two or more prices for an item). Because of the assumption of risk and because employing proper procedures and properly recording them are the only measures of quality control, the Corps has

written specifications requiring the contractor to follow detailed field direction by the contracting officer or his representative. Difficulties may arise in cases where sealing is subcontracted because the Corps then has no contractual relationship with the sealing specialist.

163. The Corps has generally used the firm fixed-price contract, with unit prices for drilling and sealant quantities. That type contract has not served the Corps' interest as well as desired because that type is most appropriate only where the job is fully defined prior to bid.

164. To alleviate the problem caused by the great variance between actual and estimated quantities, the special provision "Variations, Estimated Quantities, and Subdivided Items" has been employed but has been a source of problems itself. The majority of potential claims could be settled amicably at field level if the normal variations in quantity clause were consistently used and if unit prices were negotiated at the project level when quantities were greater than 115 percent or less than 85 percent of the estimated amount (George Washington University 1985).

165. The George Washington University report iterated three conclusions from a report on tunneling as representing the appropriate philosophy behind recommended contracting practices:

a. "...It is in the owner's best interest to conduct an effective and thorough site investigation, and then to make a complete disclosure of it to bidders...."

b. "...Disclaimers in contract documents are generally ineffective as a matter of law, as well as being inequitable and inexcusable in most circumstances...."

c. "...Contracting documents and procedures can provide for resolutions of uncertain or unknowable geological processes or conditions before and during construction, rather than afterwards...."

166. Because of the numerous contractor claims due in part to the contract language, it is of value to note recommendations contained in the George Washington University report:

a. "...Eliminate from grouting specifications disclaimers such as:

'The program shown on the drawings and prescribed herein is tentative and is presented for bidding purposes only. The amount of drilling and grouting which actually will be required is unknown and will be governed by conditions encountered.'...."

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b. "...Include a statement substantially as follows:

> 'The program shown in the drawings and prescribed
> herein is based on currently available information.
> Conditions encountered during construction may
> require additions or deletions.'...."

c. "...When grouting is subcontracted, add to the specifications a
statement substantially as follows:

> 'The grouting program shall not be modified or
> curtailed as a construction expediency. It is
> a required part of design and shall not become
> secondary to any time or scheduling restrictions.'...."

167. These recommendations were a part of others, including those regarding contracting procedures, use of Corps sealant capabilities, more thorough site investigations, and improvement in methods of estimating, which the authors of the report stressed should be considered as a whole, rather than separately.

Bid item

168. Mobilization and demobilization is a lump sum item and is compensation for assembling all necessary drilling and grouting equipment on the site and removing it therefrom. Payment for this item does not depend upon the amount of drilling and sealing performed. Provisions may be made for partial payment to the contractor after mobilizing the equipment and for payment of the remainder of the item when the work is completed and the equipment removed from the project site.

169. A bid item should be prepared for each type drilling required, for example, sealant hole drilling, exploratory hole drilling for core recovery, drilling hardened sealant, and others. If more than one size hole is required, separate items are needed for each size. The plans and specifications should indicate clearly the location and extent of the work to be done and should show limiting depths and inclinations, if any, of all holes. It is standard practice for payment to be made on a unit basis per foot of hole drilled, but better overall results may be achieved by paying for some measure of drilling effort with close supervision maintained by the Corps. Water and air required for drilling and sealing, or any auxiliary operations, are not separate pay items. The contractor is expected to recover the cost of furnishing both air and water under one or more of the designated pay items.

170. The pay item for placing sealant should cover the labor, the use of equipment, and the necessary supplies (other then sealant materials) required to mix and to inject the sealant into the holes. The stage-sealing method, if employed, may also include cleaning sealant from the holes at the completion of the sealing stage. Placing sealant is sometimes paid for by volume of the materials (except water) injected (i.e., cubic feet of solids). An estimate of the quantity of mixture must be made since the actual amount is not known in advance. Payment for injection by the hour may be more satisfactory in many cases, and it would include labor and use of equipment to inject the sealant into the holes. In cases where it is anticipated that extensive use may be made of very thin mixtures to seal fine materials, an alternative method would be to pay for placement of total volume, including water. This would ensure that a contractor is fairly compensated for long time periods required to place small amounts of sealant. It should also be realized that if mixture placement is awarded as a "unit prices item," the possibility exists for contractors to take unfair financial advantage through those provisions.

171. The stage-sealing method probably will not be applicable to rubble-mound structures in a coastal environment. This procedure is employed where it is desired to treat each seepage-causing flow separately at successively higher pressures. In sealing jetties, breakwaters, etc., an appreciable increase in pressure and multiple applications at one level would probably result in no additional benefit. A stop-sealing procedure will possibly be more applicable where hole collapse or other problems force two-phase sealing. The sealant should be allowed to set before redrilling the hole. Cleaning the hole might cause further instability. In curtain grouting specifications, redrill costs are commonly set at one half the bid price for original drilling.

172. A separate bid item should be provided for each ingredient used in the mixture (except water). Solids are usually measured for payment by the cubic foot or pound, and liquids are usually measured for payment by the cubic foot or gallon. For concrete placement, a sack of cement is considered to contain 1-cu-ft volume. This item includes all costs involved in purchasing, handling, transporting, and storing the ingredients as necessary to have it available at the mixing site when needed.

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PART VI: SUPERVISION AND INSPECTION OF SEALING OPERATIONS

173. Experience of the field personnel is of prime value in a sealing operation. Regardless of how well conceived and designed the sealing program may be, success of the program depends upon the field techniques used and upon good judgment by field personnel. Placement techniques may not be subject to contractor quality control and should be directed by the Corps field personnel. For this reason, an experienced geologist, civil engineer, or senior technician should be in charge of the sealing program and he or she should be provided with an adequate staff.

174. The art of sealing consists mainly of being able to satisfactorily treat such subsurface conditions as void sizes, shapes, and interconnections without direct observations. Sealing procedures are subject to many variations, depending on the field techniques and procedures being utilized. Such field variations include drilling, washing, selection and adjustment of mixes, changing injection pressures, flushing the holes and washing the pump system during sealing, intermittent filling of holes, determining the need for additional sealant holes, treatment of surface leads, and maintenance of up-to-date records of drilling, emplacement, and monitoring.

175. When adjustments to contract requirements are made, the designers should participate in the decision. The adjustments may include changing the spacing of primary holes or increasing or decreasing the sealing program.

Drilling Operations

176. Since drilling is a vital and costly part of the sealing program, a record of all pertinent data should be kept by the inspector during drilling operations. Entries in chronological order should be made in field books and should include all data of interest that would assist in the identification of the physical characteristics of the subsurface material examined, and should account for all time spent in drilling. A sample drill hole log sheet is shown in Figure 13. Forms for this purpose should be provided for the inspector to enter data as the work progresses. Identification of material encountered and other pertinent remarks of a geologist, engineer, or senior technician assigned to the project should also be included in the log. A sealing

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DRILLING LOG

PROJECT: South Stone Jetty Repair   **JOB No.** 1236

LOCATION: West Palm Beach, FL   3.5-in.-diam percussion drilled

HOLE No: C-102

LOCATION: Sta. 55+92.5   **DATE:** Monday, June 24, 1985

DIRECTION: Vertical   **ELEV:** +6 ft (top of hole)

TOTAL DEPTH: 12 ft   **DRILL:** Maverick Joy Air Track

NOTES: Completed H_2O to C-38 and C-39   **DRILLER:** Roger Russell

DEPTH	SCHEMATIC	CLASSIFICATION OF MATERIALS	REMARKS
		Concrete	
5'		Granite	
10'		Sand	
		Granite	
		Sand	
15'			
20'			
25'			
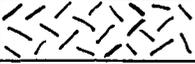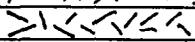
Figure 13. Sample drill hole log sheet

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data base microcomputer software package for archiving data obtained during a drilling and sealing operation has been developed by the Corps of Engineers Computer Applications in Geotechnical Engineering (CAGE) Committee. The following general information should be recorded, regardless of the data handling method employed:

 <u>a</u>. The hole number.

 <u>b</u>. Drilling time schedule.

 <u>c</u>. Names of drillers and inspectors.

 <u>d</u>. Size of hole and inclination.

 <u>e</u>. Stations or coordinates of hole.

 <u>f</u>. Type and identification number of bit used, and make of drilling rig.

 <u>g</u>. Elevations of start and completion of drilling.

 <u>h</u>. Location and cause of core losses, such as blocking of bit, soft material, and other.

 <u>i</u>. Location and nature of filled or open cavities.

177. Comments should be made on the log sheet relative to the drilling speed (penetration rate), drill pressure, and the action of the drill rig, such as jerky, smooth, rough, or steady, and the limits of such action. Particular attention should be paid to the driller if a core is being retrieved, as he may be drilling at a speed too fast to get an acceptable core, or he may be drilling at an excessively slow rate and wearing out soft material.

178. The driller's log column should show the driller's interpretation of the subsurface conditions encountered as drilling progresses. If an inspector is checking a driller's log, he will not normally reinterpret the log. Where a qualified inspector is required to log cuttings or cores, he will make the determination regarding material type, characteristic, etc., based on the official log after obtaining the driller's input on machine action, drilling difficulty, and other pertinent facts. This is true whether the inspector is provided by the Corps or by the contractor.

179. In holes drilled with percussion, plug, or other noncoring bits, much of the data from drilling must be obtained from examination of the drill cuttings and fluid. The inspector should turn in a transcript of his records at the end of each shift.

Sealing Operations

180. When sealing the interior of a structure which is filled with very fine material, the fines must be washed from the hole. Silt and clay must not interfere with sealant injection. Otherwise, windows could be eroded in the sealant barrier curtain. Open-hole washing is normally done by inserting a small-diameter wash pipe to the bottom of the hole and injecting a jet of water, sometimes in combination with air, to wash out any material in the hole. There will be instances with rotary drilled holes where it may be determined that the hole is sufficiently cleaned by washing through the drill rods for several minutes after drilling is complete. Sealant should be placed only in an unobstructed hole.

181. Pressure washing a hole consists of injecting water and, in rare cases, air under pressure into the hole through a sealed connection at the collar of the hole. The washing should be continued as long as the rate of water taken continues to increase or as long as muddy water vents from adjacent holes or surface leaks. Air injected in short bursts into the water is a method used to create turbulence and enhance the erosive action of the water. Reversing the direction of washing may also be helpful. Reverse washing will necessitate reconnecting to the original hole and washing it out for a few minutes prior to grout injection. It is important to be constantly aware that excessive pressure can damage the previously placed sealant. Water pressure and air pressure should not exceed the allowable sealing pressure during pressure washing.

182. Pressure washing of holes in rubble-mound breakwaters and jetties should be performed carefully. It may tend to wash all fines from the vicinity of the hole, increasing sealant requirements, and possibly collapsing the hole. Where washing fines out of riprap is intended, the specifications should expressly state that fact. Washing of fines may have to be continued long after water fails to exit at the top of the hole, or at the waterline in most cases.

183. Once the holes in a section of structure have been prepared, sealing may then proceed. The design mixture may need to be modified in the field to achieve desired results. Fluidizers may be added to mixtures to reduce the viscosity. Water-to-cement ratios are normally specified by volume of water

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and dry volume of cement (i.e., one 94-lb sack of cement is considered to contain 1-cu-ft volume). Figure 14 may be used for determining the cement content of various neat cement sealant mixtures.

184. A log sheet of the type shown in Figure 15 should be used to record sealing data. If the hole accepts a few batches of the starting mixture without buildup of material in the hole, thicker mixtures are required; however, thickness limits are imposed by the capabilities of the equipment to pump or otherwise handle the material. Figures 16 and 17 are for use in measuring portland cement thickening and thinning, respectively. For thickening or thinning, the cement content of a given volume of sealant is first determined.
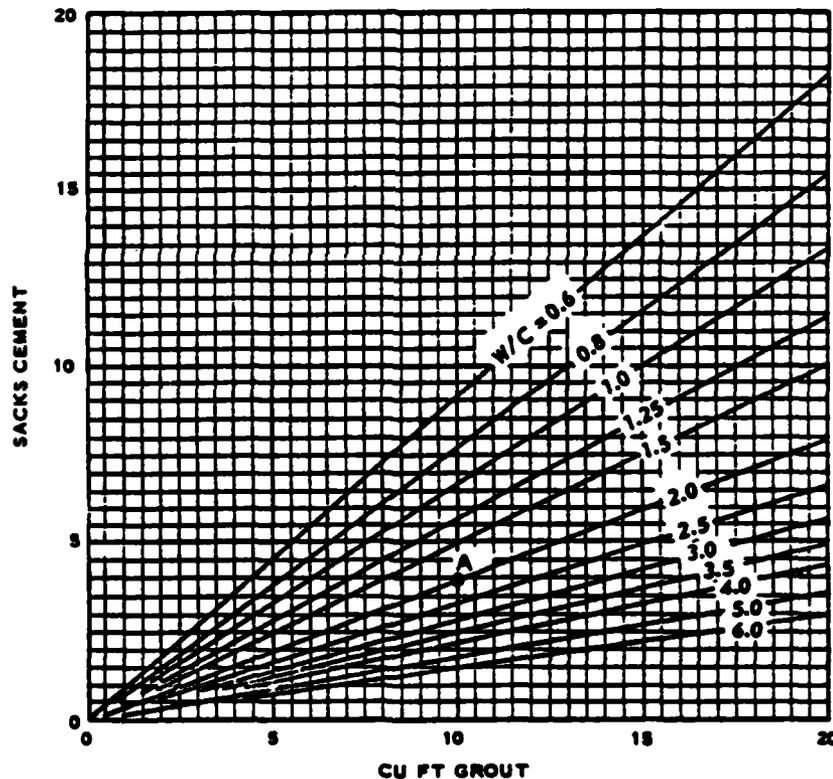
EXAMPLE: 10 CU FT OF 2.0 W/C GROUT (A) = 4.0 SACKS CEMENT.

NOTE: WATER-CEMENT RATIO (W/C) = CUBIC FEET WATER ÷ SACKS OF CEMENT.

Figure 14. Cement content of portland
cement sealant mixtures, EM 1110-2-3506
(after HQUSACE 1984)

SEALING LOG

PROJECT: South Stone Jetty Repair

LOCATION: West Palm Beach, FL

HOLE No: Sta. 55+92.5   DATE: 27 June 1985

DIRECTION: Vertical   INSPECTOR: J. Jones

TOTAL DEPTH: 0 - 12 ft (concrete cap of jetty to bottom)

Depth, ft	Gage Pressure, psi	Silicate Mix No.	Volume of Grout, gal	Time Start	Time Stop	Pump Time, min	Grout Rate gal per min
11 - 12	15	8	40	1028	1032	4	10
10 - 11	15	8	20	1032	1034	2	10
10 - 11	5	9	20	1037	1041	4	5
9 - 10	5	9	40	1041	1045	4	10
8 - 9	5	9	20	1045	1047	2	10
8 - 9	5	10	20	1049	1051	2	10
7 - 8	5	10	40	1051	1055	4	10
6 - 7	5	10	20	1055	1057	2	10
6 - 7	5	11	20	1100	1102	2	10
0 - 6	--	--	--	--	--	--	--
TOTAL			240				

Figure 15. Sample sealant hole log sheet

The total cubic feet of sealant is divided by the cubic feet of sealant obtained from a one-sack batch, based on the absolute volume of a sack of cement having approximately 1.0-cu-ft volume.

185. Slurry density has been shown (Deere 1982) to be a good index property to check and control water-to-cement ratios. Slurry density may be simply measured in the field using a mud balance. Relatively large changes in bentonite content do not appreciably affect the unit weight of the slurry. Adding excessive amounts of bentonite requires a higher water content to make the mixture pumpable, and prevents it from setting up. To this point in discussing sealing operations, open-hole conditions have been assumed. If pressure sealing is performed, some equipment would be different from that

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discussed previously, and would allow the sealer to monitor and adjust the injection rate and pressure at points in the system. With this type sealing, water-to-cement ratios are also closely monitored and may be changed more than once for a single hole as pressure and injection rates vary. It is unlikely, however, that pressure sealing would be performed on a jetty or breakwater. If required, details of pressure sealing may be obtained from EM 1110-2-3506 (HQUSACE 1984).
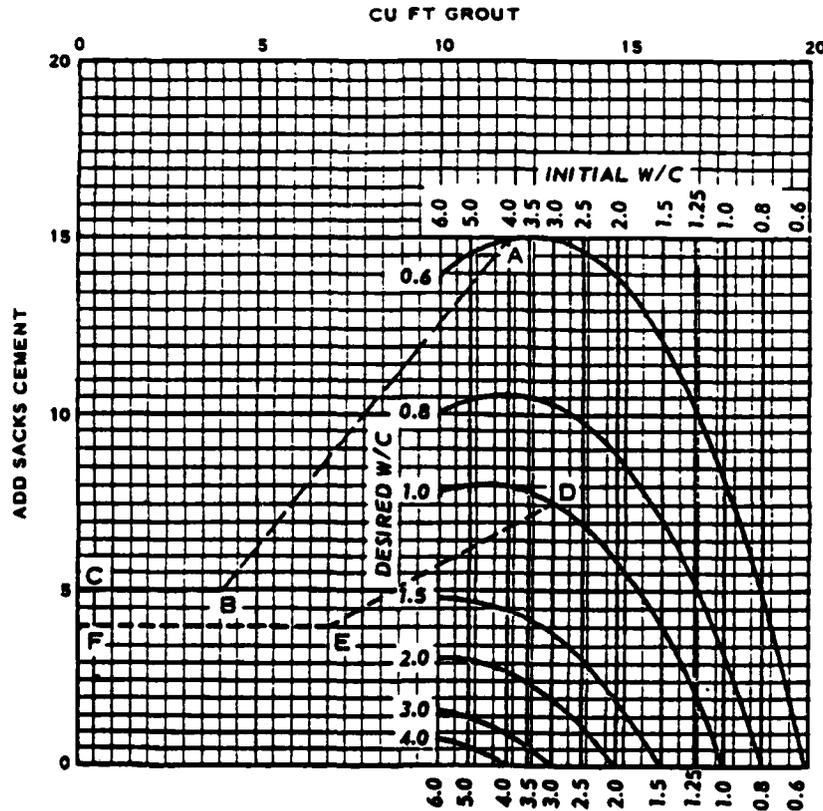
EXAMPLE 1: CEMENT REQUIRED TO THICKEN 4.0 CU FT OF 4.0 W/C GROUT TO 0.6 W/C (ABC) = 9.0 SACKS.

EXAMPLE 2: CEMENT REQUIRED TO THICKEN 7.0 CU FT OF 3.0 W/C GROUT TO 1.0 W/C (DEF) = 4.0 SACKS.

NOTE: WATER-CEMENT RATIO (W/C) = CUBIC FEET WATER + SACKS OF CEMENT.

FOR DETERMINATION OF QUANTITY OF CEMENT TO ADD, LAY STRAIGHTEDGE FROM POINT OF INTERSECTION OF DESIRED WATER-CEMENT CURVE AND VERTICAL LINE REPRESENTING INITIAL WATER-CEMENT RATIO TO POINT 0 AT LOWER LEFT-HAND CORNER OF CHART. READ AMOUNT OF CEMENT TO ADD ON LEFT SIDE OF CHART OPPOSITE POINT WHERE STRAIGHTEDGE INTERSECTS VERTICAL LINE REPRESENTING CUBIC FEET OF GROUT TO BE THICKENED.

Figure 16. Portland cement sealant thickening chart, EM 1110-2-3506 (after HQUSACE 1984)

186. Under open-hole conditions, a maximum pumping rate should be established for injecting sealant to restrain sealant travel within reasonable limits and to have better control of the job. A reasonable pumping rate for most sealing of jetties having voids unfilled by sand is considered to be 1.5 cu ft per min. The specifications should clearly indicate that the rate of injection will be controlled by the COR.
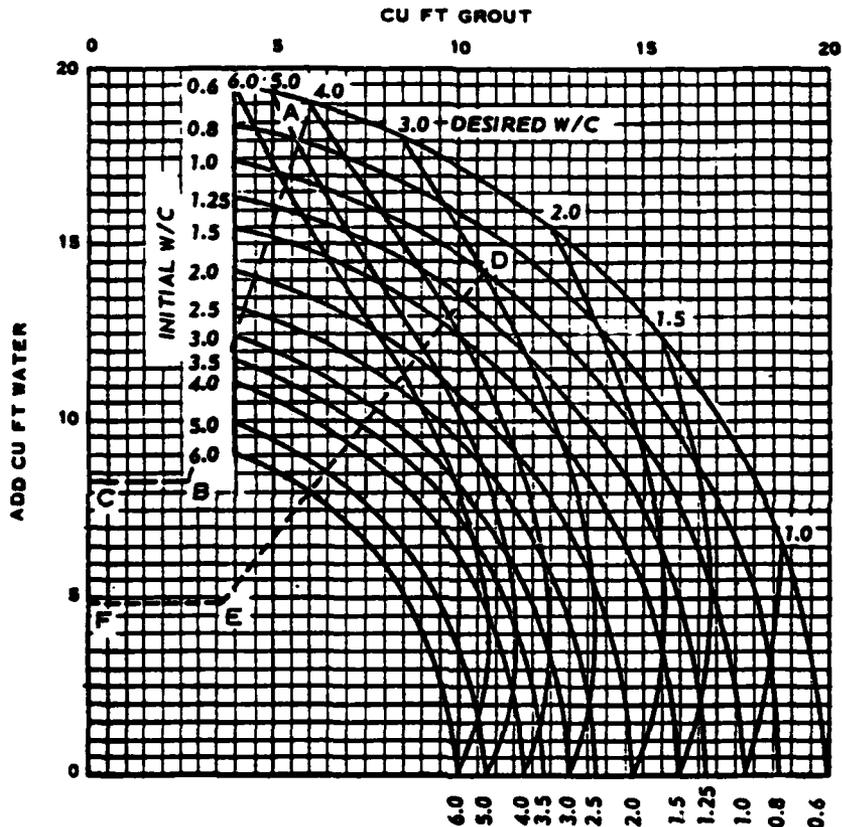
EXAMPLE 1: WATER REQUIRED TO THIN 2.7 CU FT OF 0.6 W/C GROUT TO 4.0 W/C (ABC) = 8.3 CU FT.

EXAMPLE 2: WATER REQUIRED TO THIN 3.7 CU FT OF 1.0 W/C GROUT TO 3.0 W/C (DEF) = 4.9 CU FT.

NOTE: WATER-CEMENT RATIO (W/C) = CUBIC FEET WATER + SACKS OF CEMENT.

FOR DETERMINATION OF QUANTITY OF WATER TO ADD, LAY STRAIGHTEDGE FROM POINT OF INTERSECTION OF INITIAL AND DESIRED WATER-CEMENT RATIO CURVES TO POINT 0 AT LOWER LEFT-HAND CORNER OF CHART. READ AMOUNT OF WATER TO ADD ON LEFT SIDE OF CHART OPPOSITE POINT WHERE STRAIGHTEDGE INTERSECTS VERTICAL LINE REPRESENTING CUBIC FEET OF GROUT TO BE THINNED.

Figure 17. Portland cement sealant thinning chart, EM 1110-2-3506 (after HQUSACE 1984)

187.   When sealant cannot be built up using the thickest mixes allowed or when it is desirable to prevent the sealant from spreading too far, delays may be used. They may last from a few minutes to several hours. The quantity of material injected per delay should be controlled to fulfill the intended purpose. If the delays are very long and thick material is being used, the hole and pump system should be flushed before each delay. The contractor's efforts should also be allowed to be directed elsewhere during the delay. If the delays are short and the contractor is required to stand by, provisions should be made in the contract for payment of standby time. Intermediate delays during a single injection period may be required to build up the sealant cone faster.

188.   Upon the completion of sealing a hole, any material left in the sump should be wasted. Sealant that is not injected within 2 hr after mixing should be wasted, or sooner if it shows evidence of stiffening.

189.   Split-spaced sealant holes may be mandatory, according to the contract specifications, or may be required due to sealant intakes. Split-spaced holes should normally be required on both sides of a hole that takes more sealant than the established minimum for the job. Holes that are prematurely plugged should be replaced with new holes. The process of split-spacing should continue as long as there is significant reduction of intake with each new series of split-spaced holes, or until intakes are not considered to be significant for the particular project.

190.   Drilling and sealing should not be permitted in the same section concurrently. After sealing a specified series of holes is completed and the sealant set time has elapsed, the next series of holes may be drilled in the section as required.

191.   In extremely hot weather, sealant and sealing materials should be protected from direct sunlight. It is desirable to maintain the sealant at temperatures below 90° F. The higher temperatures accelerate the setting time of the sealant, and this decreases the working time.

192.   Surveillance of the area should be made frequently during sealing to check for surface leaks and to collect monitoring data from other holes. Records should be kept of any evidence of leaks, such as discoloration of the water adjacent to the structure. If the leaks are serious, the accelerator may be modified in the mixture. Sketches of longitudinal sections should be

kept up-to-date with drilling, testing, and sealing data. Records should be made of monitoring data to evaluate the ongoing sealing program and for future reference. Sealing effectiveness must be continuously evaluated during the program. Evaluation should be a joint effort between engineering and construction personnel. If problems develop, reaction should be expeditious. Flexibility must be maintained for making changes and improvements as the program progresses.

193. It is worth recalling the observation of Lazarus White (Glossop 1961) on the danger of sealing without proper control: "...On excavating... very little of it will be found. No one knows where it went; all that one knows is that one has paid for it...."

PART VII: FIELD EXPERIENCES

194. The most recent Corps of Engineers experience in sealing voids in permeable jetties and groins occurred when the US Army Engineer District, Jacksonville, sealed the south jetty at Palm Beach Harbor, FL, in 1984, and the US Army Engineer District, San Francisco, sealed the Buhne Point groins at Humboldt Bay, CA, in 1985. Subsequent to that time, Broward County, FL, has sealed the south jetty to Port Everglades Harbor, FL, in 1988, and the US Army Engineer District, Detroit, has completed grouting and rehabilitating the north detached breakwater at Milwaukee Harbor, WI, in 1988. Asphaltic compounds were previously used successfully in Ashbury Park, NJ, in 1963, and a breakwater in the Dominican Republic was recently stabilized in 1983 using an asphaltic concrete. Portions of the north and middle jetties at Mission Bay, CA, were sealed with a cement-sand mixture in 1959 by the US Army Engineer District, Los Angeles. These projects are summarized as a means of sharing on-the-job experiences in an area in which little design guidance exists outside these specific Corps districts.

Palm Beach Harbor, Florida, South Jetty Sealing

195. A major concern regarding the Palm Beach Harbor jetties in 1984 was the passage of sand through the south jetty and into the navigation channel. Since 1978, a shoal had built up each year on the channel side of the south jetty. The shoal was relatively small in quantity (only 25,000 cu yd), but was very restrictive to the deep-draft vessels using the harbor. Usually each year, the channel shoaled to a depth of about -30 ft mean low water (mlw), which is 5 ft less than the authorized depth of -35 ft mlw. This development forced some shippers to light-load vessels, thereby significantly increasing their costs. The volume of dredging was relatively small, but a high unit cost resulted because a dredge was required to be mobilized to remove the shoal each year (US Army Engineer District, Jacksonville 1984).

196. The recommended plan was to seal the south jetty from station (sta) location sta 57+50 to sta 49+50 (Figure 18) to form a barrier impervious
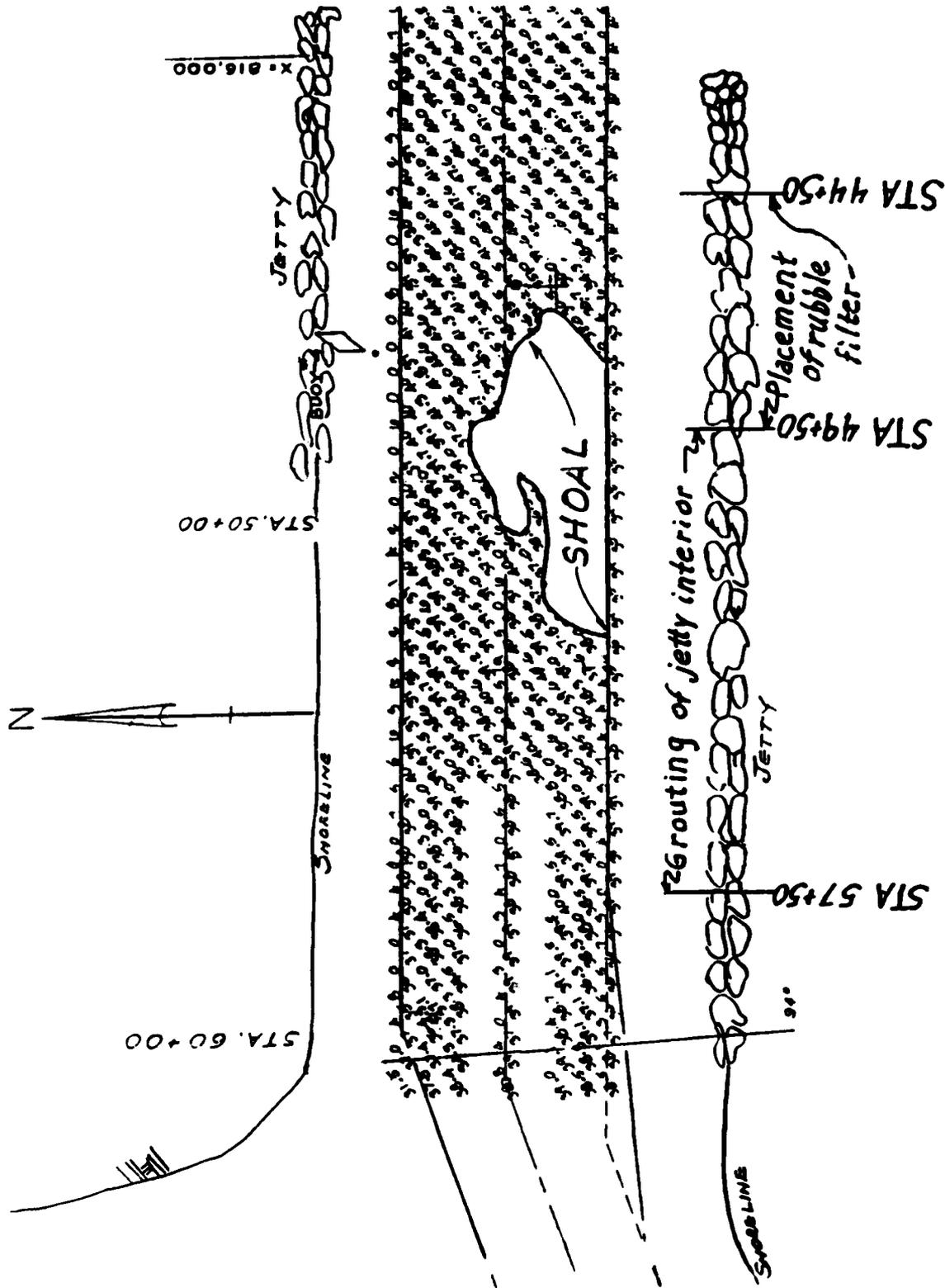
Figure 18. Palm Beach Harbor, FL, south jetty sealing project location (after US Army Engineer District, Jacksonville 1984)

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to sand movement from about el -6 to -10 ft mlw* up to el 0 ft mlw, then construct a rubble filter which would be protected with armor stone on the seaward side of the south jetty from sta 49+50 to sta 44+50.

197. The original plan identified two types of silicate sealant to be injected through the crest of the jetty by way of 2.5-in.-diam casings placed in bored holes spaced no further than 3 ft apart. Type 1 was a mixture of sodium silicate and sodium aluminate. Type 2 was a mixture of sodium silicate, sodium aluminate, water, and cement. The sealants would be mixed with or injected into the sand, depending on the specific circumstances at a localized portion of the structure. The method of operation would be to bore through the center of the structure to design depths to allow the placing of a 2.5-in.-diam casing. To ensure the formation of a barrier of sealant, the holes would be bored a maximum of 3 ft apart. The sealant would be pumped into the structure by one of two methods:

<u>a</u>. A 1-in.-diam pipe would be placed in the casing. Then, as a sand-water solution was pumped in to fill all voids prior to injection of the silicate, the casing would be pulled out. The silicate sealant would then be injected into the jetty via the 1-in.-diam pipe.

<u>b</u>. Existing sand would be washed from the jetty by water pumped through the casing. If the Type 1 sealant option was used, a water-sand mixture would be pumped into the jetty where it would be mixed with the silicate sealant. As the jetty filled, the casing would be removed. If the Type 2 sealant option was used, the silicate sealant and water-cement mixture would be pumped into the jetty, and the casing would be removed as the jetty filled.

198. Since the jetty landward of sta 53+50 was mostly filled with sand, Method "a" would be applied for sealing this reach of the structure. Seaward of sta 53+50, Method "b" would be applied. The estimated chemical sealant quantities reflected a 6-ft-wide barrier curtain of sealant extending from about 0 ft mlw to depths of about -10 ft mlw. Only a relatively narrow barrier needed to be provided to seal the structure to sand movement. To ensure that a continuous barrier would be formed, holes were to be drilled every 3 ft along the center line of that portion of the jetty to be sealed.

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* All elevations (el) cited herein are in feet referred to National Geodetic Vertical Datum (NGVD) of 1929.

199. During the plans and specifications phase of the project, the hole spacing was changed to 5 ft. Sand in the interior of the jetty to depths as great as -10 ft mlw would be chemically grouted with a mixture of sodium silicate, reactants, and accelerators. The void areas of the jetty would be filled with a sealant consisting of cement, sand, water, bentonite, and calcium chloride. The top elevation of the sealed section was changed to the level of the bottom of the concrete cap on the jetty crest.

200. The specified sequence was to seal all voids encountered with the cement-sand sealant. After drilling a hole, an injection pipe was to be inserted into the lower limits of the voids, and the cement-sand mixture would be injected in 1-ft increments as the pipe was withdrawn. The estimated amount of sealant, in order to achieve a 6-ft-wide barrier, was 18 cu ft for each 1-ft increment of height.

201. After the cement-sand mixture had stabilized, chemical sealing of the sands occupying the interior voids would be performed. Holes would be drilled through the cement-sand sealant until sand was encountered below the bottom design elevation of the jetty. An injection pipe would be lowered to the specified bottom limits of the hole, and an estimated 12 cu ft of chemical sealant would be injected for each 1-ft increment of height. The last step was to backfill the drill holes with a cement-sand sealant to the crest.

202. In the field, various sealant compositions were tried. After pumping 18 cu ft of mixture in three holes, the specified cement-sand mixture was judged to have dispersed completely, based on the plume appearance. Viscosity of the mixture was increased by adding bentonite. After 2,044 cu ft of this mixture had been pumped, it appeared that roughly 10-percent effectiveness was being achieved. The sealant that proved most effective was suggested by the contractor, which emphasizes the value of a contractor who is conscientious and experienced in mixing and injecting sealants. The suggested mixture of only cement and silicate was successfully tried in three holes, and a contract modification was issued. Figure 19 is a photo of the work under way.

203. During the sealing work, it was found that a better buildup of sealant could be attained by staging the filling in an alternate-hole sequence. Care was taken so that no mixture extruded from the exterior stones, which would change the hydraulic and wave dissipating performance of the jetty. After the sealing was completed in August 1985, samples were

Figure 19. Drilling sealant holes in
Palm Beach Harbor, FL, south jetty

extracted from exploratory holes and they showed the intent of the design had been achieved. Hydrographic surveys of the inlet taken since the completion of the project indicate that objectives of the concept are being realized.

Buhne Point, California, Groin Sealing

204. As a part of the Buhne Point Shoreline Erosion Demonstration Project, Phase III, two rock groins were constructed. One was shore-connected and the other was an extension of a groin previously constructed under an earlier phase. Each newly constructed groin exhibited the problem of permeability to sand transport, and a design for injection of concrete was developed (US Army Engineer District, San Francisco 1985).

205. The design called for drilling 4-in.-diam holes, terminating at 1 ft into the bedding material on which the jetty was constructed. Drilling was accomplished with Schramm Rotary and Chicago Pneumatic Air Track drills. Approximately 90 percent of the holes were drilled with the Schramm Rotary, but because of mechanical difficulties, approximately 30 percent of the holes were drilled with 6-in.-diam widths. The air track drilled all 4-in.-diam

holes. A total of 6,332 ft of drilling was required.

206. All drilling was done on the jetty center lines and was accomplished in several phases. Figure 20 shows the location of the work. The first phase required drilling holes on 10-ft centers, the second phase on 5-ft centers, and the last phase on 2.5-ft centers. The groin extension was drilled on 5-ft centers as a part of phase one.

207. Sealing was accomplished with a double piston positive displacement pump and a 4-in.-diam line attached to a 3-in.-diam rubber hose which was connected to a 3-in.-outside-diam tremie pipe. The pump and concrete delivery truck were placed on the jetties close to the holes to be filled. The rigid pipe specified in the contract provided assurance that the mixture completely filled the drilled hole and that it could be applied with a small pressure. Since the drilled holes were up to 14.5 ft deep, it was found that the rigid pipe and attached flexible tube became unmanageable as the pipe was withdrawn during filling near the top of the hole. Hence, the tremie pipe was shortened to about 3 ft, and this worked well when it was lowered to the bottom of the 14.5-ft holes by thrusting the pipe and flexible hose down the drilled holes.

208. The mixture required modification since the specified mixture could not be pumped. The mixture was redesigned as shown below, based on the number of pounds of constituents required to develop 1 cu yd of sealant. A photograph of the sealant operation is shown in Figure 21.

Buhne Point, California, Cementitious Sealant

Component	Specified lb	Modified lb
Coarse Aggregate	1,000	1,115
Fine Aggregate	1,450	1,655
Cement	705	705
Clay	305	37
Water	500	371
Calcium Chloride	15	15
Air	--	0.41

209. The modified mixture had a 5-in. (estimated) slump, which was increased under certain circumstances. The estimated "intake" of sealant in the holes drilled on 10-ft centers in the shore-centered breakwater was 7 cu yd
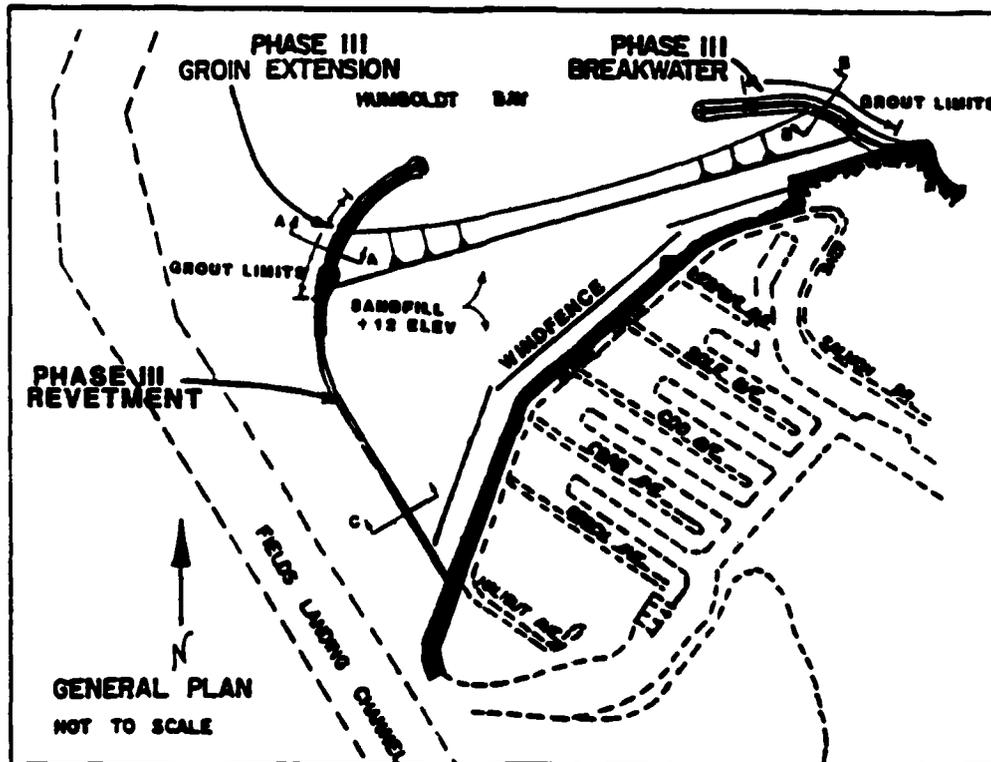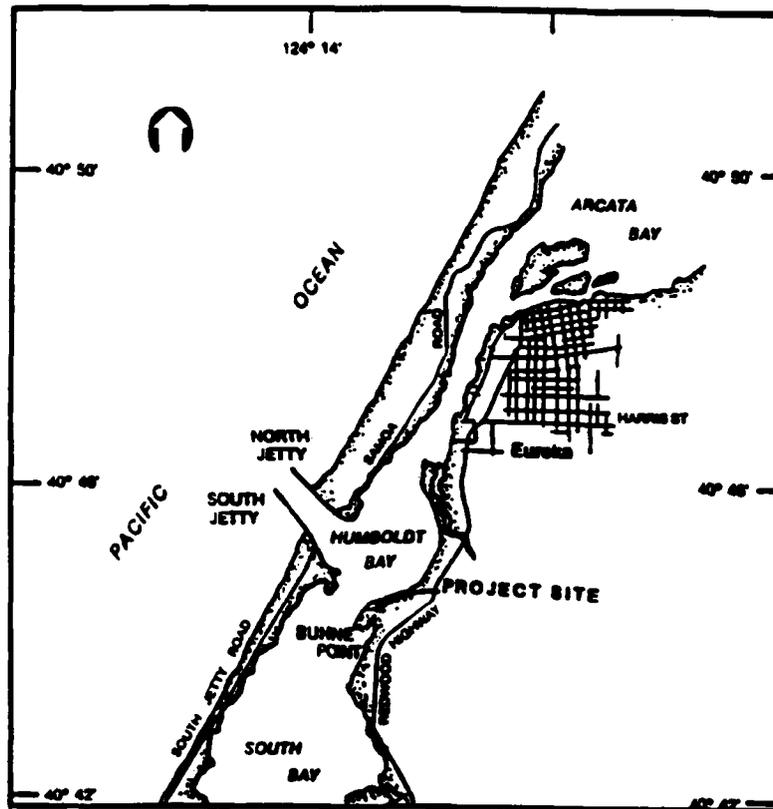
Figure 20. Buhne Point, CA, groin sealing
project location (after US Army Engineer
District, San Francisco 1985)
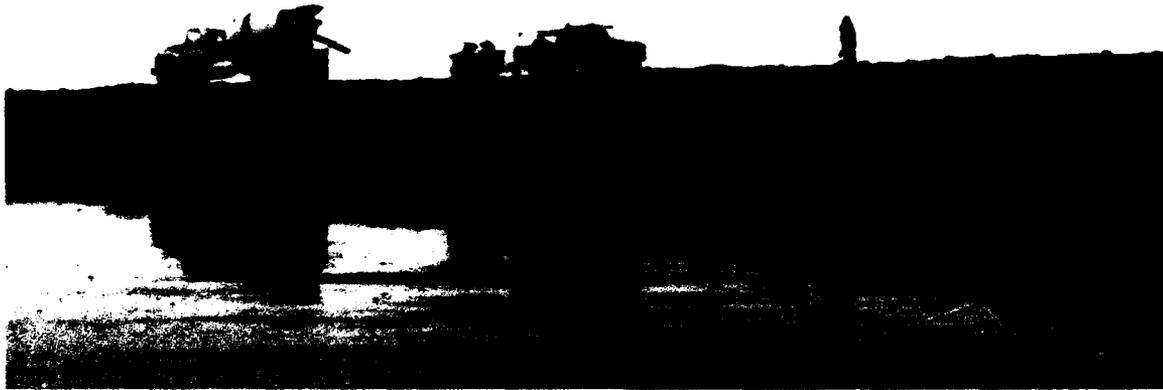
Figure 21. Sealing a groin at Buhne Point, Humboldt Harbor, CA

per hole, on the average (holes were 14.5 ft deep). Examination revealed that
additional injection was required, and a second set of holes was drilled and
filled with an average sealant intake of about 5 cu yd per hole. Another ex-
amination during high tide and 4-ft seas revealed leaks at elevations
+6 ft mlw and above. An additional set of holes was drilled and injected.
The sealant intake on the last set of holes was about 1 cu yd per hole. A
total of 256 holes were drilled between sta 0+40 and sta 7+00, with a spacing
of 2.5 ft.

211. The existing groin is composed of rubble core construction and all
injection holes were drilled 1 ft into the core, or to a hole depth of 7 ft,
and spaced 5 ft apart. After injection with sealant, holes were drilled mid-
way between these primary holes. The sealant intake was similar, being about
1 cu yd per hole on the average for both the holes on 5-ft centers and those
on 2.5-ft centers.

211. The groin extension was drilled and sealed in two phases. The
first phase involved drilling on 5-ft centers and injecting the sealant. The
intake was about 2.5 cu yd per hole. The second phase required drilling on

2.5-ft centers and injecting the sealant. The intake for this phase was about 1 cu yd per hole.

212. After completion of the work, inspection revealed 25 to 30 possible leaks in the total of 1,200 ft of sealed jetty. None are known to exist below el +5 ft mlw, or to cause a problem of sand transport in significant quantities.

213. Recommendations of field personnel associated with the sealing work include the following:

a. Better knowledge is required about mixture performance in prototype field applications.

b. Drill holes should be at least 6 in. in diam to facilitate injection operations and visual inspection.

c. Sand placement adjacent to the jetty should be delayed until all sealing is completed thereby making back-washing of holes easier.

d. Consideration should be given to sealing the jetty surface on the lee side with a material stiff enough to close the voids, thereby making the coverage of the sealant material easier to evaluate.

Port Everglades, Florida, South Jetty Sealing

214. Port Everglades Harbor is a Federal navigation project in Broward County on the southeast coast of Florida. It is located about 23 miles north of Miami Harbor, and about 48 miles south of Palm Beach Harbor (Figure 22). The existing project provides a channel 40 ft deep and 500 ft wide across the ocean bar. The channel tapers to 300 ft wide and 37 ft deep between the rubble-mound entrance jetties. Rehabilitation plans by the State of Florida and Broward County at the Port Everglades south jetty consist of sealing the jetty with sodium silicate-cement sealant and placing beach fill on the south beach.

Description of problem area

215. The Port Everglades south jetty is a 1,000-ft-long rubble-mound structure approximately 30 ft wide at the base and 11 ft wide at the crest (Figure 23). There is a 5-ft-wide paved asphalt fishing walkway on the top of the structure. The net sediment transport in the area is estimated to be 50,000 cu yd per year to the south, with the gross sediment transport rate
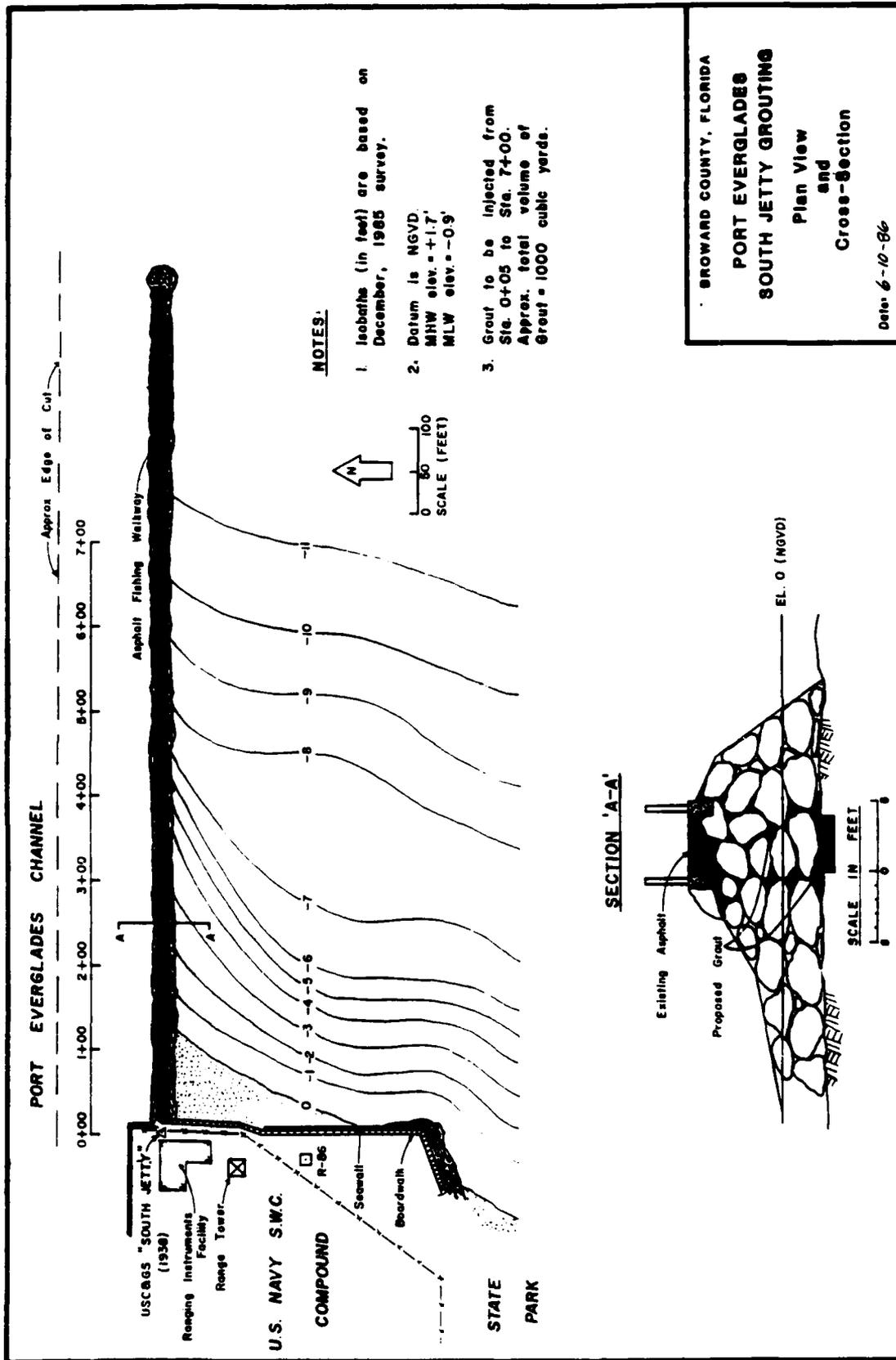
Figure 22. Port Everglades, FL, south jetty sealing project location (after Broward County Environmental Quality Control Board 1986)
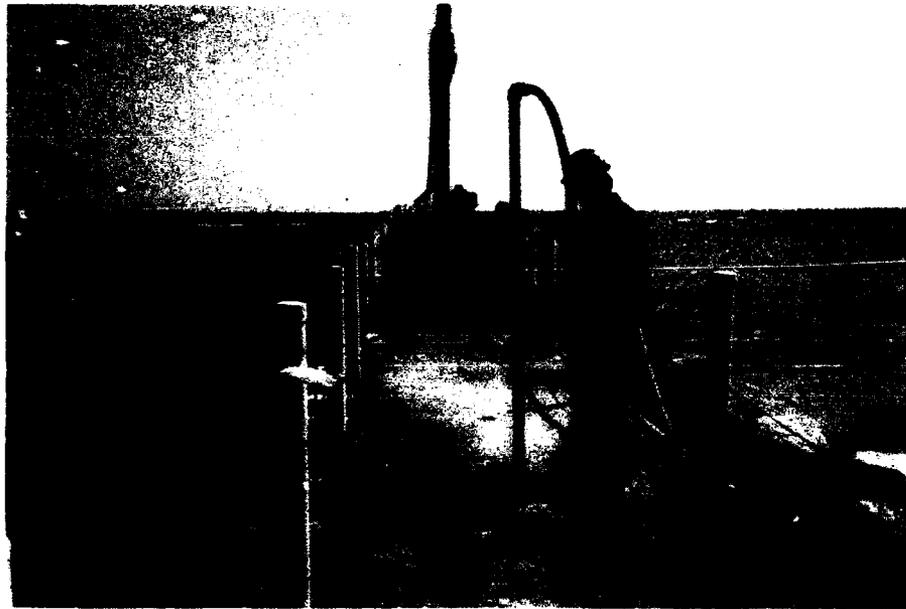
Figure 23. Sealing south jetty at Port Everglades, FL

between 20 and 40 times the net rate (Broward County Environmental Quality Control Board 1986). The high erosion rate of the natural and artificial beach placed south of the structure in 1977 and the lack of a large fillet immediately south of the structure indicated to Broward County that the structure was permeable, thus allowing northerly moving littoral material to pass through the structure and into the navigation channel. A dye study conducted by Broward County confirmed that the structure was very porous, and it was estimated that at least 5,000 cu yd per year of sediment passed through the structure, primarily on ebb tides. Nourishment of the 1.5 miles of beach south of the south jetty was planned to restore the beach, and the proposed sealing of the shoreward 700 ft of the south jetty was determined to be a cost-effective alternative to losing sediment through the structure.

WES field monitoring activities

216. The development of the jetty sealing rehabilitation of the Port Everglades south jetty provided an opportunity for WES to extensively monitor the effectiveness of the sealing procedures and obtain results and conclusions for incorporation into the ongoing WES REMR research program. The purposes of

the monitoring plan are to qualitatively and quantitatively evaluate before-
and after-sealing conditions of the structure regarding amount of sediment
passing through the structure and current flow velocities through the struc-
ture. Three phases of the monitoring plan were formulated: (a) reconnaissance
survey, (b) presealing monitoring, and (c) postsealing monitoring. The recon-
naissance survey and the presealing monitoring have been conducted, and the
presealing monitoring data have been analyzed. The postsealing monitoring has
been performed but those data have not been analyzed at this time.

217. **Reconnaissance survey.** The purpose of the reconnaissance survey
was to collect information about the south jetty infrastructure, current flow
patterns, and surrounding beach bathymetry so that later phases of the moni-
toring activities could be best designed. In particular, the following infor-
mation was collected: (a) locations, dimensions, and photographs of structure
voids for future mounting of current meters and sediment traps, (b) character-
istics and photographs of the seabed north and south of the jetty, (c) flow
currents through the structure during peak flood and ebb flows, and (d) photo-
graphs and details of dye dispersion through the structure during peak flood
and ebb flows.

218. **Structure voids.** On 27 June 1988, an inspection of the north and
south sides of the south jetty was conducted using snorkeling gear. Large
structure voids that extended far into the structure were measured, and voids
on the south side of the south jetty were identified for placement of current
meters and sediment traps during presealing and postsealing monitoring.
Photographs of all voids were taken with an underwater camera. Voids chosen
for placement of current meters and sediment traps extended deep into the
structure and were at least partially filled with water at all tide levels.
The voids were located approximately at the toe of the proposed beach fill,
the crest of the proposed beach fill, and near the existing storm breaker
line.

219. **Dye dispersion through the structure.** Three dye dispersal tests
were conducted during two peak flood flows and an ebb flow. Sand sample bags
weighted with rocks and filled with approximately one-third cup of powdered
fluorescein dye proved to provide the continuous dye source necessary for dye
visibility and longevity. The dye was placed as close to the center of the
structure as possible, and the dispersion of dye with time was mapped. Waves

approximately 2 ft high were breaking at an angle of around 45 deg to the shoreline. The test determined that a portion of the dye indeed passed through the structure and into the navigation channel.

220. **Sediment transport through the structure.** Several qualitative and quantitative measurements of sediment transport through the structure were made using a simple bottle suspended sediment sampler, a streamer trap nozzle, and a pan bedload sampler. Three suspended sediment samples were collected at the bed, middepth, and surface elevations using an 8-oz bottle on the south side of the south jetty on 27 June 1988. Weights of sediment in the bottom, middepth, and surface samples were 2, 1, and 0.5 g, respectively.

Jetty sealing design

221. The work necessary to make the south jetty impermeable to both wave and sediment transmission consisted of constructing a single-line barrier sealant curtain along the center line of the jetty from shore sta 0+00 to sea sta 7+00. Sealant holes will be drilled on 3-ft centers. Open voids will be sealed with sodium silicate-cement sealant, while sand-filled voids will be sealed with only a sodium silicate solution. The south jetty is composed of granite and limestone rock set upon sand and/or bedrock. It is topped by an asphaltic fishing walkway 10 to 12 ft wide, and 4 to 12 in. thick, with a crushed bedding layer which varies in thickness. Landward of sta 0+50 much of the space between the jetty stone will be sand-filled, but seaward there will be significant voids beneath the walkway. The jetty stone is irregular in size and shape, and drilling through it to reach the contract depth will be difficult. The sand in the jetty should be similar to the sand on the adjacent beach.

222. Standard drilling equipment will be used to perform the sealant hole drilling through the jetty stone and asphaltic fishing walkway. Equipment will be capable of accomplishing the drilling at a rate which will not result in delays to the work. The bit diameter will be such that drill cuttings can be effectively flushed from the boring during drilling operations. The minimum drill hole diameter shall be 3.5 in. Sealant holes shall be drilled as nearly vertical as possible to the following depths: (a) from sta 0+00 to sta 2+00, the sealant holes will be drilled to el -3 ft mean lower low water (mllw) (approximately 12-ft-deep holes), (b) from sta 2+00 to sta 3+50, the sealant holes will be drilled to el -6 ft mllw (appro::imately

13-ft-deep holes), (c) from sta 3+50 to sta 5+50, the sealant holes will be drilled to el -8 ft mllw (approximately 14-ft-deep holes), and (d) from sta 5+50 to sta 7+00, the sealant holes will be drilled to el -10 ft mllw (approximately 17-ft-deep holes).

223. Voids between the asphaltic fishing walkway and the natural sand elevation below the cap shall be filled with a sodium silicate-cement sealant. The composition of the sealant shall be varied as necessary to accomplish the filling of the voids with the highest strength sealant possible. The possibility of the pumping action of ocean waves washing out the sealant as it is placed requires the contractor to vary the sealant mix as required to accelerate the set time of the sealant so that the sealant is not washed away, yet still has the flowability characteristics to allow it to flow under its own weight (gravity) to spread from the point of injection and fill the voids. To accomplish these objectives, thoroughly mix and pump:

    a. Part I: 3 gal sodium silicate + 4.5 gal water.

    b. Part II: 0.3 cu ft water + 0.1 cu ft cement.

224. The sodium silicate-cement sealant shall be injected through a pipe placed at the bottom of the void zone in the jetty stone. The pipe shall be raised 1 ft at a time as the sealant is injected. The rate should be approximately 6 cu ft of sealant placed for each 1-ft rise in the pipe.

225. Due to the quick set of the sodium silicate-cement sealant being utilized and the flowability characteristics of the sealant, it is impractical to continuously mix and pump sealant into the drilled hole until refusal. The contractor shall estimate the quantity of sealant needed to construct a sealed zone approximately 4 ft wide under the asphalt cap. He will then mix and inject the estimated quantity of sealant into the drilled holes. If an injection of 6 cu ft of sealant per 1 ft of vertical drill hole fails to completely fill the voids, the contract administrator may direct additional injections of sealant. If the drill hole takes less than the estimated quantity of sealant mixed, the excess sealant will be placed into any available partially filled holes previously sealed or used to fill surface voids in the exposed jetty stone.

226. The sand-filled voids in the jetty stone shall be sealed with a sodium silicate chemical sealant after the sodium silicate-cement sealant has been placed. The chemical sealant shall be 40 percent sodium silicate used in

conjunction with the appropriate reactants and accelerators to provide an initial set within approximately 30 min after mixing. The chemical sealant will be injected into the sand using a contractor-designed injection system which will distribute the chemical sealant evenly over the vertical reach of the sanded portion of the drill hole, achieving the desired zone of influence. The chemical sealant will not be injected at a rate or pressure greater than the natural permeability of the sand.

227. The contractor will be required to perform such exploratory drilling as may be required to determine the effectiveness of the sealing operations after sealing has been completed. All exploratory drilling shall be performed with rotary drilling equipment using coring type bits. Because the maximum recovery of unpredictable soft or friable materials is of such prime importance, the contractor shall use a standard ball bearing, swivel type, double- or triple-tube core barrel with split inner tube and standard core lifter.

Milwaukee Harbor, Wisconsin, North Detached Breakwater Sealing

228. The US Army Engineer District, Detroit, rehabilitated the north detached breakwater at Milwaukee, WI (Figure 24), by sealing one aspect of the structure with sodium silicate-cement sealant and sealing another aspect with only cementitious sealant (US Army Engineer District, Detroit 1984). The purpose of the rehabilitation sealing was to reestablish structural stability and not precisely for the elimination of penetrating waves or sediment. The sodium silicate-cement sealing aspect consisted of creating two vertical barrier curtains along each side of the breakwater (parallel to the center line of the structure) to serve as forming material for retaining the cementitious sealant aspect. This structure was built during the period 1882-1893 and consists of wooden timber cribs filled with rubble-mound stone. At some later date concrete caps were placed on top of the cribs.

229. Loss of stone out of the cribs as a result of deterioration of the wooden timbers has caused voids up to 4 ft in diam to develop within the cribs, and settlement and displacement of the concrete caps have resulted. To stop the loss of stone and to restore the functional stability of the structure, 3,800 ft of the north detached breakwater which is 27 ft wide has been

Figure 24. Milwaukee Harbor, WI, north detached breakwater sealing location (after US Army Engineer District, Detroit 1984)

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successfully sealed. The first aspect consisted of utilizing quick-set sodium silicate-cement sealant placed along both edges of the breakwater. The quick-set sealant was placed through holes drilled on 4-ft centers. Set time for this sealant was approximately 15 sec. The second aspect was accomplished after the quick-set sealant had hardened and consisted of placing a low-slump, heavily sanded cementitious sealant through holes drilled on 8-ft centers to fill the interior of the cribs between the quick-set sodium silicate-cement sealant walls (Figure 25). To ascertain the viability and practicality of sealing this structure, three different sections of the breakwater were evaluated successively: (a) a prototype test section, (b) a contractor capability demonstration section, and (c) production sealing of the remaining structure section.

Figure 25. Drilling for rehabilitation sealing
of Milwaukee, WI, north detached breakwater

Sealant designs

230. **Sodium silicate-cement quick-set sealant.** Along the two barrier curtain locations, the sodium silicate-cement quick-set sealant was placed from the bottom of the concrete cap to the top of the stone in the cribs, to act as a form to prevent the flow of required cementitious sealant outside of the cribs. The quick-set sealant consisted of liquid sodium silicate, portland cement, water, and fly ash. The base material for the structural quick-set sealant was liquid sodium silicate, Grade 40, which conformed to ASTM specifications described in the Handbook for Concrete and Cement (WES 1949), Method CRD-D 3400. Portland cement conformed to ASTM Type I specifications in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 150. Fly ash comprised a minimum of 15 percent and a maximum of 40 percent of the total cementitious (cement and fly ash) content by weight in the quick-set sealant mix. The sealant was considered to have set when it had attained a compressive strength of 200 psi as determined by ASTM specifications in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 403, and should have attained a minimum compressive strength of 1,500 psi after 28 days. A minimum of three distinct design mixes were required to be submitted by the contractor for set times of 10, 15, and 20 sec, respectively. These designs were tested and submitted to the contracting officer to allow the contractor to change from one design mix to another as site conditions required to completely fill the voids within the limits desired.

231. **Cementitious sealant.** The cementitious sealant was placed from the top of the crib stone fill to the bottom of the concrete cap, thus filling all remaining voids in the cribs between the quick-set sealant walls. This sealant was composed of portland cement, fine aggregates, fly ash, and water. The fly ash could vary from a minimum of 10 percent to a maximum of 30 percent of the total cementitious (cement and fly ash) material, by weight, in the cement sealant mix. Fine aggregates conformed to the requirements of ASTM specifications in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 33. The cementitious sealant was required to have a minimum compressive strength of 3,000 psi after 28 days.

Sealant injection procedures

232. **Sodium silicate-cement quick-set sealant.** Holes for the quick-set sealing could be drilled by either rotary or percussion drills. The holes

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were drilled in a split-space manner, in which the structure was drilled and sealed at 8-ft intervals and then drilled and sealed at the intermediate 8-ft intervals. All drill holes had a diameter of 8 in. The onsite spacing could be modified due to site conditions, tierods, wood timbers, cross ties, monolith joints, and other undrillable obstructions. The sodium silicate-cement sealant was injected into the voids in and above the stone fill at a rate of placement such that the material was extruded in a slow, pastelike flow. The maximum flow rate per nozzle was 40 gal per min, and could be varied based on site conditions to ensure the complete filling of the voids. A two-stream method was utilized with the cement, fly ash, and water slurry being agitated in a separate vessel from the sodium silicate solution. When the materials from both vessels were thoroughly agitated, they were then blended using the two-stream procedure. Injection was initiated at zero pressure (gravity), then pressure was increased gradually until all voids between the concrete cap and the stone fill were filled. Injection continued until the contractor could not inject 1 cu ft of sealant in 10 min. The contractor could also inject no more than two times the estimated volume. If this limit was achieved, sealing was stopped in that hole for a minimum of 1 hr, and then resumed with no more than one additional estimated volume of sealant being injected. This limitation of injecting no more than a total of three times the estimated volume always applied.

233. <u>Cementitious sealant.</u> Holes 3 in. in diam were drilled through the concrete cap to the top of the stone fill for applying the cementitious sealant. Upon reaching final depth, the drilling apparatus was withdrawn from the drill hole, and straight casing was inserted to the bottom. Hole locations could be shifted as much as 6 in. to avoid encountering structure members other than rubble-mound stone. The cementitious sealant was injected into the voids in and above the stone fill under pressure through an open-end pipe. The maximum flow rate per nozzle was 50 gal per min, but was variable based on the site conditions to ensure complete filling of the voids with the cementitious sealant material. Inspection holes were drilled along the lines of sealant holes midway between the sealant holes for alternate holes. Each inspection hole was used to monitor the flow of cementitious sealant injected into the two adjacent drill holes.

Prototype test section

234.   The initial contract associated with rehabilitating the north de-
tached breakwater consisted of sealing 742 lin ft of the structure with both
sodium silicate-cement sealant and cementitious sealant as a prototype field
test to determine whether sealing of the structure was a viable alternative
for rehabilitation.   Regarding the sodium silicate-cement quick-set sealant,
the information obtained indicated the requirements for a variable mix de-
sign, for the ability to change the sequencing and pumping rate, and for cas-
ings which are snug within the holes.   It was also determined to be desirable
to have a sealant that sets quickly, stays where it is placed, is thoroughly
mixed, and can be extruded in a pastelike consistency.   Regarding the cementi-
tious sealant, it was concluded that there is a requirement for a variable mix
design, for the ability to change the sealant sequencing and injection rate,
for packers or casings which are snug within the holes, and for a thick
sealant that stays where it is placed, is thoroughly mixed, and can be
injected into the stone fill under pressure.   It was determined from these
tests that sealing is a viable alternative for rehabilitating this structure.
Conclusions and knowledge gained from the prototype field test were incorpor-
ated into subsequent contract features pertaining to completion of sealing of
the north detached breakwater at Milwaukee, WI.

Contractor capability demonstration

235.   Prior to the beginning of production drilling and sealing of the
entire structure length, the successful contract bidder was required to con-
duct an in-place demonstration to the satisfaction of the contracting officer
of sealing methods in a 100-ft section from sta 44+50 to sta 45+50.   Regarding
the sodium silicate-cement quick-set sealant, the capability demonstration
consisted of drilling the holes as shown on the plans; quick-set sealing using
the equipment, mix designs, and methods proposed; coring; and furnishing field
core logs and records to the contracting officer within 5 calendar days after
coring.   The demonstration was considered successfully completed when the
voids between the concrete cap and the top of the stone fill were completely
filled within the limits shown on the contract drawings.   Regarding the cemen-
titious sealant, the capability demonstration consisted of drilling the holes
as shown on the plans; cement-sealing using the equipment, mix designs, and
methods proposed; coring; and furnishing field core logs and records to the

contracting officer within 1 calendar day after coring. The demonstration was considered successfully completed when the voids between the concrete cap and the top of the stone fill, between the quick-set sealant walls, were completely filled.

Production sealing of the breakwater

236. Based on successful demonstration of the contractor's capability to drill and seal a 100-ft section of the north detached breakwater, a contract was awarded for production sealing 3,788 lin ft of this structure with both sodium silicate-cement and cementitious sealants. This contract was successfully completed during the summer of 1988.

Mission Bay, California, Jetty Sealing

237. Mission Bay lies on the coast of southern California, adjacent to the San Diego River at its mouth. A common jetty separates river discharges from tidal flows of the bay. The project has a second jetty which forms the north jetty of the bay, as well as a third jetty comprising the south jetty of the river (Figure 26). Shoaling of the Mission Bay channel was attributed to sand passing through both the north jetty and the middle jetty (Herron 1972).

238. A cement-sand material with admixtures was chosen to seal the Mission Bay jetties, with pressure injection through holes drilled through the jetty crests. This was accomplished in 1959, and sealants were tested specifically for this job to evaluate their ability to resist erosion and dilution by flowing water. Portions of a report by Loudon (1959) containing test results are reproduced as:

> ...The following admixtures were tested as stabilizing agents for beach sand-cement sealant:
>
>> Airox pozzolan (processed volcanic tuff)
>> Alfesil (fly ash)
>> Zeogel (barite clay)
>> Aquagel (bentonite)
>> Rotary drilling clay P-95 (Macco Corporation)
>> Natural sandy loam and cement
>
> The only tests made were comparative in nature. Sealant specimens were molded in a conic frustum 1-1/2 in. across the top, 3-1/2 in. across the bottom, and 3 in. high. The specimens were anchored to a steel plate with three small prongs and placed in a hydraulic flume running 12 in. deep at a velocity of 4.5 ft per sec. Time of immersion and loss of material were as follows:
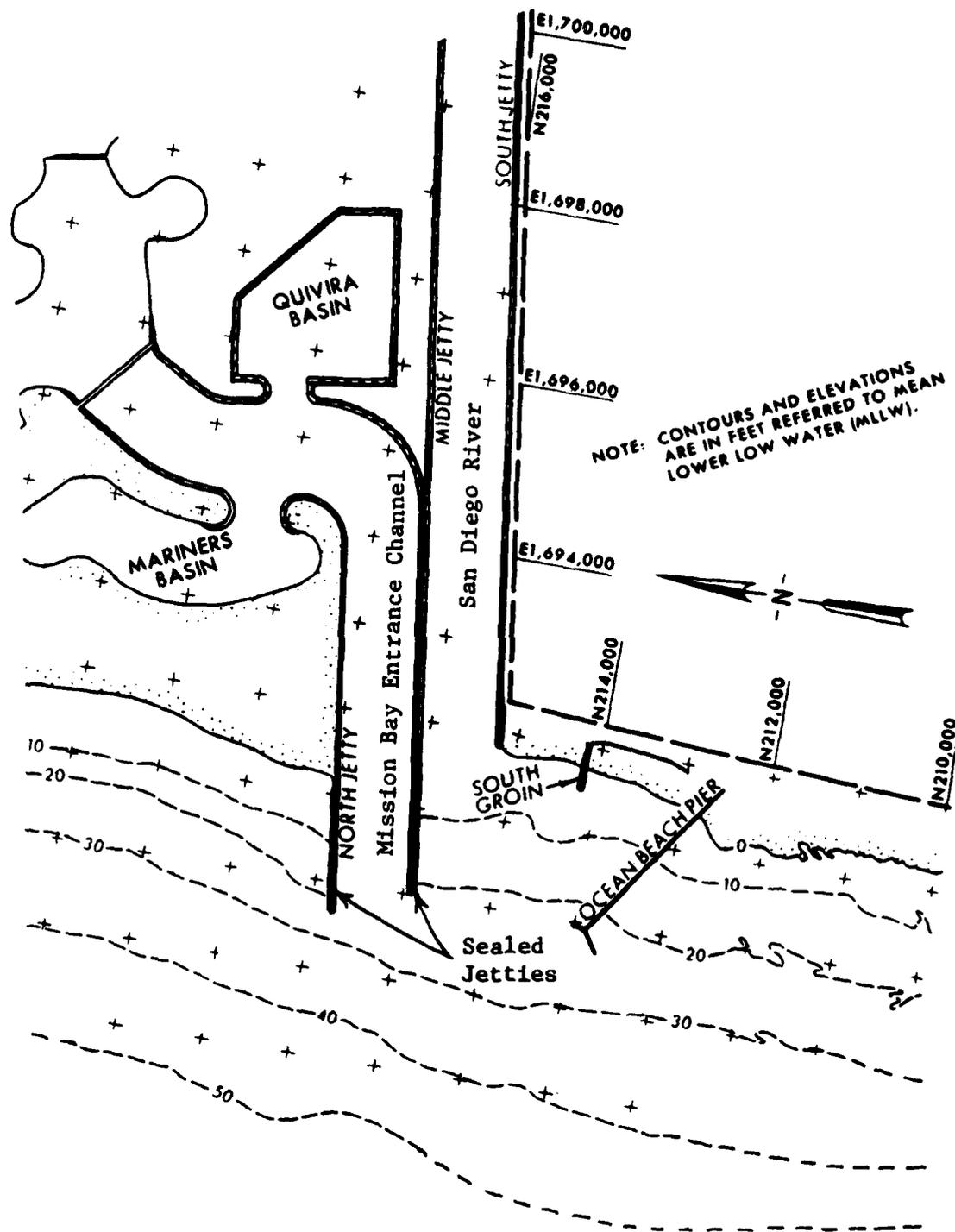
Figure 26. Mission Bay, CA, jetty sealing
project location (after Herron 1972)

Test No.	Mixture	Immersion time	Loss (%)
1	0.95 lb beach sand 0.47 lb cement 0.10 lb airox pozzolan 0.52 lb water	52 sec	100
2	0.95 lb beach sand 0.30 lb cement 0.20 lb airox pozzolan 0.35 lb water	1 min	75
3	1.00 lb beach sand 0.30 lb cement 0.30 lb alfesil 0.22 lb water	1 min	92
4	1.00 lb sandy loam 0.22 lb cement 0.27 lb water	1 min	55
5	1.00 lb beach sand 0.30 lb cement 0.30 lb aquagel 0.51 lb water	1 min	1.8
6	1.00 lb beach sand 0.30 lb cement 0.30 lb P-95 rotary clay 0.31 lb water	1 min	1.7
7	1.00 lb beach sand 0.30 lb cement 0.30 lb zeogel 0.59 lb water	1 min	14.5
8	1.00 lb beach sand 0.30 lb cement 0.30 lb P-95 rotary clay 0.31 lb water	24 min	78.8

The results of tests 1-8 indicate that only the aquage, rotary clay, and zeogel contributed materially toward making the sealant cohesive and resistant to erosion during the presetting period. Sealant with the clays added exhibited characteristics similar to those of pure clay. These properties were attributed in part to the smallness of the beach sand particles because the small particles cause less interruption of the micellar bonding forces of the clay. Thus, the attraction between water films toughened by valence bond created a sealant of high plasticity... .

239. The P-95 drilling clay, said by the refiner to be the micaceous fraction of illite, mined at Muroc Dry Lake, CA, was selected as the stabilizing admixture to be used in the sealant. Proportions of the sealant mix are shown below which yield 1 cu yd.

Sand	2,000 lb
Cement	752 lb
Clay (4 sacks)	400 lb
Calcium chloride	16 lb
Water	64.3 gal

240. An experimental contract was awarded for sealing a short reach of the middle jetty in December 1958. The contract provided for placement of 400 cu yd of sealant in that portion of the jetty passing through the surf zone. A wagon drill was used to drill 2-in.-diam holes through the crest of the jetty spaced approximately 8 ft apart on the jetty center line. Sealant was injected through a 1-1/2-in.-diam hose at an average rate of 18 cu yd per working day.

241. In some voids which extended to the surface, it was possible to observe sealant as it became stiff and set up in interior openings as large as 1 ft or more across. Some exploratory holes were drilled between filled sealant holes. The voids were filled satisfactorily. Dye tests also showed the sealant barrier curtain was effective.

242. Final construction was accomplished in the spring of 1959. Sealant holes were roughly 6.5 ft apart and between 6 and 9 cu yd of sealant was injected into each hole. Final cost, including experimental contract, was $41 per lin ft (1959 dollars). Surveys made through November 1959 indicated the sand accumulations on the channel sides of the jetties had disappeared, suggesting the sealing job was successful. However, since that time, the structures have been battered by a series of intense winter storms which have resulted in extensive armor stone displacement, and probably internal core and sealant damage. Repair and rehabilitation have been performed by placing additional armor stone on the cover layer without regard for reinforcing the barrier curtain created by the sealing process. Recent observations of these structures indicate that most of the 1959 sealing material probably has disappeared, as longshore sediments are again passing through the north and middle jetties into the navigation channel. A photograph showing results of the sealing is shown in Figure 27.

243. Jetty sealing, using materials and techniques similar to those used at Buhne Point and Mission Bay, was also accomplished in California at Oceanside north and south jetties (Figure 28), San Luis Rey River jetties (Figure 29), groins in the vicinity of Newport Beach (Figure 30), Marina Del

Figure 27. Results of sealing Mission Bay, CA, north jetty

Figure 28. Results of sealing Oceanside, CA, south jetty

Figure 29. Results of sealing San Luis Rey River jetties, CA

Figure 30. Results of sealing groins at Newport Beach, CA

Rey jetties (Figure 31), and the Santa Cruz west breakwater (Figure 32). Of all these rehabilitated structures, only the Santa Cruz effort obtained slightly less than expected effectiveness, even though the overall performance has been satisfactory with only minimal passage of sediments through the breakwater. Insufficient sealant spread is believed to be the reason for the incomplete filling of the voids.

Port of Haina, Dominican Republic, Slope Sealing

244. Asphalt application to rubble slopes for the purpose of slope stabilization was successfully accomplished at the Port of Haina, Dominican Republic, in 1983 (Schmeltz, McCarthy, and Lopez 1984). Because of the lack of suitable stone and the requirement for quickly providing wave protection for dock structural elements, the selected method of armoring the slope was to apply a designed asphalt binder. A continuous asphalt coating was applied over the relatively lightweight rubble from the top of the slope down to a distance of 1.5 times the design wave height below the datum. Below that

Figure 31. Results of sealing middle jetty at Marina Del Rey, CA

Figure 32. Incomplete filling of voids by sealant,
Santa Cruz, CA, west breakwater

level, asphalt was applied by the "pattern sealing" method, achieving a
percent coverage. By placing patches of sealant in a predetermined pat-
tern, the armor stone was partially connected and formed "clusters." Through
"pattern sealing," the apparent weight of the armor stone, in computations of
resistance to wave forces, can be increased at least 5 times (van Garderen and
Mulders 1983). The purpose of the pattern sealing was to permit relief of
pore pressures in the rock fill. Penetration of the asphalt to a depth of
1 ft was judged to be adequate to bind the primary armor.

255. The slope was intended to withstand wave heights up to 8.5 ft.
Mixes used in this type of construction, although different from routine pave-
ment asphalt, could be manufactured in any asphalt plant that was in satisfac-
tory operating condition. A structure so produced could withstand wave
heights up to approximately 13 ft. Selection of the proper mix was an itera-
tive process, and the trial mix proportions are shown on the following page.

Trial	Asphalt, lb	Sand, lb	Filler, lb	Gravel, lb	Result
1	15	70	15	--	Too fluid; penetration too great (60-70%)
2	12	52	11	25	Too viscous; rock voids not filled enough
Final	12	58	15	15	Good flow and filling

246. Most of the material was placed at approximately 330° F (165° C), with lower or higher temperatures causing trouble in placement. The material was placed on the rock slope with a 4-cu-yd clamshell dragline bucket. When placed above water, the material was moved as needed by workmen with shovels and rakes. For below-water placement, the clamshell was opened near the water surface and material was dropped in mass to the rock surface. To obtain a good pattern, a system of locating the bucket must be established at each site.

Ashbury Park, New Jersey, Groin Sealing

247. Groins were rehabilitated with asphaltic sealant near the Ashbury Park Convention Hall, NJ, in the 1960's (Avakian 1969). The first to be rehabilitated was the Deal Lake groin in 1963. The outer 75-ft section was rebuilt by incorporating an asphaltic hot-mix and has been entirely successful in terms of its service record. The method of rehabilitation was to lay down a foundation of rock, advancing seaward from the existing groin tip. Next, a hot asphalt-aggregate mixture was delivered by insulated trucks to a crane-rigged core box. The filled core box was swung into position over the placed stone, and tripped. An approximately flat layer of hot mix was thus created for a length of about 20 ft and for the width of the groin. Next, 5-ton stones were specially placed on and in the asphalt. The next layer of asphalt was made to cover those stones on all sides, and the process was repeated until the design crest elevation had been achieved. In this way the asphalt replaced the core of the "typical" jetty section, and it acted as a binder to hold the structure together as a monolithic mass. Photographs of the construction are shown in Figures 33 and 34.

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Figure 33. Placing stone on layer of hot-mix
asphalt during groin rehabilitation at Ashbury
Park, NJ (photo courtesy of Leon S. Avakian)

Figure 34. Pouring hot-mix asphalt to seal voids and
bind stones during groin rehabilitation at Ashbury
Park, NJ (photo courtesy of Leon S. Avakian)

248. In the 24 years since this work was completed, there has been no repair work necessary. Today there appear to be two stones dislodged from the end of the Deal Lake groin. This is a noteworthy record of service and shows the possible benefits to be realized from using a properly designed and emplaced asphaltic mixture.

PART VIII: SUMMARY

249. Sealing coastal structures with gels and concretes shows promise of returning high economic benefits to the project. The technologies of sealant mixtures and of injection methods are at an advanced state, due primarily to impetus from the areas of mining, tunneling, foundation engineering, and dam construction. These technologies now need to be applied in the coastal environment to reduce permeability of rubble-mound structures for the purposes of controlling shoaling in areas that must be dredged and eliminating wave energy penetration through such structures in areas of importance where wave energy effects are significant. Potentially, many Corps of Engineers projects could benefit from this technology.

250. An attempt should be made to identify those coastal projects which are candidates for being economically improved by applying sealants in the voids of the structures. Structures permitting excessive wave transmission are easily identified by local citizens and property owners at the harbor and mooring areas through personal knowledge and first-hand observations of wave effects during storm events.

251. Investigating the need for sealing to diminish shoaling on the lee side of a structure must include confirmation that the path of shoal material is definitely through the structure and not around or over it. Additionally, the amount of reduction that could be affected by the injected barrier must be cost effective. Dye tests and fluorescent sand tracer tests can track the path of movement but are not quantitative tools. Analysis of hydrographic surveys may reveal volumetric and rate information, but cannot by itself confirm that all the shoal material passed through the pervious structure. Tidal and wave-generated currents may contribute to shoal formation, and they must be eliminated as significant sources of sediment-transporting energy before sealing can be stated definitely as being worthwhile.

252. Once need is established, planning of the sealing work must be based on knowledge of field conditions, mixture characteristics, and equipment capabilities. Having a good contractor is the most important aspect of a coastal rubble-mound breakwater or jetty sealing effort. Proper spacing of the sealant holes is probably the second most important aspect of a sealing project. Drill hole spacing determines the drilling costs and radius of the

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sealant volume at each hole. The spacing, in turn, is determined by the injectibility, set time, and cost of the mixture.

253. The contract types and provisions should promote quality of work, firstly, because of the assumption of risk by the Corps and timely completion of the project with appropriate economy, secondly. Service-type contracts should be considered for such sealing operations because only the best methods utilized will ensure the highest quality of work. Effectiveness sometimes cannot be ascertained until several years after the work is completed.

254. The importance of having an experienced contractor cannot be overemphasized. Having a good inspector is also exceedingly important. Field conditions may vary from hole to hole, and proportions of the mixture may have to be quickly adjusted accordingly. Staging and sequencing the injection may become necessary or may need revising in a fast response time. Experienced evaluation of the sealing as it is proceeding and revising operations accordingly are necessary to avoid waste and to achieve a continuously injected barrier sealant curtain.

255. Many aspects of coastal engineering projects rely heavily on experience. Applying sealing technology to rubble-mound structures in the coastal environment especially will require studying documentation of past sealing jobs, utilizing imaginative, flexible thinking, and maintaining attentive recordkeeping during each new construction or rehabilitation work.

256. A chemical sealant was used to seal the south jetties at West Palm Beach, FL, to the infiltration of sand. A concrete sealant was applied at Buhne Point, CA. The length of time is not yet sufficient to evaluate the long-term effectiveness of these sealing jobs, but initial results seem to appear promising. A cementitious sealant applied to the Mission Bay, CA, jetties has not endured for the long term because repetitive battering by intense winter storms resulted in extensive armor stone displacement and probable core and sealant damage which have not been rehabilitated. Asphaltic mixtures have practically been ignored as a sealing material by US coastal engineers. A limited number of documents show, however, that an asphalt-aggregate mixture has desirable properties for such applications.

257. Reasonable caution should guide the preparation, repair, and cleanup phases of repair activities involving potentially hazardous and toxic chemical substances. Manufacturers' directions and recommendations for the

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protection of occupational health and environmental quality should be careful-
ly followed. Material safety data sheets should be obtained from the manufac-
turers of such materials. In cases where the effects of a chemical substance
on occupational health and environmental quality are unknown, chemical sub-
stances should be treated as potentially hazardous or toxic materials.

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