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STATE OF THE ART OF UNDISTURBED SAMPLING OF COHESIONLESS SOILS

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An important phase of any major site investigation is the obtaining of high-quality undisturbed samples of the subsurface materials. This report describes the current state of the art in obtaining undisturbed samples of cohesionless material--specifically, sands, silts, gravels, and mixtures--primarily as it is reflected in the experience of the Waterways Experiment Station (WES) and of others on the North American continent.

(Continued)

20. ABSTRACT (Continued).

The report discusses general considerations in planning an undisturbed sampling program; methods of access to the soil materials for sampling, testing, or observation; and methods of sampling cohesionless soil. Methods of access and methods of sampling are described in tables which also note the areas of applicability of the various methods, important limitations and pitfalls, and important references. It offers further discussions on special considerations in methods of sampling, such as characteristics of sampling devices, drilling fluids, and sample intervals; the care of soil samples; and evaluation of sample disturbance.

It is concluded that: (a) high-quality, undisturbed samples of many sands can be obtained with a fixed-piston sampler and drilling mud, with proper care and attention to details of sampling, handling, and transportation (this sampling process yields very good samples of medium dense sands, but tends to densify loose sands and loosen dense sands); (b) the use of radiographs is recommended as a nondestructive method of evaluating sample disturbance; (c) in gravels, the only proven means of recovering undisturbed samples is by hand-carving block samples; and (d) recent studies indicate that freezing in situ, followed by coring, offers a promise for obtaining undisturbed samples of much higher quality than is presently possible.

Preface

The investigation reported herein was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers, Department of the Army, as part of CWIS Work Units 31145 entitled "Liquefaction of Dams and Foundations During Earthquakes," and 31619 entitled "Development of Technique and/or Device to Evaluate Liquefaction Potential of In Situ Cohesionless Materials."

The work was performed and this report was prepared by Drs. W. F. Marcuson III and A. G. Franklin, under the general supervision of Dr. P. F. Hadala, Chief, Earthquake Engineering and Geophysics Division, Geotechnical Laboratory (GL), and Mr. James P. Sale, Chief, GL, WES. This report is essentially the same as a paper prepared and submitted to the International Symposium on Soil Sampling, sponsored by the International Society for Soil Mechanics and Foundation Engineering, in Singapore, July 1979.

COL John L. Cannon, CE, was Commander and Director of WES during the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

Contents

STATE OF THE ART OF UNDISTURBED SAMPLING OF COHESIONLESS SOILS

Introduction

1. Preconstruction site investigations are required to determine geotechnical conditions that affect the feasibility of a project and the design, cost, performance, and ultimate safety of the structure. It is necessary that they be adequate in terms of thoroughness, suitability of methods used, and quality of execution of the work to assure that all important conditions have been detected and reliably evaluated. An important phase of any major site investigation is the obtaining of high-quality undisturbed samples of the subsurface materials. The purpose of this paper is to describe the current state of the art in obtaining undisturbed samples of cohesionless material--specifically, sands, silts, gravels, and mixtures. The viewpoint of the writers is, of course, most strongly influenced by the experience of the U. S. Army Engineer Waterways Experiment Station (WES) and of others on the North American continent. Other views of the current state of the art may be found in papers presented at the Annual Convention of the American Society of Civil Engineers (1978).

2. The need for high-quality undisturbed samples of cohesionless soils has been highlighted in recent years by increasing awareness of the need to evaluate the seismic stability (previously referred to in the literature as the liquefaction potential) of soils in the foundations of important structures such as nuclear power plants and earth dams. In order to evaluate the seismic stability of cohesionless soils, high-quality undisturbed soil samples are needed for the laboratory determination of cyclic strength and for accurate determination of in situ density. Consequently, it is necessary to preserve, as well as possible, both the in situ density and the in situ soil structure, including grain-to-grain contacts, with a minimum of disturbance. The in situ density and the in situ structure are separate and distinct properties of the soil. Preservation of the in situ density does not necessarily imply

preservation of the in situ structure, and both must be preserved if laboratory test results are to be truly representative of the soil behavior in situ.

3. There is no such thing as a truly undisturbed sample, primarily for two reasons: (1) a sampling tube displaces a certain amount of soil, which inevitably produces strain and some disturbance of the sample; and (2) even in "perfect sampling," an imaginary process that eliminates disturbance due to soil displacement, the state of stress in the soil sample undergoes a complex, and to some degree indeterminate, history of change during the sampling, handling, shipping, storage, extrusion, specimen preparation, and laboratory setup processes. Moreover, the in situ state of stress, stress history, and state of stress in the sample are seldom known except by crude approximation. These shortcomings are widely recognized, and the term "undisturbed" sample is conventionally used to mean a sample that is obtained and handled by methods designed to minimize these effects.

4. Even a cursory review of the literature on soil sampling shows that the most important work in the area is that of M. Juul Hvorslev. His monograph entitled "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes," published in 1949, is the classic work in soil sampling, and after three decades remains the fundamental reference on subsurface soil exploration for students and practitioners of foundation engineering.

Considerations in Planning an Undisturbed Sampling Program

5. General requirements for subsurface investigations, including drilling and sampling, are discussed in an American Society of Civil Engineers (ASCE) Task Committee Report (1972). The undisturbed sampling program normally should be preceded by a preliminary exploration program that includes representative sampling, penetration resistance tests, groundwater measurements, and surface surveys of the site, and may include (depending on the scope and importance of the project) geophysical investigations, remote sensing studies, surface soil mapping, etc.

These preliminary investigations define the soil profile, soil classifications, relative consistency of the various soil layers, groundwater regime, and other site conditions.

6. From consideration of the soil conditions delineated in the preliminary soil investigation, the geotechnical problems are identified and the technical course of action is planned. On this basis, the laboratory testing program is planned to provide the necessary geotechnical data for input to the analyses. The laboratory program in turn defines the requirements for the undisturbed sampling program. Specific considerations include depths, locations, number, and redundancy of the samples to be obtained, and coordination of the laboratory and field schedules to minimize storage time. (See Arman and McManis, 1976, for a description of the effects of duration of storage on sample properties.)

7. The need to obtain undisturbed samples of cohesionless soils is generally encountered when it is necessary to predict the seismic stability of these soils during an earthquake. For this evaluation, the results of stress-controlled, consolidated-undrained cyclic triaxial tests are generally used. The number of high-quality test specimens needed for a typical laboratory cyclic testing program varies from 12 to 36 for each distinct material. The need for redundancy in sampling should be recognized to allow for unavoidable and inadvertent losses occurring at various phases from sampling to testing and for additional testing needs that are recognized during the investigation. An appropriate degree of redundancy will eliminate the need for costly returns to the field for additional samples.

8. The overriding consideration in sample size is the laboratory testing requirement that the specimen diameter must be at least six times the diameter of the maximum-size particle. If facilities do not exist for testing specimens of such a size, there is no point in securing undisturbed samples except for density determinations. Additionally, conditions such as equipment limitations, soil density, and overburden pressure may be such that sample tubes of the required size cannot be advanced in some materials. In this case, the only recourse is to use test pits or other accessible excavations. In U. S. practice,

the smallest diameter sampler generally used for important projects is a nominal 3 in. (7.6 cm) diameter.

9. Various methods and types of samplers are used in obtaining undisturbed samples of granular soil, and it is the writers' experience that there is no single method or tool that works in every case. Consequently, in planning a sampling program for unfamiliar soil deposits, provision should be made for the use of alternative methods or for an experimental phase in the field program to identify the most successful equipment and/or method of sampling.

Methods of Access for Sampling

10. Methods of access to the soil materials for sampling, testing, or observation are listed in Table 1.

11. In most cases, access for sampling is provided by drilling, and in North American practice rotary drilling or test pits are used for important projects.

12. In most cohesionless materials that are free of boulders and gravel particles, adequate undisturbed samples can be obtained from boreholes with fixed-piston samplers using thin-wall metal tubes. Undisturbed samples of boulders, gravels, or sand-gravel mixtures generally cannot be obtained from boreholes by means of presently available samplers. Test pits, shafts, or other accessible excavations may be used with hand-sampling methods where undisturbed samples are required. However, this procedure is expensive and time-consuming, particularly where the materials in question are below the groundwater table, in which case, dewatering by means of well points or other suitable methods, such as freezing, is required. Osterberg and Varaksin (1973) describe a sampling program in sand in which an annular ring was frozen to permit dewatering of the interior and excavation of a shaft for access to the soil.

13. The dewatering and excavation process can greatly change the in situ state of stress in the material to be sampled. Changes in the state of stress may produce significant changes in void ratio or density.

It is important to remember that small shear strains can result in large changes in soil structure and consequently in the dynamic soil properties. Efforts to determine the change in the state of stress as a result of excavation and dewatering (including measurements of soil heave) are worthwhile.

Methods of Sampling Cohesionless Soil

14. Methods and devices for obtaining undisturbed samples of cohesionless soils are listed in Table 2.

15. No single sampling device or sampling procedure yields satisfactory results in every cohesionless material. WES experience indicates that, in general, the best choice of sampling device is governed by the relative consistency of the material to be sampled. In loose to medium dense sands, silts, and sand-silt mixtures, fixed-piston, thin-wall tube samplers have the best chance of yielding high-quality undisturbed samples. Both the Hvorslev fixed-piston sampler and the Osterberg hydraulic piston sampler are in this category.

16. An important consideration in the choice of samplers is the control of sample disturbance by maintaining a specific recovery ratio* of unity. The specific recovery ratio as an incremental quantity is distinct from the total recovery ratio, which is the ratio of the total length of sample recovered to the total length of sampler push. While maintenance of a specific recovery ratio of 1.0 does not in itself assure minimum disturbance of the soil, a specific recovery ratio other than 1.0 clearly means that the sample has deformed and therefore is disturbed. A notable advantage of the fixed-piston sampler is that under most conditions the fixed piston provides positive control over the specific recovery ratio during the push of the sampler.

17. Another advantage of the fixed piston, especially important in sampling cohesionless soils, is that it produces a vacuum at the top

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* The ratio of the increment of sample entering the tube to the increment of tube advance (Hvorslev, 1949).

of the sample in response to any tendency for the sample to slip out of the tube. For easy and gentle removal of the tube and sample from the sampler, this vacuum should be relieved. The Hvorslev device has a convenient means of accomplishing this. While a vacuum release has not been provided for on the Osterberg sampler, the vacuum can be relieved by drilling a small hole near the top of the sample tube and below the piston. A later version of the Osterberg sampler includes a vacuum release as well as other improvements (Osterberg, 1973). Other types of piston samplers, including the so-called stationary piston samplers (see Table 2), also provide the vacuum at the top of the sample, but lack positive control of the specific recovery ratio.

18. The primary disadvantage of the Hvorslev sampler is that it is complex in construction and operation, and therefore requires highly skilled operators. Like most fixed-piston samplers, the Hvorslev sampler requires an inner string of drill rods in addition to the normal drill string. The inner rod string is clamped at the top of the boring to provide fixity for the piston. With the Osterberg sampler, only the normal single string of rods is required. The piston is fixed through the sampler body to the drill string, which is clamped at the top of the hole. The sample tube is advanced by hydraulic pressure applied through drilling fluid pumped down the drill string.

19. In dense to very dense and/or cemented sands, silts, and sand-silt mixtures, it may not be possible to push thin-walled tubes with conventional tube samplers. If tubes can be pushed in such sands, the samples obtained will be less dense than the in situ material (Potamology Investigations Report No. 12-1, WES, 1952). If soil samples must be obtained from boreholes, the Pitcher or Denison sampler should be considered. These samplers use core bits to assist in advancing the thin-walled tubes. They have been used with varying degrees of success in granular materials. They are most successful in soils with cementation or material cohesion.

20. If soil samples are to be obtained from accessible excavations, such as test pits or shafts, either hand-carved block samples or the GEI sampler should be considered. This device, shown in Figure 1,

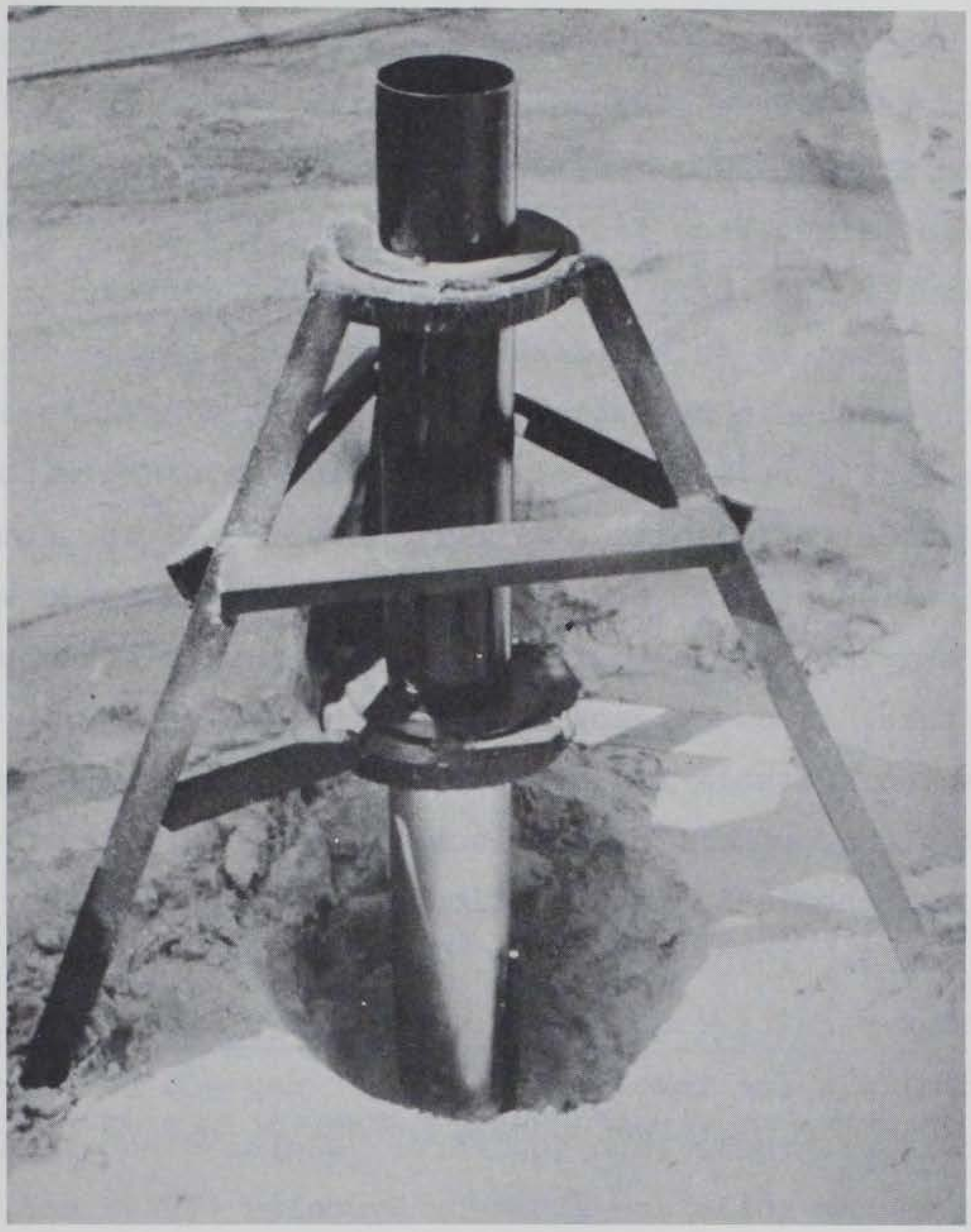


Figure 1. GEI sampler

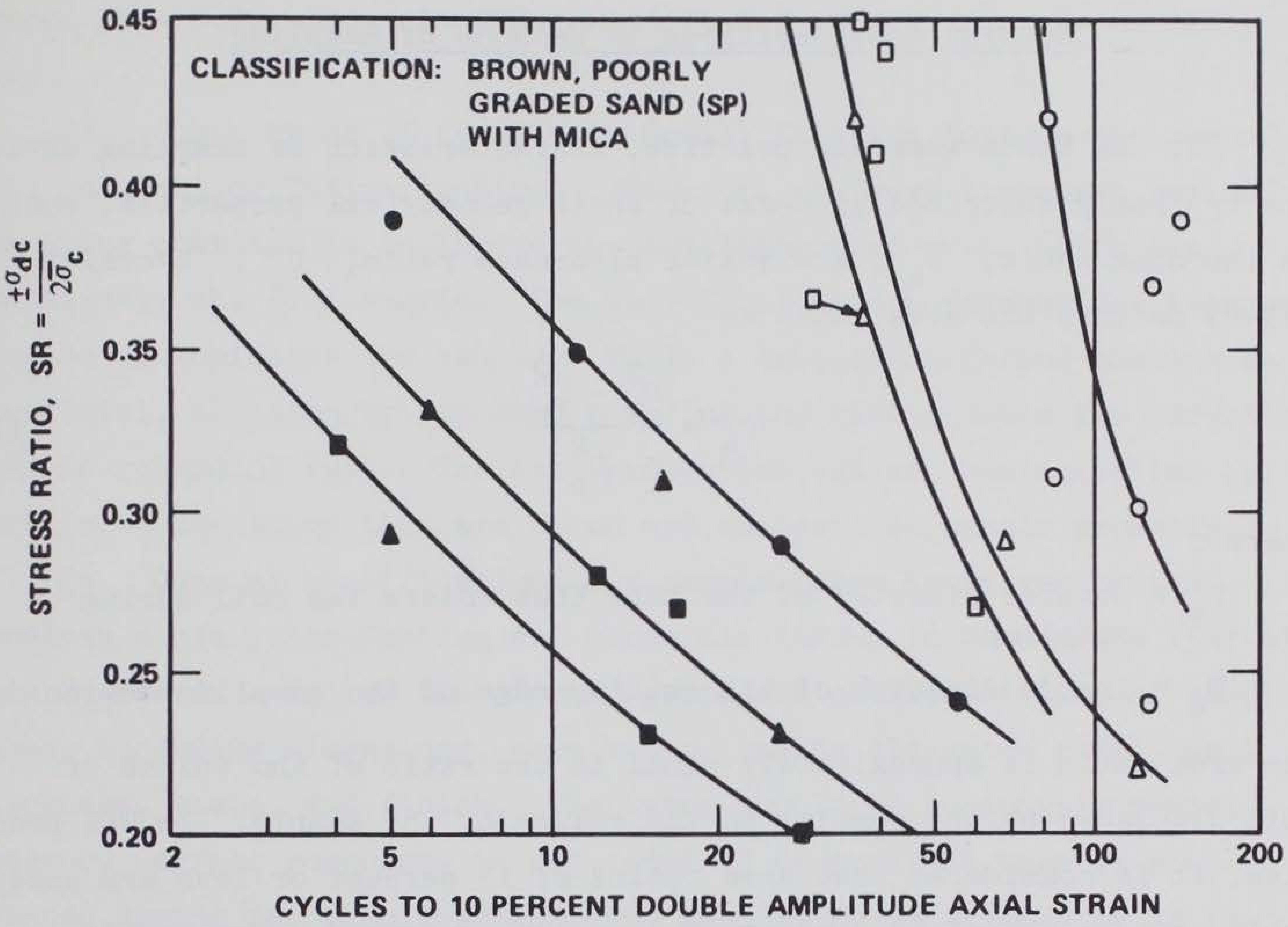
consists of a tripod holder and a 7.6-cm-diameter brass Denison tube. The sampling procedure begins with trimming the soil carefully for a distance of about 0.5 cm ahead of the tube to a diameter slightly larger than that of the tube. Then, light vertical pressure is applied by hand to advance the tube, and the cutting edge shaves off the excess soil. This procedure is repeated until the desired sample length is recovered. Use of this method in cohesionless materials requires that they be drained and possess apparent cohesion.

21. An indication of relative sample quality, as obtained in dense sand with the GEI sampler and a fixed-piston sampler, can be seen in the results of an investigation of Savannah River sand by the Corps of

Engineers. The sand was placed in a test fill and compacted by a vibratory roller. Samples were initially taken with a fixed-piston sampler, and were found to have an average dry density of 102 lb/ft^3 (1632 kg/m^3), compared to an average sand-cone dry density of 113 lb/ft^3 (1808 kg/m^3). Samples later obtained from test pits with the GEI sampler had an average dry density of 105 lb/ft^3 (1680 kg/m^3). The difference in sample quality is reflected in this modest difference in sample density and in a dramatic difference in resistance to cyclic loading. As shown in Figure 2, the cyclic resistance of the samples obtained with the GEI sampler is an order of magnitude higher, in terms of the number of cycles to 10 percent axial strain, than that of the samples taken with the fixed-piston sampler, an indication that the in situ structure is better preserved in these sands by sampling with the GEI sampler.

22. Samples suitable for density determinations, though not for tests of mechanical properties, may sometimes by obtained from boreholes with the help of chemical stabilization or impregnation (Karol, 1971; Windisch and Soulie, 1970). However, such methods are not yet developed to a degree that permits routine use. Special precautions are required when toxic chemicals are involved. Also, it may not be permissible to inject chemicals or grouts into aquifers. Useful discussions of methods of sampling granular soils are given by Hvorslev (1949) and Barton (1974).

23. Recent studies (Yoshimi et al., 1978; Singh et al., 1978) on freezing of sand samples in situ and in the laboratory indicate that, if confining pressure is maintained and drainage is not impeded during freezing, volume change during freezing is insignificant and the static and dynamic soil strengths are not altered upon thawing. The necessary drainage condition can be achieved by unsaturation, or in saturated soils, by freezing in such a way that there is free drainage on the unfrozen side of the freezing interface. The preliminary research results cited suggest that the in situ structure of the soil can be preserved essentially without disturbance by the use of freezing in situ followed by sampling with a core drill, and thawing only after confining pressure has been reapplied in the test cell. While this technique has not yet been fully developed or proven by substantial field experience, it



LEGEND

GEI	FIXED PISTON	$\bar{\sigma}_c$ TSF	$\bar{\sigma}_c$ kPa
○	●	1.0	96
△	▲	2.0	192
□	■	3.0	288

NOTE: σ_{dc} = CYCLIC DEVIATOR STRESS

$\bar{\sigma}_c$ = EFFECTIVE HYDROSTATIC CONFINING PRESSURE AT THE END OF CONSOLIDATION

Figure 2. Cyclic triaxial test data for Savannah River sand

offers hope for obtaining undisturbed samples of much higher quality than can be achieved with current practice.

Special Considerations in Methods of Sampling

24. In North American practice, characteristics of sampling devices are typically described in terms of their geometrical properties, such as the area ratio, C_a, and inside clearance ratio, C_i. Hvorslev (1949) defines the area ratio as

$$C_a = \frac{D_w^2 - D_e^2}{D_e^2} \tag{1}$$

where

D_w = outside diameter of the tube that enters the soil during sampling

D_e = inside diameter of the cutting edge of the sampling device

The area ratio is approximately equal to the ratio of the volume of soil displaced by the sampler to the volume of the sample. In WES practice, it is considered that area ratios of 13 percent or less are acceptable, but values of 10 percent or less are preferred. The inside clearance ratio is defined by Hvorslev (1949) as

$$C_i = \frac{D_s - D_e}{D_e} \tag{2}$$

where D_s = inside diameter of the sample tube. Inside clearance is produced by swaging the cutting edge of the tube. This reduces the friction between the sample and the inside wall of the tube during the sampling process. Without this provision, friction would increase with sampler penetration so that after a short advance no more soil would enter the tube, or so much additional force would have to be applied to advance the sampler that high stresses would be placed on the sample in and just below the tube. Depending on the in situ density, these would either loosen or densify the material. Inside clearance also permits lateral expansion of the sample after it enters the tube, and thus produces disturbance of soil structure and reduction of density in dense soils. To minimize expansion of the soil sample and accompanying disturbance, the smallest inside clearance ratio that gives full sample recovery should be used. In WES practice, 0.5 to 1 percent is normally used.

25. Other means of reducing sidewall friction include the use of oil, lacquer, or Teflon coatings. However, the most important reason for using coatings is to impede the development of rust, which can contaminate the soil sample. The use of oil is not recommended because it also contaminates the sample. While a lacquer or Teflon coating is beneficial, abrasion by the sand entering the tube reduces its effectiveness in retarding rust. The best protection against contamination by rust is to use tubes that are clean and to test the sample promptly.

26. General specifications for sample tubes are given by the American Society for Testing and Materials (ASTM) in Standard D 1587-67. This Standard describes the general geometric characteristics of sample tubes, including dimensions, area ratio, inside clearance ratio, wall thickness, shape, and finish. The tubes should be reasonably round; however, perfect roundness is not required because the tube is not rotated during the push. Whether the tube is round or not, it is important that the cross section be uniform over its length and that it be free of bumps and dents.

27. In drilling in cohesionless materials below the groundwater table, it is essential to use drilling mud to support the wall of the hole. Mud also helps to prevent heave of the bottom of the hole and balances artesian pressures. In normal WES practice, a drilling mud consisting of approximately one 23-kg sack of bentonite per 400 litres of water is used; however, the precise proportioning is not critical. Where artesian pressures are encountered, the drilling mud may be weighted by the addition of a suitable amount of powdered barite, which has a specific gravity of 4.5. It is important that the presence of artesian conditions be known beforehand if samples are required from the first 2 to 3 m of the zone of artesian pressure, and heavy mud should be introduced before the artesian zone is encountered. The mudded hole

will not be suitable for piezometer or well point installation.

28. The required sample interval depends on the variability of the deposit and the importance of the structure. Frequently, continuous sampling is used. Continuous sampling in WES practice means that a sample 76 cm long is obtained in each 91-cm interval. Between samples the hole is advanced and cleaned out with a modified fishtail bit. Conventional fishtail bits have downward-directed jets through which the drilling mud is pumped, and this jetting action causes disturbance of the soil immediately below the bottom of the hole. To minimize such disturbance, baffles should be added to deflect the drilling fluid upward. Figure 3 is a photograph showing examples of WES-modified fishtail bits.

29. In order for the piston in a fixed-piston sampler to be effective, the drill rig must be securely anchored. This is customarily done with screw-type earth anchors approximately 30 cm in diameter. Measurements of rig heave during the push of the sample tube in medium dense, fine to medium grain-size sand, made at WES, indicate that with such anchorage, and regulated thrust pressure, the heave can be kept to

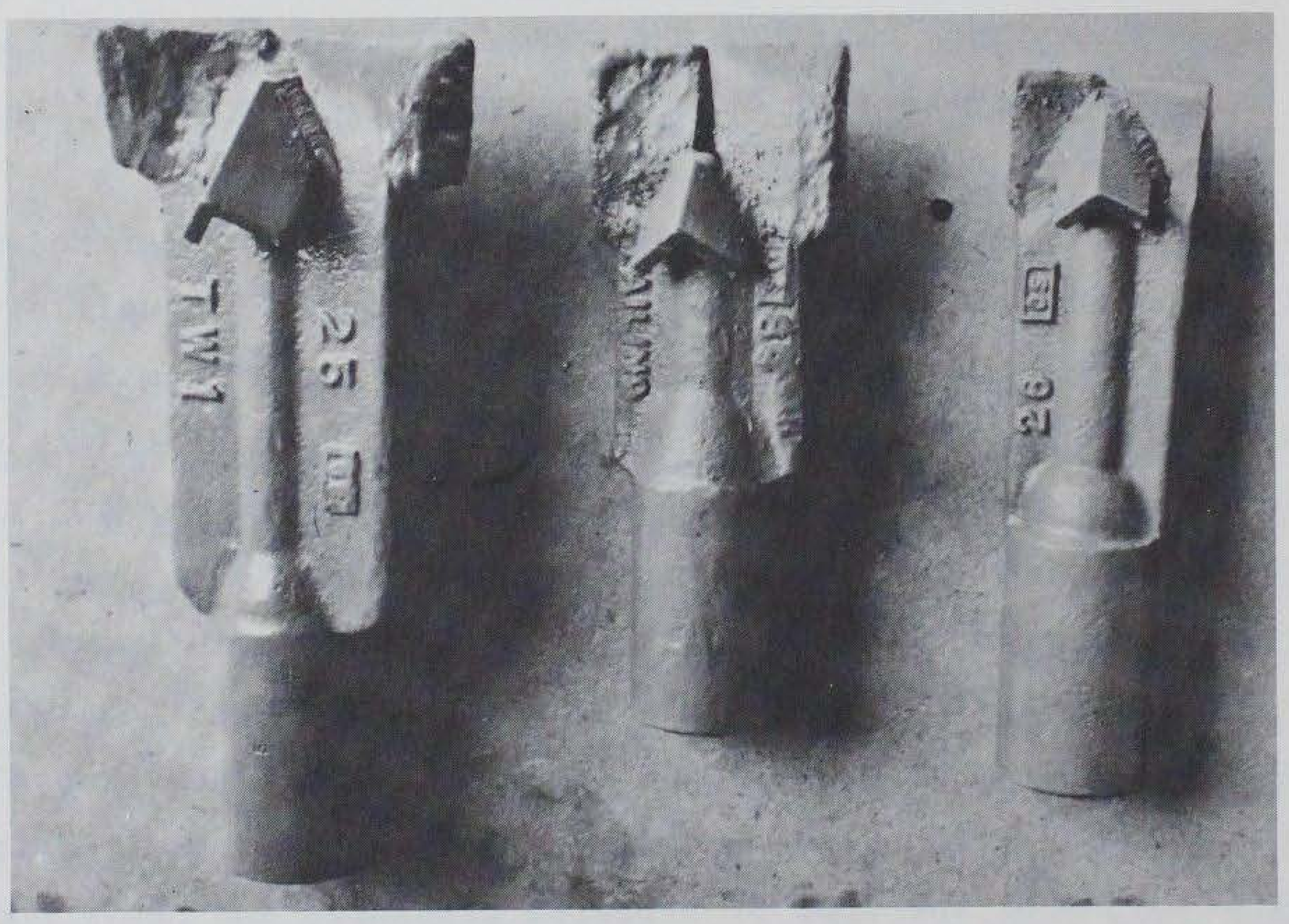


Figure 3. Fishtail bits modified with upward baffles

within a few hundredths of a centimetre.

30. The sampler should be advanced in one continuous push at a uniform rate, and should not be rotated during the drive. If, for any reason, the drive is interrupted, it should not be restarted. Restarting the drive results in increased penetration resistance, disturbance of the sample, and a decrease in the total recovery ratio. The most satisfactory method of pushing a thin-walled tube sampler is with the hydraulic drive mechanism of the drill rig. It is desirable to have a gauge to monitor the hydraulic fluid pressure as a measure of the force required to push the sampling tube into the soil. Force levels consistent with good sampling practice for 3-in.(7.6-cm)-diam samples using 16-gauge tubes are less than 3000 kg.

31. After completion of the sampling drive, the samples should be withdrawn slowly and uniformly, without rotation, and with a minimum of shock and vibration. Fast withdrawal tends to create a vacuum below the sampler and causes disturbance and/or loss of sample. Drilling fluid should be added as the sampler is removed to keep the borehole full at all times.

Care of Soil Samples

32. Undisturbed samples of cohesionless soils are particularly vulnerable to damage caused by rough or careless handling and impacts or vibrations. The removal of the tube from the sampler is a critical operation which needs the careful attention of the engineer or technician supervising the operation. The sample should be kept in a vertical position at all times, from the time it is removed from the borehole until it is tested. Current WES practice is to allow cohesionless samples to drain, on the theory that capillary forces will tend to stabilize them. This may take as long as 24 hr, or longer in some cases. Drained samples are sometimes frozen in the field to further guard against damage caused by handling and shipping. For truly cohesionless materials, this freezing process greatly facilitates the preparation of a laboratory test specimen and laboratory test setup, and the available

evidence (Singh et al., 1978; Walberg, 1978) indicates that it does not itself cause significant disturbance of the soil structure. Caution should be exercised if layers of impervious material are suspected. Only free-draining soils can be frozen without disturbance. Careful attention to the mode of sample transportation between the field and the laboratory is required in order to keep the sample disturbance at a minimum. It is obvious that control of the sample handling is best accomplished by the personnel responsible for the investigation. Commercial shipping cannot provide this service.

Evaluation of Sample Disturbance

33. Criteria for visual evaluation of undisturbed samples were given by Hvorslev in 1949. These are:

a. The specific recovery ratio shall not be greater than 1.00 nor smaller than $(1 - 2C_i)$, where C_i is the inside clearance ratio at the cutting edge. When thin-wall drive samples, samples with stationary pistons,* or core barrels are used, it is generally sufficient that the total recovery ratio be equal to or slightly smaller than unity.

b. On the surface of or in sliced sections of the sample, there must be no visual distortions, planes of failure, pitting, discoloration, or other signs of disturbance which can be attributed to the sampling operation or handling of the sample.

c. The net length and weight of the sample and the results of other control tests must not change during shipment, storage, and handling of the sample.

34. Insofar as sample disturbance in cohesionless soils is concerned, the engineer's primary areas of interest are in changes in soil density and changes in the nature of the grain-to-grain contacts produced by sampling and handling, and the change in the state of stress (about which he can do nothing except counterbalance artesian pressure).

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* The present writers recommend that this qualification be used only for fixed pistons, as distinguished in this paper from stationary pistons (see Table 2).

WES studies (Marcuson, 1978; WES, 1952; Cooper, 1976; Marcuson et al., 1977) show that the sampling process, no matter how carefully executed, tends to densify loose sands and loosen dense sands (see Figure 4).

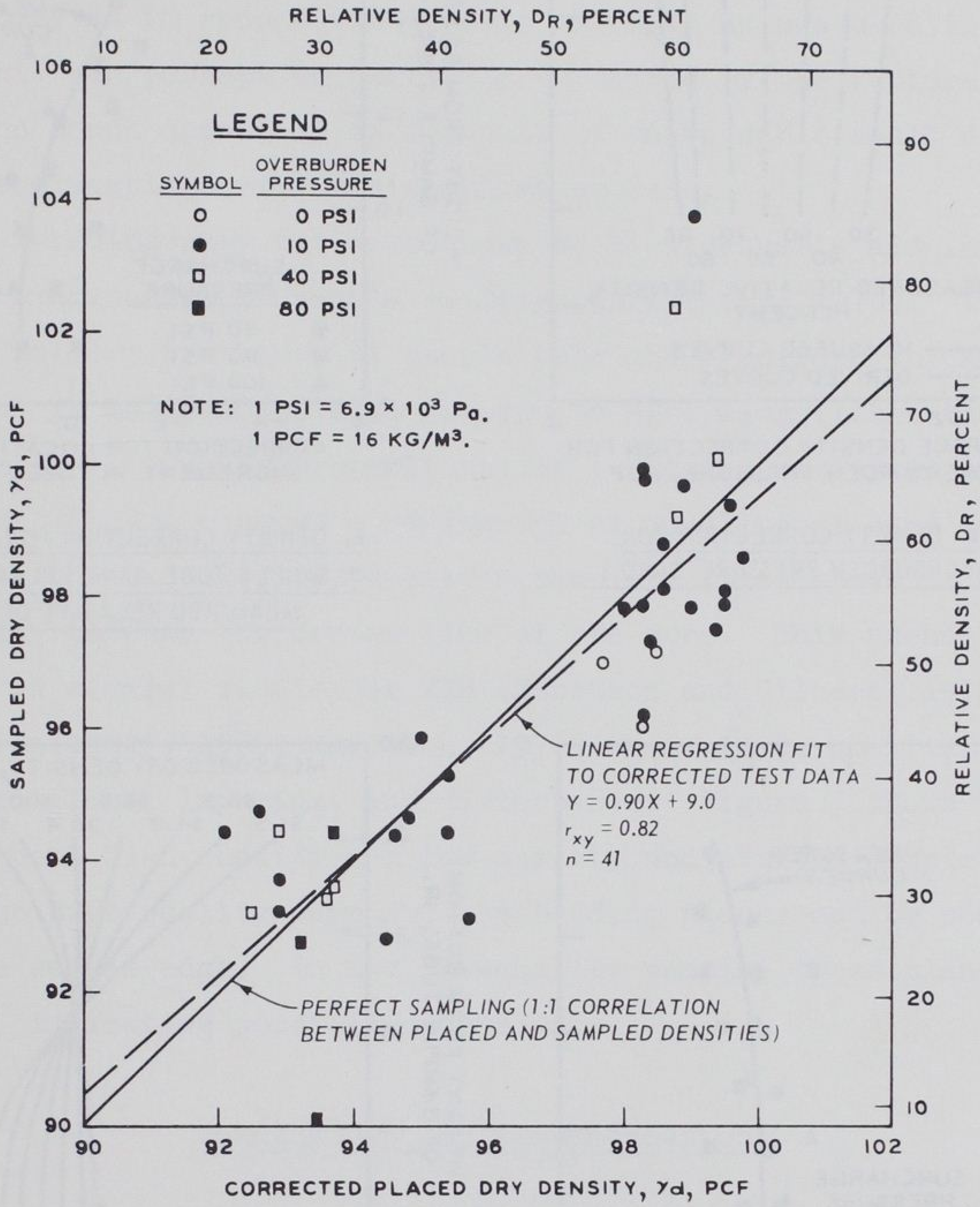
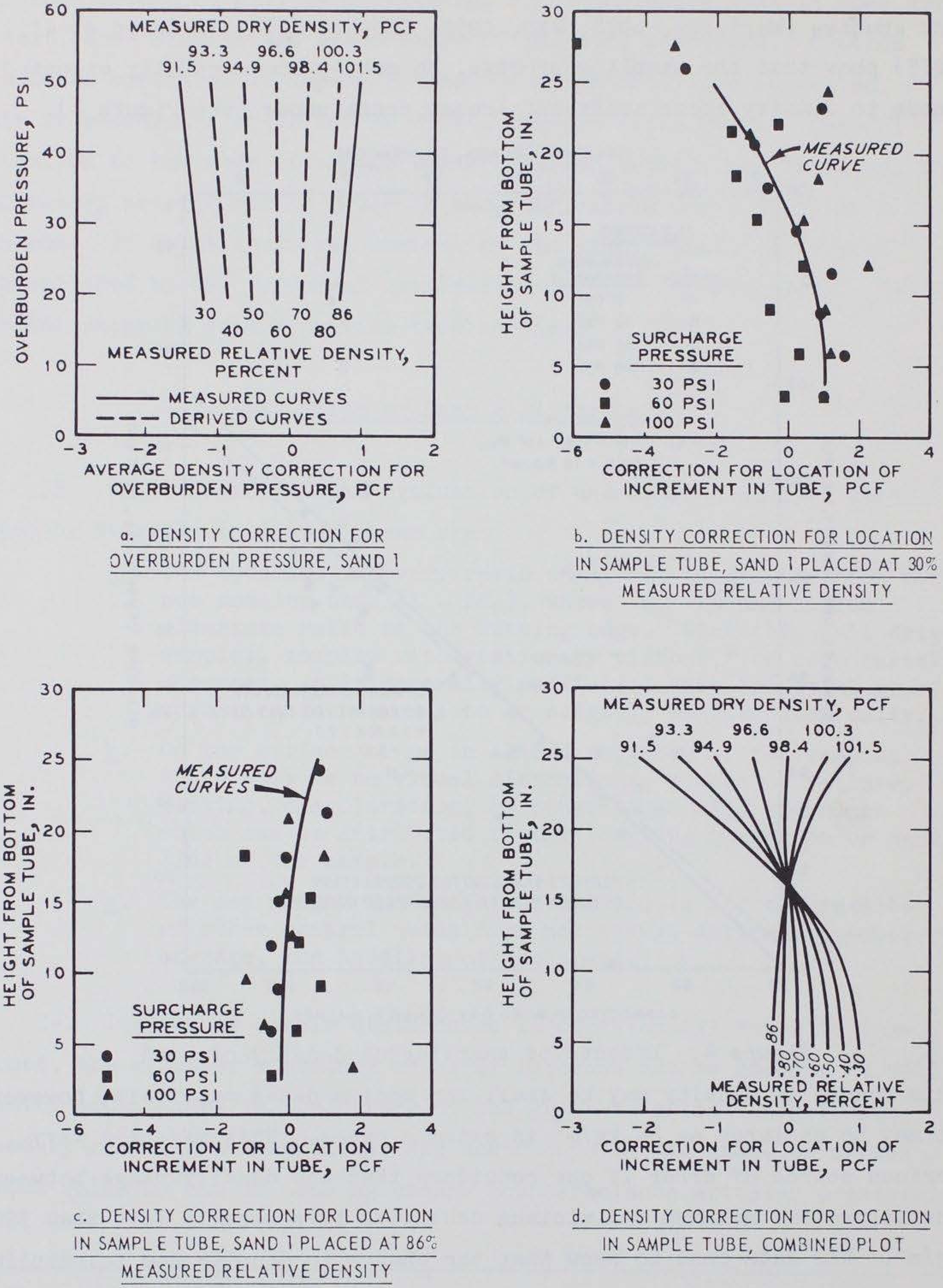


Figure 4. Effects of sampling on density of sand

This change in density may be small for medium dense materials; however, it may be as large as 64 kg/m^3 in extreme cases. This may be a very serious source of error if one considers that the density range between the laboratory maximum and minimum densities is generally less than 320 kg/m^3. WES data tend to show that the change in density due to sampling increases with increasing overburden pressure and is smallest in the middle third of the sample tube (see Figure 5). Where the materials are accessible in test pits, comparison of sample densities with sand cone



a. DENSITY CORRECTION FOR OVERBURDEN PRESSURE, SAND 1

b. DENSITY CORRECTION FOR LOCATION IN SAMPLE TUBE, SAND 1 PLACED AT 30% MEASURED RELATIVE DENSITY

c. DENSITY CORRECTION FOR LOCATION IN SAMPLE TUBE, SAND 1 PLACED AT 86% MEASURED RELATIVE DENSITY

d. DENSITY CORRECTION FOR LOCATION IN SAMPLE TUBE, COMBINED PLOT

NOTE: TO CONVERT PSI TO kN/M², MULTIPLY PSI BY 6.9.
TO CONVERT PCF TO kg/M³, MULTIPLY PCF BY 16.02.
TO CONVERT IN. TO CM, MULTIPLY IN. BY 2.54.

Figure 5. Effects of overburden pressure and position in sample tube on changes of sand density

densities can also be useful in evaluating sample quality.

35. Recent North American data (Mori et al., 1978) suggest that the sampling process changes the nature of the grain-to-grain contacts in such a way as to reduce the dynamic strength as measured in the laboratory. This can perhaps be partially explained by the rupture of cementation bonds occurring as a result of unavoidable small deformations of the sample during the sampling process.

36. X-radiography has been shown to be a valuable aid in nondestructive examination of sample quality (Krinitzsky, 1970). If one assumes a uniform thickness of sample tube and a uniform thickness of a sample that is homogeneous with respect to mineralogy, then the density of the sample is roughly proportional to the film density in an X-radiograph. Figure 6 shows a radiograph of an alluvial sand sample obtained with the Hvorslev fixed-piston sampler. Also shown is a plot of film density through the center line of the core. This technique has been used in several studies at WES (Marcuson and Gilbert, 1972; Marcuson and Krinitzsky, 1976; Marcuson, 1976) to evaluate qualitatively sample variations, layering, and disturbance. Figure 7 shows radiographs of both high-quality and low-quality undisturbed samples. Notice that in the high-quality samples, the bedding planes can be seen all the way to the sample edge. In the low-quality sample, these planes are contorted, indicating possible disturbance.

Conclusions and Recommendations

37. Based on the experience summarized herein, the following conclusions and recommendations can be made:

a. High-quality, undisturbed samples of many sands can be obtained using a fixed-piston sampler and drilling mud, if proper care and attention to the details of the sampling, handling, and transportation process are exercised. This sampling process yields very good samples of medium dense sands, but tends to densify loose sands and loosen dense sands. This disturbance appears to be a function of relative density, overburden pressure, and position in the sample tube. It may cause the sample density to be in error as much as 64 kg/m^3 in extreme cases.

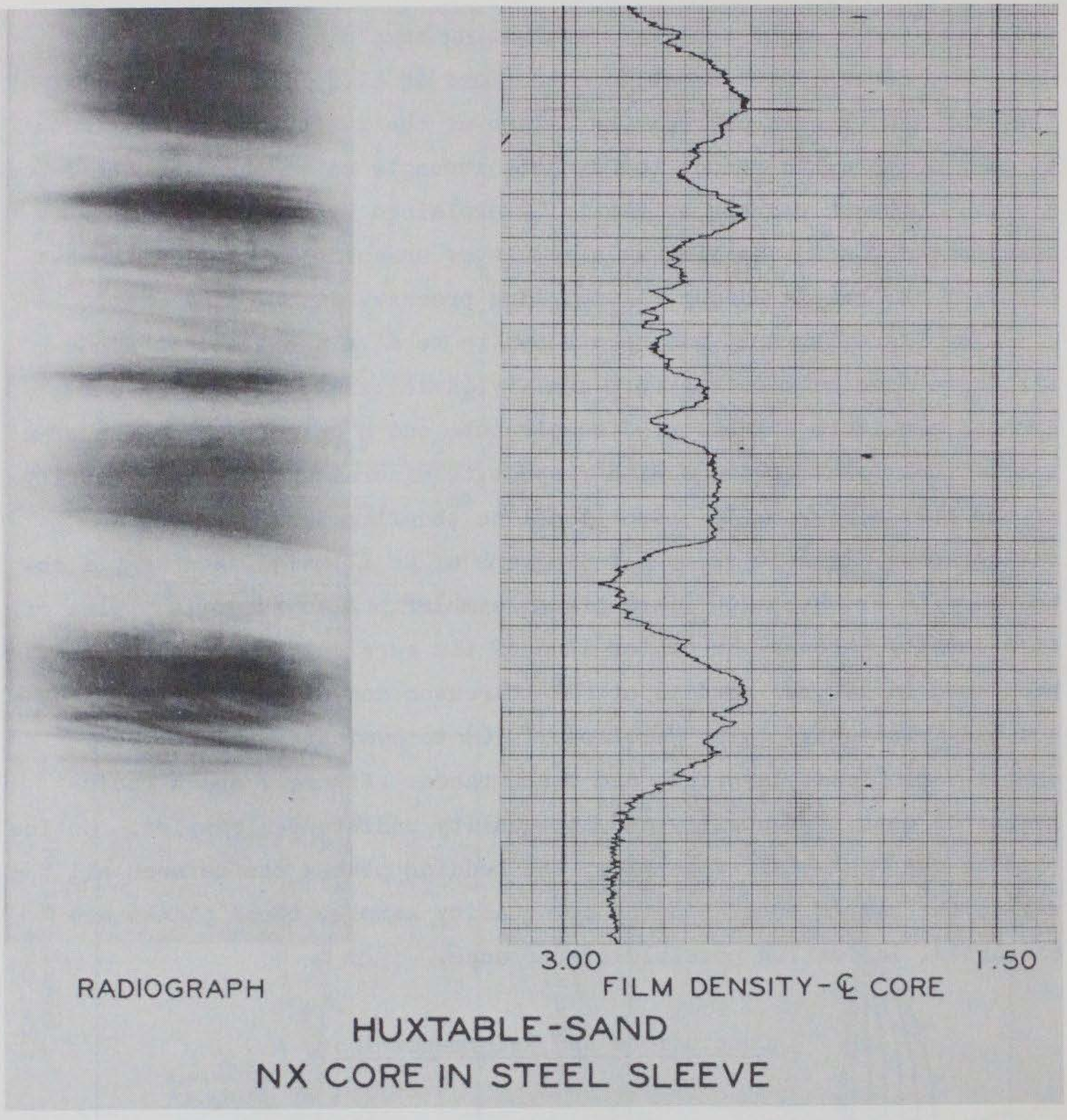


Figure 6. Use of radiograph film density to indicate variation of soil density in sample tube

b. The use of radiographs is an adequate and reliable nondestructive method for determining the layering of the sample and the degree of disturbance inside the sample tube. If facilities are available, this method of examining the sample should be routinely used.

c. Where gravels are encountered, the only proven effective means of recovering undisturbed samples is by hand-carving block samples in test pits.

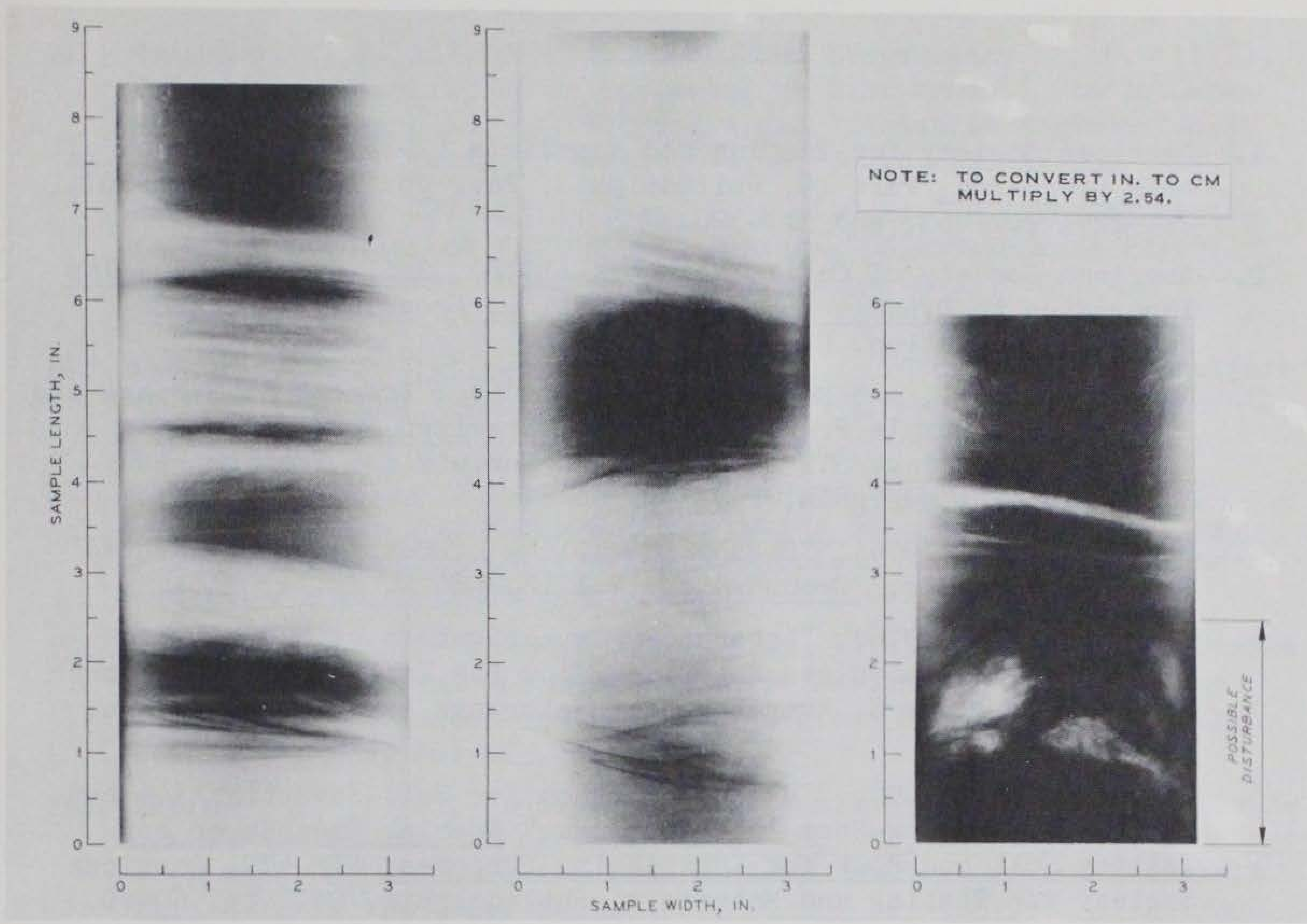


Figure 7. Use of radiograph to evaluate sample disturbance

d. Studies made recently (Singh et al., 1978) suggest that freezing in situ, in such a way that drainage is not impeded, followed by coring, may offer a promise for the future of obtaining undisturbed samples of much higher quality than presently possible.

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Table 1

Methods of Access for Sampling Soil

Method	Procedure	Applicability	Limitations and Pitfalls
Pits, trenches, shafts, tunnels	Excavation made by hand, large auger, or digging machinery (Hvorslev, 1949, pp. 66-71)	Visual observation, photography, disturbed and undisturbed sampling, in situ testing of soil and rock	Depth of unprotected excavations is limited by groundwater or safety considerations
Auger boring	Boring advanced by hand auger or power auger (Hvorslev, 1949, pp. 61-64)	Recovery of remolded samples, location of groundwater table. Access for undisturbed sampling of cohesive soils	Will not penetrate boulders or hard rock
Hollow auger	Boring advanced by means of continuous-flight helix auger with hollow center stem (Davis, 1969)	Access for undisturbed or representative sampling through hollow stem with thin-wall tube sampler, core barrel, or split-spoon sampler	Should not be used with plug in granular soils. Not suitable for undisturbed sampling in loose sand or silt (Peck et al., 1974, pp. 105-106)
Wash boring	Boring advanced by chopping with light bit and by jetting with upward-deflected jet (Hvorslev, 1949, pp. 52-54)	Cleaning out and advancing hole in soil between sample intervals	Suitable for use with sampling operations in soil only if done with low water velocities and with upward-deflected jet
Rotary drilling	Boring advanced by rotating drilling bit with cuttings removed by circulating drilling fluid (Hvorslev, 1949, pp. 57-61)	Cleaning out and advancing hole in soil or rock between sample intervals	Drilling mud should be used in granular soils. Bottom-discharge bits are not suitable for use with undisturbed sampling in soils, unless combined with protruding core barrel, as in Denison sampler
Percussion drilling	Boring advanced by air-operated impact hammer	Detection of voids and zones of weakness in rock by changes in drill rate or resistance. Access for in situ testing or logging	Limited to small-diameter hole
Cable drilling	Boring advanced by repeated dropping of heavy bit and removal of cuttings by bailing (ibid.)	Advancing hole in soil or rock. Access for sampling, in situ testing, or logging in rock. Penetration of hard layers, gravel, or boulders in auger borings	Causes severe disturbance in soils; not suitable for use with undisturbed sampling methods
Continuous sampling or displacement boring	Boring advanced by repeated pushing of sampler, or closed sampler is pushed to desired depth and sample is taken (ibid.)	Recovery of representative samples of cohesive soils, undisturbed samples in some cohesive soils	Effects of advance and withdrawal of sampler result in disturbed sections at top and bottom of sample. In some soils, entire sample may be disturbed. Not suitable for use in cohesionless soils

Table 2

Methods of Undisturbed Sampling of Cohesionless Soil

Method	Procedure	Applicability	Limitations and Pitfalls
Hand-cut block or cylindrical sampler	Sample is cut by hand from soil exposed in excavation (USBR, 1960, pp. 346-349; Terzaghi and Peck, 1968, pp. 312-314)	Highest quality undisturbed samples in cohesive soils, cohesionless soils, and soft rock	Requires accessible excavation and dewatering if below water table. Extreme care is required in sampling cohesionless soils. The state of stress is changed by the excavation
GEI sampler	Sample is hand-trimmed into cylindrical sample tube that is supported and guided by a tripod holder (Geotechnical Engineers, Inc., 1976; Marcuson, 1978)	Undisturbed samples in cohesionless soils, of quality comparable to hand-cut block sample	Requires accessible excavation and dewatering if below water table. The state of stress is changed by the excavation
Thin-walled tube samplers	Thin-walled tube is pushed into soil at bottom of boring. (ASTM D1587-67; U. S. Army, 1972, Ch. 4)	Undisturbed or representative samples in cohesive soils and cohesionless soils that are free of gravel particles.	Not suitable for use in extremely hard soils, gravel, or stony soils. Strict attention to details of equipment and procedure is required to obtain undisturbed samples of good quality (ibid., Ch. 3 & 4; Hvorslev, 1949, pp. 83-139)
	Major Types of Thin-Walled Tube Samplers Are Listed Below		
Fixed-piston sampler	Thin-walled tube is pushed into soil, with fixed piston in contact with top of sample during push. (U. S. Army, 1972, Ch. 3; Hvorslev, 1949, pp. 128-130; USBR, 1960, pp. 349-379)	Undisturbed samples in cohesive soils, silts, and sands, above or below the water table	Some types do not have positive prevention of piston movement
Hydraulic piston sampler (Osterberg)	Thin-walled tube is pushed into soil by hydraulic pressure. Fixed piston in contact with top of sample during push. (Osterberg, 1952 and 1973; U. S. Army, 1972, Ch. 3)	Undisturbed samples in cohesive soils, silts, and sands, above or below the water table	Not possible to limit the length of push or to determine amount of partial sampler penetration during push. Earlier version does not have vacuum breaker in piston
Stationary piston sampler	Thin-walled tube is pushed into soil. Piston at top of sample is free to move upward but is restrained from downward movement by a friction lock	Undisturbed samples in stiff cohesive soils; representative samples in soft to medium cohesive soils, silts, and some sands	Piston does not provide positive control of specific recovery ratio
Free-piston sampler	Thin-walled tube is pushed into soil. Piston rests on top of soil sample during push (ibid., Ch. 3; Hvorslev, 1949, p. 131)	Undisturbed samples in stiff cohesive soils. Representative samples in soft to medium cohesive soils and silts	Not suitable for sampling in cohesionless soils. Free piston provides no control of specific recovery ratio
Open-drive sampler	Thin-walled, open tube is pushed into soil (ibid., p. 133; USBR, 1960, pp. 361-367)	Undisturbed samples in stiff cohesive soils. Representative samples in soft to medium cohesive soils and silts	Not suitable for sampling in cohesionless soils. No control of specific recovery ratio
Pitcher sampler	Thin-walled tube is pushed into soil by spring above sampler while outer core bit reams hole. Cuttings removed by circulating drilling fluid (Terzaghi and Peck, 1968, pp. 310-312)	Undisturbed samples in hard, brittle, cohesive soils and sands with cementation. Representative samples in soft to medium cohesive soils and silts. Disturbed samples may be obtained in cohesionless materials with variable success	Frequently ineffective in cohesionless soils
Denison sampler	Hole is advanced and reamed by core drill while sample is retained in nonrotating inner core barrel with core-catcher. Cuttings removed by circulating drilling fluid (ibid., pp. 312-313; USBR, 1960, pp. 355-361)	Undisturbed samples in stiff to hard cohesive soil, sands with cementation, and soft rocks. Disturbed samples may be obtained in cohesionless materials with variable success	Not suitable for undisturbed sampling in loose cohesionless soils or soft cohesive soils
Submersible vibratory (vibracore) sampler	Core tube is driven into soil by vibrator. (Tirey, 1972)	Continuous representative samples in unconsolidated marine sediments	Because of high area ratio and effects of vibration, samples are disturbed
Underwater piston corer	Core tube attached to drop weight is driven into soil by gravity after a controlled height of free fall. Cable-supported piston remains in contact with soil surface during drive (Noorany, 1972)	Representative samples in unconsolidated marine sediments	Samples may be seriously disturbed (McCoy, 1972)
Gravity corer	Open-core tube attached to drop weight is driven into soil by gravity after free fall (Noorany, 1972)	Representative samples at shallow depth in unconsolidated marine sediments	No control of specific recovery ratio. Samples are disturbed