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Reprinted from
A paper of the Journal of Geotechnical Engineering, ASCE
Vol. 113, No. 7, pp. 739-757
1987

DISTURBANCES DUE TO "IDEAL" TUBE SAMPLING

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ABSTRACT: The "ideal sampling approach" (ISA) for elucidating, formulating, and predicting minimum disturbance effects in deep tube samples of saturated clays is proposed. The ISA relies on approximate solutions based on the strain path method to incorporate tube penetration disturbances. Laboratory test results on normally consolidated Boston blue clay indicate that the ISA provides more realistic predictions than the existing perfect sampling approach and that tube penetration disturbances are significant in "undisturbed" tube samples of soft clays obtained by means of existing thin-walled sampling techniques.

INTRODUCTION

Geotechnical engineers routinely conduct site exploration and testing programs to determine the stratigraphy and the engineering properties of the soils necessary for foundation analyses and design. A common component of soil exploration consists of drilling borings from which tube samples are recovered for purposes of soil identification and laboratory engineering testing. Laboratory tests generally provide well-defined, controllable boundary and drainage conditions in addition to uniform stresses (or strains) within soil specimens, thereby enabling easy interpretation of test results. The major disadvantages of laboratory testing are: (1) sampling disturbance effects that generally cause significant differences in properties between soil specimens and the in situ foundation soils; and (2) uncertainties associated with estimating the in situ spatial variation of soil parameters from the very small volume of soil normally tested.

In situ tests have therefore attracted considerably increased interest among the geotechnical profession as a means of complementing laboratory tests in soil exploration. In situ tests can provide a more detailed description of the vertical variation of soil properties, but generally have complicated boundary conditions and involve significant stress (and strain) variations within the soil and uncontrollable drainage conditions. Therefore, interpretation of in situ test results is difficult and requires varying degrees of empiricism in estimating soil parameters for design purposes. As a result, tube sampling and laboratory testing of soils still constitute the backbone of current site-investigation studies for determining the engineering properties of soils.

The influence of sampling disturbances on the ability of laboratory tests conducted on recovered samples to duplicate the in situ behavior of

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Note.—Discussion open until December 1, 1987. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 18, 1986. This paper is part of the *Journal of Geotechnical Engineering*, Vol. 113, No. 7, July, 1987. ©ASCE, ISSN 0733-9410/87/0007-0739/$01.00. Paper No. 21649.

foundation soils has long been recognized. In fact, these disturbances had such an impact on practices and procedures adopted by the geotechnical profession that, without their overwhelming effects, geotechnical engineering would be very different from what it is today. For example, without disturbances, heavy reliance on empirical design procedures would be probably eliminated and replaced by more exact and reliable methods, which can then be easily adapted to new and different conditions.

Research on the effects of sampling on the behavior of clayey soils was especially active in the 1940s, and culminated in the work of Hvorslev (10) whose concepts, recommendations, and methods on sampling procedures are widely known and still constitute the basis of our current practice. Since then, and in the last four decades, many investigators have attempted to establish the extent and nature of disturbances associated with sampling and laboratory testing (9, 11, 13, 16–19, 21, 23–25, and others). However, in view of the absence of analytical techniques to predict the effects of sampling on soil deformations, most of the research has been limited to comparative experimental investigations.

This paper proposes the "ideal sampling approach" (ISA) as a rational and systematic framework for elucidating, formulating, and predicting minimum disturbance effects in deep-tube push samples. The framework is based on the strain path method (SPM) (2) and, for purposes of simplicity and clarity, is limited herein to saturated clays with emphasis on soft, slightly overconsolidated deposits.

SAMPLING DISTURBANCES

Minimum Sampling Disturbances.—Tube sampling offers many opportunities for soil disturbances. Following the history of the sample, basic disturbances occur due to: (1) changes in soil conditions ahead of the advancing borehole during drilling operations; (2) penetration of the sampling tube and sample retrieval to ground surface; (3) water content redistribution in the tube; (4) extrusion of the sample from the tube; (5) drying and/or changes in water pressures; and (6) trimming and other activities required to prepare specimens for laboratory testing. Additional disturbances can be significant in special applications. Examples include the expansion of dissolved gases when (very deep offshore) samples are brought to the surface; dynamic effects in hammered samples or during rough handling and transportation; temperature changes in chemically or biologically active deposits, etc.

Basic sources of disturbance can be classified in many ways depending on the objective at hand. For the purposes of this study aimed at establishing a rational framework for analyzing and predicting sampling disturbances and their effects, it is important to distinguish between operator-dependent disturbances and minimum sampling disturbances. Operator-dependent disturbances refer to disturbances that are mainly dependent on the performance of operator(s) in charge of field work, transportation, extrusion, trimming, and laboratory testing and hence can be reduced by close adherence to good practices of sampling and testing operations. These types of disturbance are believed to include most of disturbances, 1, 5, and 6 just mentioned. On the other hand, minimum sampling disturbances refer to disturbances that, for a given set of sampling tools and equipment, cannot be reduced by improving sampling operations. Minimum sampling disturbances are principally due to disturbances 2–4 previously mentioned. This means that, given the best available sampling equipment and exercising the most careful sampling methods, minimum (yet possibly significant) disturbances will occur, primarily due to the penetration sampling tube and its retrieval to the surface, as well as the redistribution of water content in the tube and the extrusion of the sample from the tube.

The following sections focus on minimum sampling disturbances, since they lend themselves to analysis and formulation, whereas operator-dependent disturbances can hardly be incorporated in a unifying rational predictive framework.

Perfect Sampling Approach.—Existing rational methods for the analysis of minimum sampling disturbances and their effects revolve around the "perfect sampling approach" (PSA) (13,24). Perfect sampling of saturated clays denotes the idealized process of undrained shear stress relief from the initial anisotropic in situ stress state to the final isotropic stress condition of the sample before testing. Hence, when applied to tube sampling, the PSA considers no operator-dependent disturbances and neglects tube penetration disturbances, water content changes, and the detailed straining history of the sample during retrieval and extrusion.

Fig. 1 shows the effects of perfect sampling on the stress-strain behavior [Fig. 1(*a*)] and the effective stress path [Fig. 1(*b*)] of resedimented K_0-normally consolidated (NC) Boston blue clay (BBC) during undrained shear in triaxial compression tests reported by Ladd and Varallyay (15). Curve 1 in Fig. 1 shows the "undisturbed" behavior of the NC soil when shearing starts from point A located along the K_0-line ($K_0 = 0.52$) and corresponding to a vertical consolidation stress, σ'_{vc}. Curve 2 shows the behavior after perfect sampling involving the undrained shear stress relief from point A to the isotropic state of stress denoted by point B, and a minor reduction (8%) in the mean effective stress to $\sigma'_{ps} = 0.63\ \sigma'_{vc}$. Comparing Curves 1 and 2 in Fig. 1, we note that perfect sampling dis-

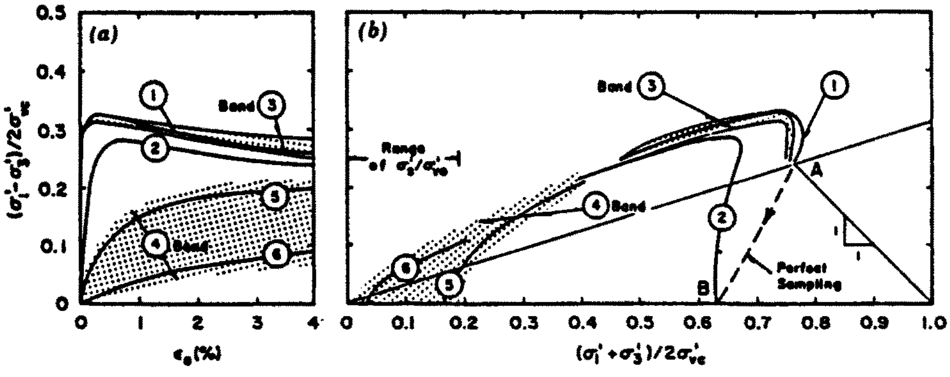

FIG. 1.—Undrained Behavior of BBC in Triaxial Compression Tests: (*a*) Stress-Strain ($0 \leq \epsilon_a \leq 4\%$); and (*b*) Effective Stress Paths ($0 \leq \epsilon_a \leq 10\%$)

turbances have the following effects on the undrained behavior of resedimented normally consolidated BBC:

1. A significant change in the stress-strain behavior of the soil at small strain levels (axial strain, $\epsilon_a < 0.5\%$) due to differences in the initial state of stress prior to shear. However, (at the risk of oversimplification), if the undrained secant Young's modulus at 50% of the shear stress required to reach the peak strength, E_{50}, is used as a measure of soil stiffness, perfect sampling slightly reduces E_{50} by about 20% (from 340 σ'_{vc} to $270\sigma'_{vc}$).
2. An increase in the axial strain required to mobilize the peak shearing resistance, ϵ_p, by about 140%.
3. A decrease in the (peak) undrained shear strength, c_u, by 15%.

On the other hand, perfect sampling disturbances in Fig. 1 show little effect on behavior beyond ϵ_p as described by the effective stress path and the brittleness (or strain-softening tendency) of the soil. More typically, however, perfect sampling tends to reduce the undrained brittleness of soft clays without affecting the ultimate strength obtained at high strain levels (8,24).

Ladd and Lambe (13) and others (20,21) used the PSA to establish a measure for the degree of clay sample disturbance (due to reasons other than initial shear stress relief) through the ratio σ'_s/σ'_{ps} where σ'_s is the mean effective stress in the sample before testing. Experiments show that small values of σ'_s/σ'_{ps} indicate more severe sampling disturbances. They also proposed that the ratio σ'_s/σ'_{ps} can serve as a useful guide to evaluate and correct shear strength measurements of uncemented clays in unconsolidated undrained (UU) tests.

Sampling Disturbance Effects on Boston Blue Clay Behavior.—Boston blue clay (BBC) is a marine illitic clay of medium sensitivity ($S_t = 7 \pm 2$) of the late Pleistocene ice age. BBC covers large areas of the Boston Basin and, at locations where the deposit exceeds about 20 m in depth, the lower clay is quite uniform and soft with an overconsolidation ratio, OCR < 1.3. The lower BBC typically has a liquid limit of 42.5 ± 4%, a plastic limit of 22 ± 1.5%, a plasticity index of 20 ± 2.5%, and a natural water content of 43.5 ± 4%.

The shaded band 3 in Fig. 1 and the results in Table 1 show typical undrained shear behavior exhibited by K_0-normally consolidated samples of natural BBC in triaxial compression tests (CK_0U). These results were obtained by Ladd and Luscher (14) after consolidating thin-walled tube samples of the lower BBC to a consolidation stress, σ'_{vc}, in excess of twice the estimated in situ maximum past pressure, σ'_{vm}, in order to reduce sampling disturbance effects. The mean effective stress prior to shear, σ'_s, in these samples was therefore equal to the octahedral effective consolidation stress, $\sigma'_c = (1 + 2K_0)\sigma'_{vc}/3$. Similarities between band 3 and curve 1 representing the undrained behavior of the "undisturbed" NC resedimented clay are clear. Hence, band 3 (or curve 1) will be used in this section as a reference in discussing and evaluating sampling disturbance effects.

Table 1 and the shaded band 4 in Fig. 1 describe the range of undrained behavior exhibited by 15 thin-walled tube push samples of the

TABLE 1.—Effects of Tube Sampling Disturbances on Undrained Behavior of Lower Boston Blue Clay[a]

Dimensionless parameter (1)	K_0-Consolidated Undrained (CK_0U) OCR = 1		Unconsolidated Undrained (UU)[b] OCR < 1.3			
	Parameter (2)	Mean (3)	Parameter (4)	Min (5)	Mean (6)	Max (7)
Initial mean effective stress ratio	σ'_s/σ'_{vc}	0.67	σ'_s/σ'_{v0}	0 *S*	0.06	0.19 *M*
Undrained strength ratio	c_u/σ'_{vc}	0.32	c_u/σ'_{v0}	0.05 *S*	0.14	0.24 *M*
Strain at peak strength	ϵ_p%	0.28	ϵ_p%	5 *M*	11	18 *S*
Undrained modulus ratio	E_{50}/σ'_{vc}	365	E_{50}/σ'_{v0}	3 *S*	15	68 *M*

[a] In situ OCR ≤ 1.3.

[b] 15 samples from three sites.

Note: *S* = severe disturbance; *M* = mild disturbance.

lower BBC recovered from three sites and tested at the Massachusetts Institute of Technology (MIT) in an unconsolidated undrained (UU) triaxial compression mode of shearing (7,14,22). The results in Fig. 1 were plotted assuming OCR = 1 in normalizing UU data, i.e., assuming $\sigma'_{vc} = \sigma'_{vm} = \sigma'_{v0}$. Since σ'_{vm} is actually larger than the vertical effective stress, σ'_{v0}, this assumption leads to underestimation of disturbance effects in UU tests on thin-walled tube samples.

An examination of UU data and an evaluation of results in Fig. 1 and Table 1 indicate the following:

1. Disturbance effects in thin-walled tube samples can be quite variable as indicated by the wide range of UU data. However, no clear correlation could be established between the disturbance level and the diameter of the sampling tubes (127 versus 76.2 mm), the location of the sample within the middle half of the tube height, and the testing program (site, data, field, and lab personnel). This implies that operator-dependent disturbances can be significant and cannot always be reliably and consistently predicted.
2. Sample quality can be consistently correlated to the mean effective stress level in the soil before shearing, σ'_s. Disturbance decreases with σ'_s as shown by curves 5 and 6 representing typical UU behavior of good- and poor-quality tube samples, respectively.
3. Comparing results of UU and CK_0U tests disturbance increases the strain at peak strength, ϵ_p, and decreases the effective stress in the sample, σ'_s, the undrained strength, c_u, and the soil stiffness, E_{50}. Qualitatively, these effects are in agreement with PSA predictions.
4. Comparing soil behavior after perfect sampling (curve 2 in Fig. 1) with the typical behavior of good-quality tube samples (curve 5 in Fig. 1), it is clear that the PSA seriously underestimates the severity of disturbances in tube samples.

STRAIN PATH PREDICTIONS

The strain path method (2) provides an integrated and systematic framework for approaching deep geotechnical problems in a consistent and rational manner. Observations of soil deformations caused by the undrained penetration of rigid objects in saturated clays led Baligh (1) to hypothesize that, due to the severe kinematic constraints that exist in "deep" penetration problems, soil deformations and strains are, by and large, independent of the shearing characteristics of the soil. For applications to sampling disturbances, the strain path method (SPM) can provide approximate predictions of soil deformations, strains, stresses, and pore pressures caused by deep-push sampler penetration. Due to space limitations, results described in the following are limited to soil deformations and strains during undrained penetration of an idealized sampler (the simple sampler) in saturated incompressible clays, assuming that the soil exhibits no shearing resistance.

The Simple Sampler.—Fig. 2 presents predictions of soil distortions due to steady penetration of a "simple sampler" (S-sampler) with an outer diameter to wall thickness ratio, $B/t = 40$, in an incompressible clay. The S-sampler solution was obtained (5,6) by superimposing the effects of a ring source and a uniform flow within the framework of potential theory and according to the method described by Baligh (2). The walls of the S-sampler in Fig. 2 have curved tips and involve a slight reduction in the inner sampler diameter from a uniform value B_i ($= B - 2t$) to a minimum inner diameter B_e ($<B_i$) located a small distance

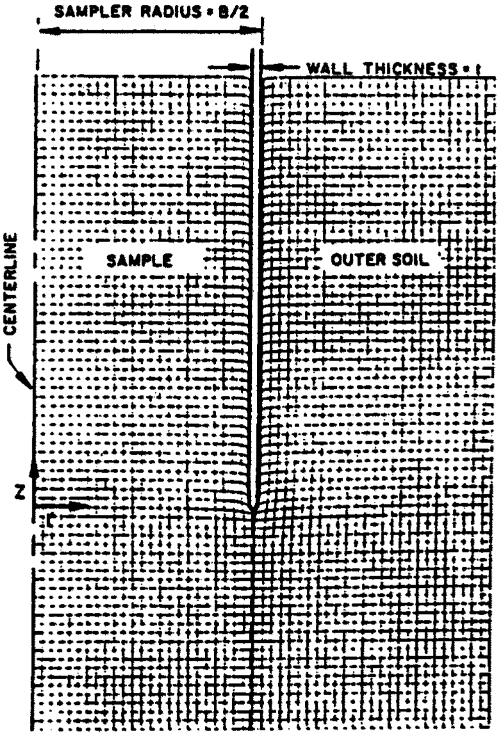

FIG. 2.—Soil Deformations during Undrained Simple Sampler Penetration in Saturated Clays ($B/t = 40$, ICR ≈ 1%)

(0.1B) behind the wall tips. Moreover, the S-sampler has an inside clearance ratio (ICR) [$= (B_i - B_e)/B_e \times 100$] of 0.98% and hence has similar (yet not identical) geometrical characteristics as thin-walled Shelby tubes routinely used in "undisturbed" sampling of clays with $B/t = 40$–47 and nominal values of the ICR = 1% (ASTM-D1587). In the United States, thin-walled Shelby tubes typically have diameters $B = 50.8$–127 mm and ICR's between 0.5 and 1.5%. The main difference between S-samplers and Shelby tubes is in the geometry of the walls within a distance, L, above the cutting edge. Specifically, the inner diameter of S-samplers involves a more gradual increase for B_e to B_i over a relatively large distance $L \approx 2B$ compared to Shelby tubes having a minimum value of $L = 12.7$ mm.

Visual examination of the distorted grid in Fig. 2 indicates that: (1) Soil deformations develop near the tip of the sampler walls and rapidly reach a steady condition inside the sampler; (2) at some distance behind the tip, clear distortions can be seen only near the sampler walls; and (3) virtually no distortions can be detected in the inner core of the sample, say, within a radius $B/4$ from the centerline. In practice, such samples would thus be classified as "excellent" based on x-ray techniques or visual observations.

Soil Strains.—Fig. 3 presents contour lines of the strain components ϵ_{rr}, $\epsilon_{\theta\theta}$, ϵ_{zz}, and ϵ_{rz} due to undrained penetration of an S-sampler with $B/t = 40$ and ICR = 0.98%. Considering compression positive, ϵ_{rr}, $\epsilon_{\theta\theta}$,

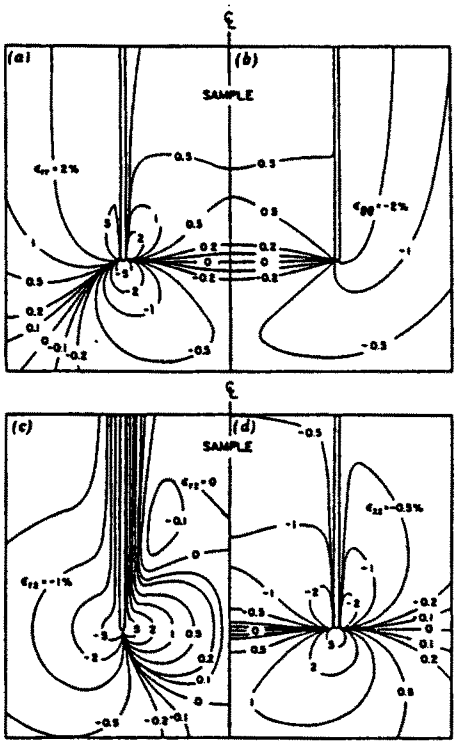

FIG. 3.—Deviatoric Strain Contours during Undrained Simple Sampler Penetration in Saturated Clays ($B/t = 40$, ICR $\approx$ 1%): (*a*) Radial Strain, ϵ_{rr}; (*b*) Tangential Strain, $\epsilon_{\theta\theta}$; (*c*) Meridional Shear Strain, ϵ_{rz}; and (*d*) Vertical Strain, ϵ_{zz}

and ϵ_{zz} represent the radial, tangential, and vertical normal strains, respectively; and ϵ_{rz} is the meridional shear strain. Results in Fig. 3 show that soil disturbance, as expressed by the level of shear distortions, decreases towards the center of the samples. Specifically:

1. In the outer half of the sample, strains are large and involve significant gradients, especially near the sampler walls.
2. In the inner half of the sample:
   (a) Relatively minor variations in soil strains exist;
   (b) the dominant straining component is ϵ_{zz};
   (c) the other strain components are approximately given by $\epsilon_{rr} \simeq \epsilon_{\theta\theta}$ and $\epsilon_{rz} \simeq 0$; and
   (d) hence, reasonable estimates of soil disturbances within the inner half of the tube can be obtained from results at the sample centerline.

Effect of Simple Sampler Geometry.—Fig. 4 shows the strain history of an element located at the centerline of S-samplers having aspect ratios B/t = 20, 40, and 50; and inside clearance ratios, ICR = 1.86%, 0.98%, and 0.79%, respectively. Conditions of cylindrical symmetry and incompressibility imply that this element, suffering the least disturbance inside the sampler, is subjected to triaxial shearing only with $\epsilon_{rr} = \epsilon_{\theta\theta} = -(1/2)\epsilon_{zz}$ and $\epsilon_{rz} = 0$. Results in Fig. 4 indicate that the soil is subjected to three distinct phases of undrained triaxial shearing: (1) an initial compression phase (ab) ahead of the sampler ($z \leq -0.35B$) where the axial strain, ϵ_{zz}, increases from zero to a maximum value, $\epsilon_{\max}$; (2) an extension phase (bc) in the vicinity of the cutting edge ($|z| < 0.35B$) where ϵ_{zz} decreases rapidly from $\epsilon_{\max}$ to a minimum, $\epsilon_{\min}$; and (3) a second compression phase (cd) inside the sampler ($z > 0.35B$) during which ϵ_{zz} approaches zero.

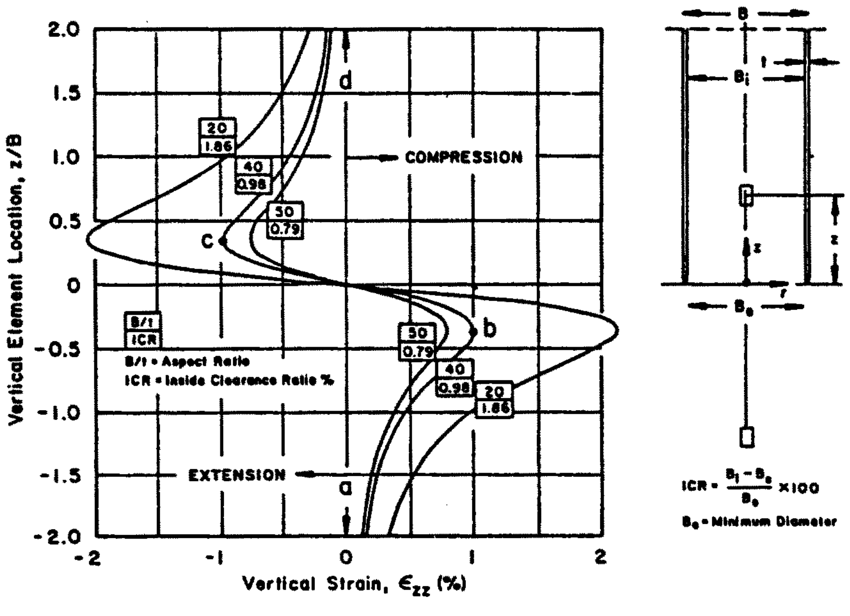

FIG. 4.—Straining History at Centerline of Simple Samplers

Chin (5) shows that, for thin-walled S-samplers ($B/t >> 1$), the ICR depends on the aspect ratio, B/t, and results in Fig. 4 can be approximated by

$$\epsilon_{zz} \simeq -\ln\left(1 + \frac{2t}{B}\frac{\left(\frac{z}{B}\right)}{\left[1 + 4\left(\frac{z}{B}\right)^2\right]^{3/2}}\right) \qquad (1)$$

Moreover, ϵ_{max} and ϵ_{min} occur at $(z/B) = \mp 1/(2\sqrt{2})$ and are approximately equal to $|\epsilon_{max}|$ given by

$$|\epsilon_{max}| \simeq \left(\frac{2}{3^{3/2}}\right)\frac{t}{B} = 0.385\frac{t}{B} \qquad (2)$$

For simple samplers with $B/t = 20$, 40, and 50, Eq. 2 predicts that the maximum axial strain levels, $|\epsilon_{max}|$, reached by soil particles at the centerline are approximately equal to 1.93%, 0.96%, and 0.77%, respectively. These values are close to the ICRs of the S-samplers considered, and are close to the peak strains in Fig. 4 and hence indicate that Eq. 2 provides very reasonable predictions even for the relatively thick-walled sampler with an aspect ratio $B/t = 20$. In fact, the simplicity of Eqs. 1 and 2 and their accuracy represented important factors in the selection of the S-sampler to show the basic aspects of tube penetration disturbances and to estimate disturbances of thin-walled Shelby tubes with $B/t = 40$–47 and ICR = 0.5%–1.5% as used in United States practice. Predictions corresponding to more realistic tip geometries and/or new sampler geometries designed to minimize disturbances can be obtained by the SPM, but involve more complicated solutions of more than one ring source (6).

Finally, it can be shown (3,5) that S-sampler predictions during the initial compression phase (from a to b in Fig. 4) ahead of the tube are exact and independent of the shearing behavior of the soil at locations where strains are sufficiently small to enable soil behavior to be assumed as linear and isotropic (and thus elastic). This increases the reliability of approximate SPM solutions during the initial compression phase, and in view of similarities between S-samplers and Shelby tubes commonly used in practice, suggests that these predictions provide reasonable estimates of compressive straining levels of the soil during actual thin-walled tube sampling.

IDEAL SAMPLING APPROACH

The "ideal sampling approach" (ISA) is proposed herein as an extension to the perfect sampling approach (PSA) required for the analysis and prediction of minimum levels of tube-push sampling disturbances in saturated clays. ISA denotes an idealized method of incorporating the effects of tube penetration, sample retrieval to the surface, and sample extrusion from the tube, but neglects all other types of disturbances, including operator-dependent disturbances and water content changes in the soil. The proposed method for implementing the ISA consists of two steps:

1. Estimate tube penetration disturbances on the basis of undrained S-sampler predictions at the centerline of the sample. These predictions are given in Fig. 4 or Eqs. 1 and 2.
2. Estimate the effects of sample retrieval and extrusion by assuming an idealized process of undrained shear stress relief from the (generally) anisotropic stress conditions in the tube to the final isotropic stress state of the sample before testing.

Step 2 adopts the same simplification adopted by perfect sampling regarding sample retrieval and extrusion simulation. Therefore, the only difference between the proposed ISA and the PSA is the incorporation of tube penetration disturbances, i.e., step 1, and hence the ISA reduces to the PSA in the case in which tube penetration disturbances are insignificant. This condition can be achieved by block sampling, i.e., by eliminating tube penetration effects, or by means of tube samplers with very thin walls or very large diameters (see results in Fig. 4 and Eqs. 1 and 2 when $t/B \rightarrow 0$).

Finally, it is noted that by proposing the ISA as an alternative to the PSA, it is inherently assumed that tube-penetration disturbance effects are significant. This assumption is supported by ample experimental evidence indicating that thin-walled samplers achieve major reductions in clay disturbance compared with thick-walled samplers (10,23,25). The following section presents laboratory test data on ideal sampling effects showing that tube penetration disturbances are also significant in case of thin-walled samplers currently used in practice.

IDEAL SAMPLING DISTURBANCE EFFECTS IN BOSTON BLUE CLAY

Clay and Ideal Sampling Simulation.—A limited laboratory testing program was performed on resedimented samples of Boston blue clay (BBC) to evaluate the effects of the proposed ISA on the undrained stress-strain strength characteristics of normally consolidated clays under K_0-conditions, i.e., no lateral straining. Saturated blocks of BBC were carefully prepared by K_0-consolidation from slurry, using a 305-mm diameter oedometer, to a vertical effective stress of 98 kPa. The BBC blocks were then swelled under K_0-conditions to an overconsolidation ratio (OCR) of 4. The water content after rebound varied in various batches between 39.5 ± 0.5%, and the liquid limit, plastic limit, and plasticity index varied within the ranges 41.5 ± 0.8%, 21.5 ± 0.6%, and 20 ± 1%, respectively.

Specimens for triaxial testing were cut from the block samples and reconsolidated in the triaxial cell under K_0-conditions to an initial vertical consolidation stress, $\sigma'_{vc} = 294 - 392$ kPa, i.e., three to four times the maximum past pressure of 98 kPa, in order to eliminate the effects of preconsolidation of the block samples and achieve specimens of K_0-normally consolidated (NC) BBC with a maximum past pressure, $\sigma'_{vm} = \sigma'_{vc}$. Ideal sampling disturbances were then simulated by subjecting the NC samples to: (1) The undrained strain path predicted by the SPM for soil elements along the centerline of an S-sampler with an aspect ratio $B/t = 40$ and ICR $\simeq$ 1% (Fig. 4 and Eq. 1) to simulate tube penetration;

TABLE 2.—Effects of Ideal Sampling Disturbances on Undrained Behavior of K_0-Normally Consolidated Resedimented Boston Blue Clay

		UNDRAINED DISTURBANCE SIMULATION				UNDRAINED SHEAR BEHAVIOR				
				Effective Stresses after Disturbance		Effective Stresses Prior to Shear				
Test (1)	Description/effect (2)	Tube penetration (3)	Sample retrieval and extrusion (4)	σ'_s/σ'_{vc} (5)	$K_s = \sigma'_{hs}/\sigma'_{vs}$ (6)	σ'_c/σ'_{vm} (7)	$K_c = \sigma'_{hc}/\sigma'_{vc}$ (8)	c_u/σ'_{vc} (9)	ϵ_p(%) (10)	E_{50}/σ'_{vc} (11)
1	Undisturbed[b]	No	No	—	—	0.654	0.481	0.319[a]	0.16[a]	350[a]
2	Ideal sampling[b]	Yes	Yes	0.278	1.0	0.278	1.0	0.263	4.42	88
3	Tube penetration[b]	Yes	No	0.267	0.426	0.267	0.426	0.253	4.35	17
4	Recompression	Yes	Yes	0.263[b]	1.0	0.654[b]	0.481	0.351	1.07	265
5	SHANSEP-1.5	Yes	Yes	0.23[b]	1.0	0.981[c]	0.481	0.320	0.30	450
6	SHANSEP-2	Yes	Yes	0.242[b]	1.0	1.308[d]	0.481	0.317	0.23	250

[a] Average of six tests.
[b] $\sigma'_{vc} = \sigma'_{vm}$.
[c] $\sigma'_{vc} = 1.5\sigma'_{vm}$.
[d] $\sigma'_{vc} = 2\sigma'_{vm}$.

and (2) the undrained stress relief to an isotropic stress state to model sample retrieval and extrusion according to the proposed ISA. All undrained triaxial shearing was conducted at a fixed axial strain rate, $\dot{\epsilon}_a$ = 0.5%/hr and hence, no attempt was made to realistically simulate the rate of soil straining.

Laboratory Testing Program.—The laboratory testing program consisted of six tests on K_0-NC resedimented BBC ($K_0 = 0.481 \pm 0.003$) with a maximum past pressure, σ'_{vm}, as defined in Table 2. In test 1, the sample was subjected to monotonic undrained shearing to determine the reference "undisturbed" NC behavior of the soil before disturbance. In test 2, the soil was subjected to the simulated disturbances of ideal sampling described previously in order to determine their effects on undrained behavior. In test 3, the soil was subjected to the same disturbances as in test 2, but without the undrained stress relief simulating sample retrieval and extrusion in order to isolate tube penetration disturbances and determine their relative importance. Tests 4–6 investigate existing techniques of reducing disturbance effects by reconsolidating samples subjected to ideal sampling disturbances prior to undrained shear. In test 4, the sample was K_0-reconsolidated to a vertical consolidation stress prior to shear equal to the maximum past pressure, σ'_{vm}, i.e., $\sigma'_{vc} = \sigma'_{vm}$), which corresponds to a mean (octahedral) effective consolidation stress, σ'_c, equal to $0.654\sigma'_{vm}$. Tests 5 and 6 were conducted in accordance with the SHANSEP procedure (12) where the samples were K_0-reconsolidated to $\sigma'_{vc} = 1.5\sigma'_{vm}$ and $2\sigma'_{vm}$, respectively. The corresponding values of σ'_c are 0.981 and $1.308\sigma'_{vm}$, respectively.

Ideal Sampling Disturbance Effects.—Fig. 5 and Table 2 present the behavior of the six samples during first undrained shearing from K_0-NC conditions. Sample 1 was subjected to monotonic compression, sample

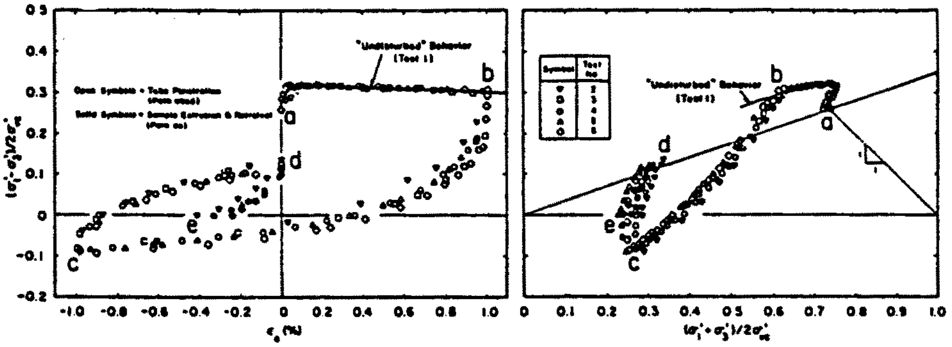

FIG. 5.—Ideal Sampling Disturbance of K_0-Normally Consolidated Resedimented BBC

3 to tube-penetration disturbances, and the other four (2,4–6) to ideal sampling disturbances. Examination of these data indicates the following:

1. Results during the initial compression phase (path ab, Fig. 5) and the extension phase (path bc, Fig. 5) are consistent and repeatable as evidenced by the very narrow band containing all the data. However, measurements during the second compression phase (path cd, Fig. 5) and the undrained stress relief phase (path de, Fig. 5) involve more scatter and lead to values of the mean effective stress after ideal sampling, σ_{is}', ranging between 0.23 and $0.278\sigma_{vc}'$.
2. The axial strain at peak strength, ϵ_p, is significantly exceeded during the initial compression phase. This implies that even under the ideal conditions of minimum disturbance (at the centerline) considered herein, the soil fails before entering the sampler.
3. During initial monotonic shearing (path ab), the six specimens exhibit a consistent behavior with $c_u/\sigma_{vc}' = 0.319$ (± 0.003), $\epsilon_p = 0.16\%$ ($\pm 0.07\%$), and $E_{50}/\sigma_{vc}' = 347$ (± 190). Moreover, with the exception of a less pronounced brittleness (strain-softening), the behavior of these resedimented samples is not significantly different from results of CK_0U tests on natural samples of the lower BBC (band 3 in Fig. 1) or the resedimented clay tested by Ladd and Varallyay (15; curve 1 in Fig. 1).
4. After ideal sampling simulation, the mean effective stress in four samples (2,4–6) was reduced from an initial value of $0.654\sigma_{vc}'$ to $\sigma_{is}' \approx 0.25\sigma_{vc}'$. This represents a significant reduction (62%) compared to perfect sampling disturbances involving only an 8% reduction (15).

Fig. 6 and Table 2 present measurements obtained in test 2 representing the undrained behavior of the soil after ideal sampling disturbances as well as the "undisturbed" behavior obtained in test 1. For comparison purposes, Fig. 6 also shows soil behavior after perfect sampling disturbance (curve 2 in Fig. 1) and the typical behavior exhibited by good-quality tube samples of the lower BBC in UU tests (curve 5 in Fig. 1) after neglecting the slight overconsolidation (OCR < 1.3) of the natural soil. An examination of these results shows that the ISA estimates much more significant disturbance effects compared to the PSA

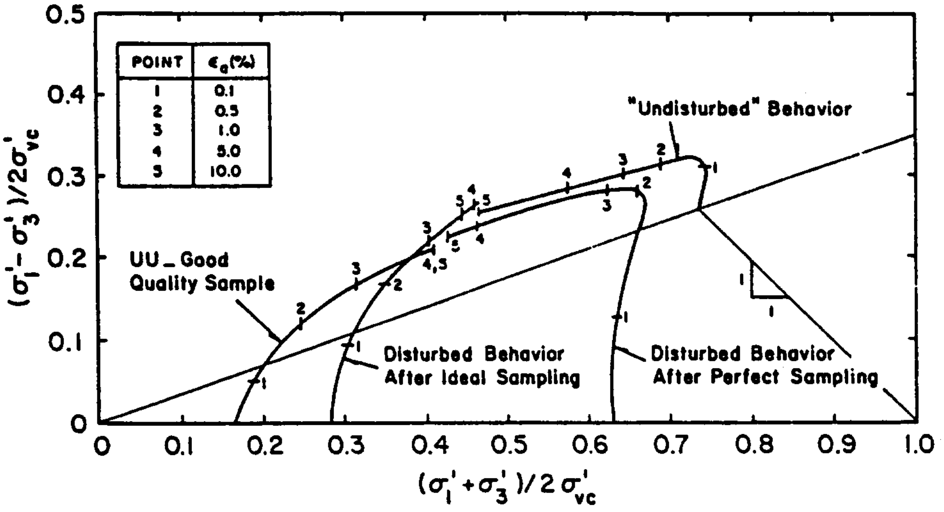

FIG. 6.—Comparison of Ideal versus Perfect Sampling Disturbance Effects on Undrained Behavior of Normally Consolidated Resedimented BBC

and seems to explain most of the disturbance effects observed in UU tests on good-quality tube samples. This is evidenced by the following aspects of undrained behavior:

1. The effective stresses in the soil prior to shear—Actual tube sampling disturbances typically reduce the mean effective stresses from about $0.66\sigma_{v0}'$ to $\sigma_s' = 0.19\sigma_{v0}'$.or much less. Predictions of the ISA overestimate this value of σ_s' by 35 (±13)% (versus 230% in case of the PSA).
2. The undrained shear strength—Tube sampling reduces c_u from $0.32\sigma_{v0}'$ to $0.24\sigma_{v0}'$ or less. The ISA overpredicts this value by 10% (versus 15% for the PSA).
3. The strain at peak strength—Actual disturbances typically increase ϵ_p from 0.16% to 5% or more. The ISA underestimates this value by only 12% (versus 625% for the PSA).
4. The soil stiffness—Actual disturbances typically reduce E_{50} from about $350\sigma_{v0}'$ to $68\sigma_{v0}'$ or less. The ISA overestimates this value by about 30% (versus 300% for the PSA).
5. The post-peak behavior and undrained stress path—The ISA predicts an undrained stress path similar in shape to that of the UU test, which is distinctly different from that predicted by the PSA. In particular, the ISA correctly predicts the virtual elimination of strain softening exhibited by the "undisturbed" clay beyond the peak.

Tube Penetration Disturbance.—The relative importance of tube penetration disturbances versus sample retrieval and extrusion disturbances, as incorporated in the proposed ISA, can be determined by comparing results of tests 2 and 3 presented in Fig. 7 and Table 2. Test 2 represents the undrained behavior after ideal sampling disturbances, whereas test 3 represents the behavior after tube penetration disturbances only. Examination of these data indicates the following: (1) The two tests give virtually identical stress paths and identical stress-strain

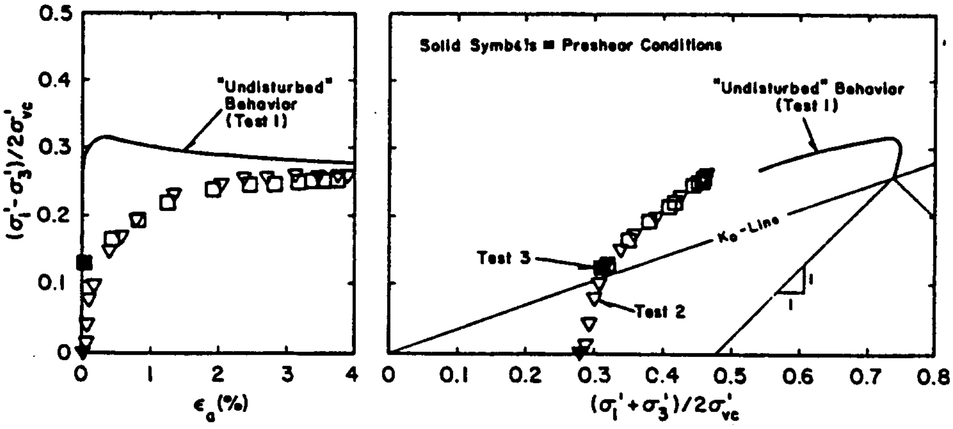

FIG. 7.—Tube Penetration Effects in Ideal Sampling Disturbances

behavior at strain levels exceeding 0.5%; and (2) at small strain levels (<0.5%), the rebounded sample (test 2) exhibits a higher stiffness, $E_{50} = 88\sigma_{vc}'$, than the sample subjected only to tube penetration disturbances having $E_{50} = 17\sigma_{vc}'$.

Therefore, it is concluded that, with the exception of soil stiffness at small strain levels, tube-sampling disturbance effects estimated by the proposed ISA are primarily due to tube-penetration disturbances.

Reduction of Sampling Disturbance Effects.—Sampling disturbance effects on the undrained behavior of clays can be reduced by reconsolidating the soil prior to shearing. Two methods are commonly used: (1) the Recompression method (4), in which the soil is reconsolidated under K_0-conditions to σ_{vc}' equal to the in situ vertical effective overburden pressure, σ_{v0}'; and (2) the SHANSEP method (12), in which the reconsolidation stress σ_{vc}' should exceed 1.5 to 2 times the estimated maximum past pressure, σ_{vm}', and then the sample is rebounded to the estimated in situ OCR before undrained shearing. For normally consolidated deposits of interest herein ($\sigma_{v0}' = \sigma_{vm}'$), the difference between the two methods is most pronounced. Fig. 8 and Table 2 compare the two methods with regards to the undrained behavior of K_0-NC resedimented BBC after ideal sampling disturbances. Results in Fig. 8 and Table 2 correspond to test 4 (recompression, $\sigma_{vc}' = \sigma_{vm}'$), test 5 (SHANSEP-1.5, $\sigma_{vc}' = 1.5\sigma_{vm}'$) and test 6 (SHANSEP-2; $\sigma_{vc}' = 2\sigma_{vm}'$), as well as test 1 representing the "undisturbed" behavior of the resedimented clay.

Examination of these data shows the following: (1) By reconsolidating the soil prior to shear, both methods reduce disturbance effects significantly (see results of test 2 in Fig. 7); (2) the recompression method overpredicts c_u of the "undisturbed" soil by 10% and ϵ_p by 570%; and (3) reconsolidation according to the SHANSEP method leads to an undrained (normalized) behavior that is closer to the "undisturbed" soil. SHANSEP-2 gives basically the same results as SHANSEP-1.5, with virtually the same c_u/σ_{vc}' as the "undisturbed" soil, and overpredicts ϵ_p by only 45%.

In summary, test results indicate that most aspects of ideal sampling disturbance effects on the undrained behavior of K_0-NC resedimented

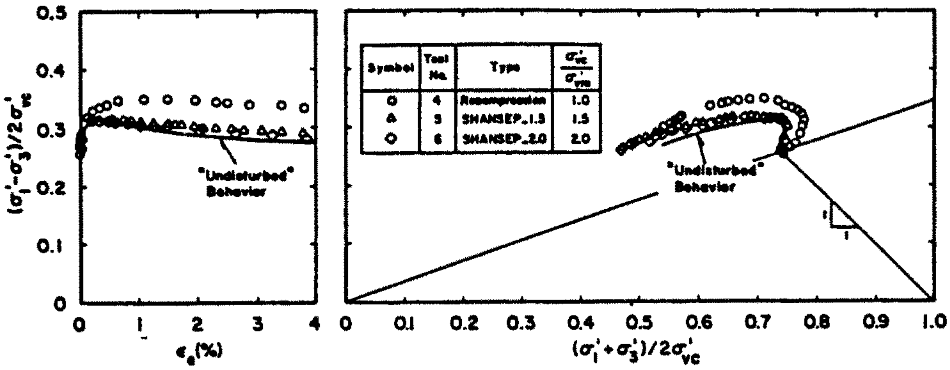

FIG. 8.—Reconsolidation Effects on Ideal Sampling Disturbances of Normally Consolidated Resedimented BBC

BBC can be reduced by reconsolidating the soil and can, in effect, be virtually eliminated by the SHANSEP method. This is due to the fact that resedimented BBC after ideal sampling disturbances shows the same undrained normalized behavior as exhibited before disturbance, and the SHANSEP method was developed for such clays (12). It is believed that this result remains valid in the case of smaller levels of clay disturbance and is applicable to less sensitive clays subjected to the same levels of disturbance. On the other hand, extrapolation of this result to higher levels of disturbance or its generalization to more brittle clays requires validation from tests on the clay(s) of interest where the pertinent disturbance levels are simulated. Finally, for very high levels of disturbance, and in cases involving very brittle clays with a pronounced structure, e.g., quick and cemented clays, elimination of disturbance effects by reconsolidation is unlikely to succeed, and block samples or improved tube sampling methods are required (11,16–19,26).

SUMMARY AND CONCLUSIONS

This paper presents the ideal sampling approach (ISA) as an extension to the perfect sampling approach (PSA) that is required for the rational formulation and prediction of minimum disturbance effects due to tube-push sampling of clays. The ISA incorporates the important effects of tube penetration disturbances on the basis of approximate predictions of the strain path method (SPM) (2), in addition to the effect of undrained shear stress relief considered by perfect sampling. In particular, the approach adopts the undrained strain paths of soil elements located at the centerline of a simple sampler considered representative of thin-walled tube samplers currently used in practice.

Two basic reasons are believed to make predictions of the ISA more relevant than the existing PSA: (1) In current sampling practice, tube penetration induces significant straining of the soil and thus represents a dominant source of disturbance, especially in slightly overconsolidated sensitive clays; and (2) deep tube penetration is, by and large, a strain-controlled process where the strain history (or path) of the soil is not very sensitive to soil properties and can hence be more easily and reliably estimated according to the SPM than its stress path.

In support of the preceding, this paper presents the following results and data regarding deep undrained thin-walled push sampling of saturated (incompressible) clays:

1. Predictions of soil strains due to the undrained penetration of a simple sampler (S-sampler) obtained according to the SPM, which neglects the shearing resistance of the soil, show that:
   a. Soil disturbance, as described by the level of shear distortions, decreases towards the center of the sample (Fig. 3). Hence, soil elements located at the sample centerline suffer the least disturbance.
   b. For an S-sampler with a diameter to wall thickness ratio, $B/t = 40$, and an inside clearance ratio, ICR $\simeq$ 1%, soil disturbances in the outer half of the sample involve significant nonuniformities. Practically, this implies that the soil located in the outer half of the tube sample should be avoided in the preparation of representative specimens for laboratory testing. On the other hand, tube penetration disturbances in the inner core are very similar to disturbances at the sample centerline.
   c. Soil elements at the tube centerline are subjected to three distinct phases of undrained triaxial shearing (Fig. 4): (i) An initial compression phase ahead of the sampler; (ii) an extension phase near the elevation of the cutting edge; and (iii) a second compression phase inside the sampler. For thin-walled tube samples, the maximum axial strains experienced in compression and extension are approximately equal and given by $|\epsilon_{max}| = 0.385 (t/B)$. This means that, for S-samples with an aspect ratio, B/t, between 50 and 40 and an ICR between 0.8% and 1%, the maximum strains $|\epsilon_{max}|$ are also between 0.8% and 1%. These predictions are believed to provide reasonable estimates of $|\epsilon_{max}|$ in the case of 50.8- to 127-mm thin-walled Shelby tubes commonly used in practice where B/t is between 40 and 47 and ICR is typically between 0.5% to 1.5%.
2. Triaxial tests conducted on resedimented K_0-normally consolidated Boston blue clay (BBC) show that soil disturbances predicted by the proposed ISA have significant effects on the undrained behavior of the clay. Specifically, results of simulated ideal sampling disturbances for a thin-walled S-sampler with an aspect ratio $B/t = 40$ and inside clearance ratio, ICR = 1%, show that:
   a. The measured axial strain at peak strength, $\epsilon_p \simeq 0.16\%$, is much lower than the maximum strain, $|\epsilon_{max}| = 1\%$, predicted during the initial compression phase ahead of the sampler. This implies that, in actual thin-walled tube sampling of (soft lean sensitive) clays having a low value of ϵ_p, failure of the soil in triaxial compression is likely to take place even before the sample enters into the tube.
   b. The ISA predicts significant reductions in mean (octahedral) effective stresses due to sampling disturbances (from about $0.66\sigma'_{vc}$ to $\sigma'_{is} = 0.25\sigma'_{vc}$) compared to the PSA ($\sigma'_{ps} = 0.63\sigma'_{vc}$). On the other hand, the ISA underestimates the severity of ac-

tual disturbances in good quality tube samples of the slightly overconsolidated lower BBC (OCR < 1.3), where measurements show the effective stresses to be $\sigma'_s = 0.19\sigma'_{v0}$ or less.

c. After simulated disturbances, measurements of undrained behavior in triaxial compression tests also show that the ISA predicts more severe sampling disturbance effects than the PSA that are in better agreement with, yet consistently underestimate, actual sampling disturbance effects exhibited by good quality tube samples of the lower BBC in unconsolidated undrained (UU) tests. These results imply that the ISA is superior to the PSA as a method of estimating minimum disturbance effects.

d. Sampling disturbances predicted by the ISA are primarily due to tube-penetration effects rather than to sample retrieval and extrusion effects when the latter are simulated by an idealized process of undrained shear stress relief.

e. Ideal sampling disturbances can be reduced by the recompression or the SHANSEP procedures consisting of reconsolidating the samples under K_0-conditions to a vertical effective stress, σ'_{vc}, before undrained shearing. Samples of resedimented BBC recompressed to σ'_{vc} equal to the maximum past pressure, σ'_{vm}, exhibited a slightly higher peak strength than the "undisturbed" normally consolidated soil, but a much higher strain at peak. On the other hand, samples consolidated to $\sigma'_{vc} = 1.5\sigma'_{vm}$ in accordance with the SHANSEP procedure exhibited virtually the same behavior (after normalization by σ'_{vc}) of the "undisturbed" soil and samples consolidated to $\sigma'_{vc} = 2\sigma'_{vm}$.

Based on these results and in spite of uncertainties associated with the proposed ISA due to the approximate nature of tube penetration disturbances predicted by the SPM, the following practical conclusions and recommendations are advanced:

1. The PSA can provide reasonable estimates of minimum disturbances in good-quality block samples of clays.
2. Predictions of the ISA are more representative than the PSA with regards to sampling disturbances associated with thin-walled tube samplers commonly used in practice. This implies that effective stresses in the sample, σ'_{is}, estimated on the basis of the ISA, should be used (instead of σ'_{ps} estimated by the PSA) as a reference to establish a quantitative measure of avoidable disturbances in tube samples retrieved according to current sampling methods. Specifically, in applications to soft slightly overconsolidated clays, the ratio σ'_s/σ'_{is} should be used instead of σ'_s/σ'_{ps} to describe the disturbance level and possibly to correct the normalized strength parameters obtained in unconsolidated undrained tests performed on these samples.
3. Using the proposed ISA and its extensions, improvements in current tube sampling and laboratory testing practices can be achieved by systematic investigations of the important remaining factors on tube sampling disturbances and their effects in various types of soils: (a) sampler geometry (e.g., B/t, ICR, geometry of cutting shoe, etc.) and inside wall friction; (b) water content and volume changes during and after

sampling; (c) ratio of specimen to sampler diameter; and (d) extrusion and drilling disturbances. Improvements are especially needed for brittle clays with a well-defined structure, e.g., quick and cemented clays, as well as noncohesive deposits, e.g., sands and silts, where sufficient reduction in sampling disturbance effects cannot be achieved by reconsolidation prior to shear.

ACKNOWLEDGMENTS

The writers wish to express their sincere gratitude to C. C. Ladd for carefully reviewing the manuscript and, more importantly, for providing them with the necessary background in the area of soil behavior that made the conception of this research possible. Special thanks to D. Lutz, former research engineer at M.I.T., for his diligence and care in performing the testing program under the guidance of J. Germaine, director of the M.I.T. Geotechnical Lab. Portions of the work described herein were supported by the Sea Grant Program at M.I.T.

APPENDIX.—REFERENCES

1. Baligh, M. M., "Theory of Deep Site Static Cone Penetration Resistance," *Research Report R75-56, No. 517,* Dept. of Civil Engineering, M.I.T., Cambridge, Mass., 1975, 133 pp.
2. Baligh, M. M., "Strain Path Method," *Journal of Geotechnical Engineering,* ASCE, Vol. 111, No. 9, Sept., 1985, pp. 1108–1136.
3. Baligh, M. M., "Undrained Deep Penetration II: Pore Pressures," *Geotechnique,* Vol. 36, No. 4, 1986, pp. 487–501.
4. Bjerrum, L., "Problems of Soil Mechanics and Construction on Soft Clays," State-of-the-Art Report, Session 4, *Proceedings of the 8th International Conference on Mechanics and Foundation Engineering,* Moscow, USSR, Vol. 3, 1973, pp. 109–159.
5. Chin, C. T., "Open-Ended Pile Penetration in Saturated Clays," thesis presented to M.I.T., at Cambridge, Mass., in 1986, in partial fullfillment of the requirements for the degree of Doctor of Philosophy.
6. Chin, C. T., and Baligh, M. M., "Deformation and Strains Due to Open-Ended Pile Installation in Saturated Clays," *Research Report R83-17, Order No. 757,* Dept. of Civil Engineering, M.I.T., Cambridge, Mass., 1983, 81 pp.
7. Guertin, J. D., "Stability and Settlement Analyses of an Embankment on Clay," thesis presented to M.I.T., at Cambridge, Mass., in 1967, in partial fulfillment of the requirements for the degree of Master of Science.
8. Hight, D. W., Gens, A., and Jardine, R. J., "Evaluation of Geotechnical Parameters from Triaxial Tests on Offshore Clay," *Proceedings, International Conference on Offshore Site Investigation,* Society for Underwater Technology, London, England, 1985, pp. 253–268.
9. Holm, G., and Holtz, R. D., "A Study of Large Diameter Piston Samplers," *Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering,* Tokyo, Japan, Vol. 1, 1977, pp. 73–78.
10. Hvorslev, J. M., "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes," Waterways Experiment Station, Vicksburg, Miss., 1949, 521 pp.
11. Lacasse, S., Berre, T., and Lefebvre, G., "Block Sampling of Sensitive Clays," *Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering,* San Francisco, Calif., 1985, pp. 887–892.
12. Ladd, C. C., and Foott, R., "New Design Procedure for Stability of Soft Clays," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 100, GT7, Jul., 1974, pp. 763–786.

13. Ladd, C. C., and Lambe, T. W., "The Strength of 'Undisturbed' Clay Determined from Undrained Tests," *American Society for Testing and Materials, STP 361*, 1963, pp. 342–371.
14. Ladd, C. C., and Luscher, U., "Engineering Properties of the Soils Underlying the MIT Campus," *Research Report R65-68, No. 185*, Dept. of Civil Engineering, M.I.T., Cambridge, Mass., 1965.
15. Ladd, C. C., and Varallyay, J., "The Influence of Stress System on the Behavior of Saturated Clays During Undrained Shear," *Research Report R65-11, No. 177*, Dept. of Civil Engineering, M.I.T., Cambridge, Mass., 1965, 263 pp.
16. La Rochelle, P., "Discussion of State-of-the-Art Report in Session 4," *Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 4.2, 1973, pp. 102–106.
17. La Rochelle, P., Sarrailh, J., Tavenas, F., and Leroueil, S., "Causes of Sampling Disturbances and Design of a New Sampler for Sensitive Soils," *Canadian Geotechnical Journal*, Vol. 18, No. 1, 1981, pp. 52–66.
18. La Rochelle, P., and Lefebvre, G., "Sampling Disturbance in Champlain Clays," *American Society for Testing and Materials, STP 483*, 1970, pp. 143–163.
19. Lefebvre, G., and Poulin, C., "A New Method of Sampling in Sensitive Clay," *Canadian Geotechnical Journal*, Vol. 16, 1979, pp. 226–233.
20. Nelson, J. D., and Brand, E. W., Moh, Z. E., and Mason, I. D., "The Use of Residual Stress to Define Sample Quality," *Proceedings of the Special Session on Quality in Soil Sampling, 4th Asian Conference*, International Society for Soil Mechanics and Foundation Engineering, Bangkok, 1971, pp. 82–87.
21. Okumura, T., "The Variation of Mechanical Properties of Clay Samples Depending on its Degree of Disturbance," *Proceedings of the Special Session on Quality in Soil Sampling, 4th Asian Conference*, International Society for Soil Mechanics and Foundation Engineerinig, Bangkok, 1971, pp. 73–81.
22. "Proceedings of the Foundation Deformation Prediction Symposium," *Research Report R75-32, Order No. 512*, Dept. of Civil Engineering, M.I.T., Cambridge, Mass, 1975, 157 pp.
23. "Quality in Soil Sampling," *Proceedings of the Special Session, 4th Asian Conference*, International Society for Soil Mechanics and Foundation Engineering, Bangkok, Vol. 2, 1971.
24. Skempton, A. W., and Sowa, V. A., "The Behavior of Saturated Clays During Sampling and Testing," *Geotechnique*, Vol. 13, No. 4, 1963, pp. 269–290.
25. "Special Procedures for Testing Soil and Rock for Engineering Purposes," *American Society for Testing and Materials, STP 479*, 1970.
26. Tavenas, F., and Leroueil, S., "Discussion of Theme Lecture 2-B," *Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering*, San Fransico, Calif., in press.