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J. H. Schmertmann[1]

Use the SPT to Measure Dynamic Soil Properties?—Yes, But..!

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ABSTRACT: The author briefly reviews the factors important to the blowcount (N) values obtained from the standard penetration test (SPT), and describes the dynamics of the SPT in terms of wave transmission theory and measurements. The SPT appears to correlate well qualitatively with sand liquefaction potential, with N proportional to the factor of safety against liquefaction. The SPT can also provide the basis for the field-model determination of the J_s and J_p damping coefficients in the wave equation analysis of pile-driving problems. An example indicates it may also correlate locally with shear wave velocity in sands. Because of its current variability, however, the profession needs an improved, possibly alternative ASTM standard before we use the SPT in important dynamic design problems. The author suggests using a mechanized hammer drop system producing a fixed energy content in the first compression wave in the rods, and the use of rotary drilling with the hole filled with drilling mud at all times.

KEY WORDS: standard penetration test, dynamics, wave equation, liquefaction, shear wave velocity (or shear modulus), ASTM standard, energy, soils, design

Worldwide interest in the standard penetration test (SPT) has increased greatly in the past five years, primarily as a result of the great economic importance of SPT data for the evaluation of possible liquefaction behavior when siting major onshore and offshore structures. Perhaps deMello [*1*][2] started this renewed interest through his exhaustive but frustrating state-of-the-art paper on the SPT. "Frustrating" because he found, despite an exhaustive search, virtually no carefully controlled research on the SPT. Since then the present author and others have performed controlled research involving both the statics and dynamics of the SPT, which has led to important new insight into what happens during the SPT.

[1] Professor, Department of Civil Engineering, University of Florida, Gainesville, Fla. 32611.
[2] The italic numbers in brackets refer to the list of references appended to this paper.

The author believes that understanding the SPT first requires an understanding of its dynamics. It then becomes clear that the SPT blowcount measurement, or N-value, results from the dynamic interactions between hammer, rods, sampler, and soil. In principle, a dynamic test such as the SPT should model a dynamic structure-soil interaction problem or at least sense some dynamic behavior properties of the soil sampled.

The SPT models the pile-driving problem and there exists a good theoretical connection between SPT behavior and the damping coefficients, J_p and J_s, very important in any wave equation analysis of pile-driving problems. Seed [*2*] showed that SPT N-values also appear to correlate well, at least qualitatively, with liquefaction behavior. Also, as shown subsequently by an example, the SPT N-values may correlate well empirically with shear wave velocity, V_s. The dynamic SPT should, in principle, correlate better with dynamic soil behavior than with any static or quasi-static test such as the Dutch cone penetration test (CPT).

Unfortunately, before any of these important dynamic soil property correlations can reach a quantitatively useful point of reliability and reproducibility, matching what we usually expect from our engineering tests, the profession must make important modifications to the present ASTM Penetration Test and Split-Barrel Sampling of Soils (ASTM D 1586) standard. This paper includes suggestions for such modifications.

A Minisurvey of New Research Knowledge

Schmertmann [*3*] showed in a discussion to deMello [*1*] that soil friction or adhesion along the inside and outside surfaces of the SPT sampler could account, and probably did account, for a major portion of the total static and dynamic soil resistance against sampler penetration. The percentage of side shear to total resistance usually increases as the cohesiveness of the soil increases. This means that a major portion of the energy of the sampling goes into shear. As a practical demonstration of this fact, Stokoe and Woods [*4*], found the SPT an acceptable way of introducing waves rich in shear energy in their crosshole shear wave velocity measurements.

Reasoning that the variables that affect the CPT would likely affect the SPT in a similar manner, Schmertmann [*3*] pointed out the probable major importance of the *in situ* horizontal effective stresses in determining the N-value in a soil. Zolkov and Weisman [*5*] had already suggested this possibility in their study of sand overconsolidated by the removal of overburden. Rodenhauser [*6*], working in a triaxial test chamber at Duke University, obtained SPT results in a dry sand, indicating N proportional to the octahedral stress to the ⅔ power. Marcuson and Bieganousky ([*7*] Fig. 10) report a marked increase in N at overconsolidation ratio (OCR)

= 3 compared with the same sand at OCR = 1, presumably due to the greater lateral stresses after overconsolidation. From all of this it seems clear that *in situ* horizontal stresses play a major role, perhaps a dominant role, in determining N.

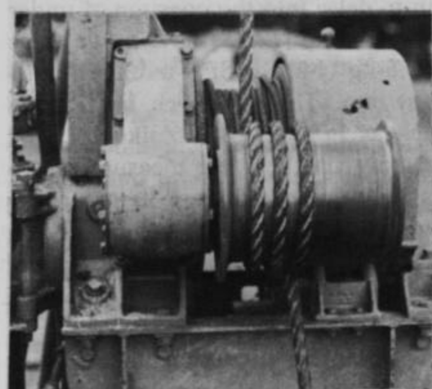
N-values have played an important role in the field evaluation of liquefaction potential. Seed and Idriss [*8*] used N-values to estimate relative density, then compared field liquefaction and no-liquefaction cases with relative density and earthquake acceleration, and then finally prepared N-value and depth charts to indicate the likelihood of liquefaction. The first step in this reasoning, estimating D_r from N, received severe criticism at the time [*9–11*]. More recently, the controlled N-D_r study recently completed by the Waterways Experiment Station and reported by Marcuson and Bieganousky [*7*] tends to further discredit the quantitative use of any such correlation unless made specifically for a given site. Although the Seed and Idriss double use of N-values reduces the importance of the N-D_r first step, Seed has responded to such criticism and to new research knowledge and has now eliminated this step entirely by suggesting the direct use of N-values without an intermediate correlation with relative density. With this new method, the factor of safety against liquefaction varies linearly with the N-value. Thus, a 100 percent error in N would result in a 100 percent error in factor of safety.

Only recently have researchers begun to delve into the question of understanding the dynamics of the SPT. Kovacs et al [*12,13*] have made direct measurements of the velocity of the 63.5-kg (140 lb) SPT hammer at the instant of impact with the anvil-rod system. Their research has demonstrated quantitatively what others, such as Frydman [*4*], Zolkov [*11,15*], and Serota and Lowther [*16*], showed only via the gross measurement of blowcount ratios—the large variations in N due to different hammer-drop systems. Their data showed definite trends from which they deduced that increasing the energy in the hammer at impact would decrease N, with some preliminary indications of N proportional to the inverse of hammer energy.

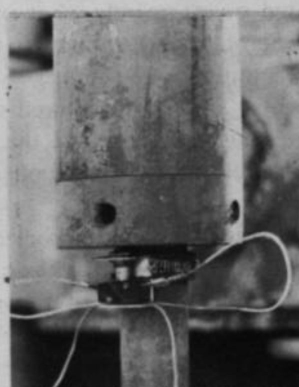
Schmertmann [*17*] reported on perhaps the first experimental investigation of the dynamic behavior involved when an SPT sampler penetrates the soil in response to the stress waves generated by the SPT hammer blow. The following section of this paper discusses in a summary way some of the findings from this research. The reader interested in details can consult the Ref *17*. This research involved a coordinated study of dynamic force-time measurements obtained just below the hammer and just above the sampler, resistance measurements during the quasi-static penetration of an SPT sampler, associated quasi-static friction-cone penetration tests, and computer simulations using the one-dimensional wave equation. Figure 1 shows some photos from the research.

(a) Screwing the dynamic load cell into the string of rods

(b) The SPT hammer-rod system with load cell in place

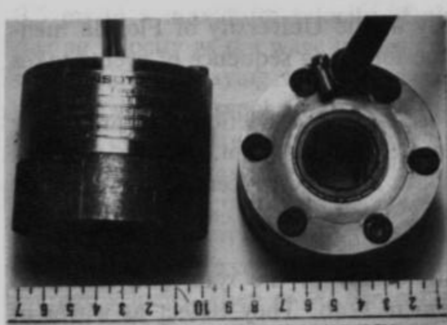


(c) Typical manila rope & cathead system used to raise and drop the SPT hammer (note 3 turns)

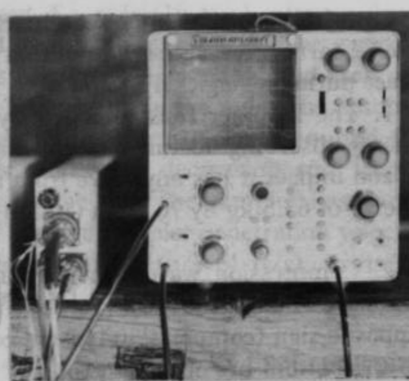


(d) Hammer strikes anvil & simultaneously hits trigger to begin force-time record from load cell

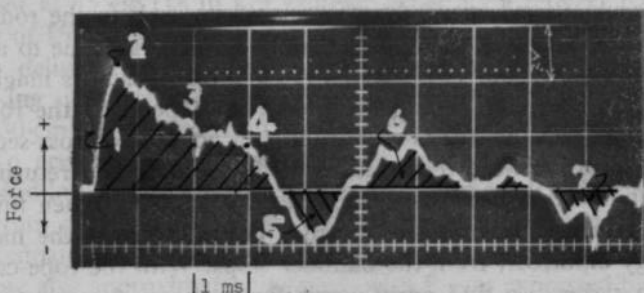
FIG. 1—*Measuring the dynamic energy input into the SPT rods for research or calibration or both.*



(e) The hollow dynamic load cell, 40,000 lb capacity, custom made by Sensotec Co.



(f) The load cell signal then put on a storage oscilloscope, photographed, digitized, and integrated for energy content



(g) Typical oscilloscope force-time record from a single SPT hammer blow. Numbers indicate:

1) Rapid rise of force in initial compression wave.

2) Peak force in this wave - about 21,000 lb.

3) Force decays with successive wave traverses in hammer.

4) Time at which the tension wave reflected from the sampler reaches the load cell. Rods then pull away from the hammer and hammer energy transfer stops.

Note: $E_i \sim \int_{1}^{4} F^2\,dt$

5) The first tension wave.

6) The second compression wave after reflection of the tension wave at the top of rods (note reduced energy content compared to first compression wave)

7) The second tension wave, etc.

FIG. 1—*Continued* (*1 lb = 0.45 kg*).

Review of Dynamics of SPT Sampler Penetration

From the coordinated research study at the University of Florida mentioned earlier, the author found that the following sequence of events takes place during a single SPT blow:

1. The hammer falls impeded by rope-cathead friction and any other energy-absorbing features of the hammer drop system. At the moment of rod impact it has anywhere from about 30 to 80 percent of its supposed energy of 63.5 kg by 76.2 cm (140 lb by 30 in.) = 4840 cm-kg (4200 in.-lb) = E^*.

2. Compression waves start simultaneously in the rods and hammer, traveling about 5030 m/s (16 500 ft/s) in both. They reflect as waves of opposite sign (compression-tension-compression, etc.) each time they come to the bottom or top of the rods or hammer. Because of its short length, many more wave traverses take place in the hammer than in the rods. Each time the compression wave pulse in the hammer reaches the hammer-rod contact, some of the hammer wave energy transfers to the rods, with a gradual and stepped decay in the amount per transfer.

3. The aforementioned energy transfer manifests itself in the rods as a compression wave with a short (approximately 0.6 ms) rise time to a peak compression stress of about 110 320 kPa (16 000 psi). Then its magnitude decays stepwise with time. These wave properties depend on the rod and hammer materials (steel in cases investigated) but not on rod cross-sectional area. The compression wave then reflects at the sampler and returns as a tension wave but with a net loss of energy to the sampler. When this first tension wave reaches the hammer, the rods pull away from the hammer and the energy input, E_i, from the hammer stops. With the rope-cathead hammer drop system we find great variability in E_i, with an average E_i equal about 50 percent of E^* *[18,19]*. The longer the rods, the greater the hammer-rod contact time and the more hammer energy that enters the rods for possible sampler penetration. Rod lengths less than 6 m (20 ft) cause progressively more significant reductions in hammer energy input because of the progressively earlier separation of rods from the hammer.

4. The compression wave entering the rod depends only on the hammer-rod system. It does not depend on the soil strength properties and therefore does not depend on N. For rod lengths exceeding 6 m (20 ft), 90+ percent of the compression wave energy has already entered the rods before the hammer senses any effect from the soil around the sampler. Soil resistance at the sampler, and therefore the N-value, has virtually no effect on determining E_i. Because of inevitable energy loss to heat during hammer impact as well as some energy always getting trapped in the anvil, the energy in the hammer at impact must exceed E_i. The energy loss from the impact can equal about 10 to 20 percent of E^* *[18,19]*.

5. The sampler does not begin its penetration until the first compression

wave reaches the bottom of the sampler. Then it accelerates in about 0.5 ms to a maximum velocity of about 4.5 m/s (15 ft/s), afterward reducing velocity as the wave passes and its force level reduces. The sampler penetrates in decaying surges or cycles of suddenly increased and then decreasing velocity, synchronous with the wave cycles in the rods. The number of such cycles increases with decreasing N because the time required for penetration increases as N decreases, and with decreasing rod length because the time per cycle decreases. By the time the sampler has penetrated to 90 percent of its final set, the average sampler penetration velocity *during* this 90 percent has reduced to about 1.2 m/s (4 ft/s), with the average velocity when *at 90 percent* reduced to about 0.45 m/s (1.5 ft/s) [*17,20*].

6. The time for the sampler to reach 90 percent of its final set under each blow varies inversely with N, taking approximately 10 ms when N = 20 and 40 ms when N = 5.

7. The set/blow, equal to 30 cm/N' (12 in./N'), decreases steadily over the 15 to 45 cm (6 to 18 in.) total penetration to measure N. The set per blow at 45 cm (18 in.) of sampler penetration reduces compared with the set of 15 cm (6 in.) in the same soil and when using the same hammer system delivering the same E_i. This decrease results from the steadily increasing side-friction soil resistance against the sampler. Note that $N = N'$ at 30-cm (12 in.) penetration.

8. To accomplish its penetration, the sampler uses about 80 percent of the rod input energy, E_i, to overcome dynamic soil resistance. The other 20 percent partly radiates away in soil "quake" and partly gets trapped and dissipates in the rods. N' varies inversely with the energy used, and therefore also approximately inversely with E_i—as expressed by Equation 1.

9. Equation 1, which results from wave equation simulation [*17,20*] of five typical SPT blows obtained by Palacios [*18*], expresses the average total end bearing and side-friction dynamic soil resistance to sampler penetration, F_{td}, during its penetration

$$F_{td}\,(\text{lb}) \simeq 280 \left(\frac{E_i}{E^*}\right) N\,(\text{blows/ft}) \tag{1}$$

The total quasi-static soil resistance at the sampler at our University of Florida research site averaged about 50 percent of the total dynamic resistance in clays and sandy clays but increased to as high as 90 percent in sands.

What Dynamic Soil Properties Can We Hope to Measure With the SPT?

It seems to the author that we can only hope to measure those dynamic soil properties where the SPT provides either a direct model of the problem at hand, or the factors that control the behavior of the SPT also similarly control the dynamic property we wish to correlate against. The author suggests the following possibilities.

The Wave Equation Soil Damping Coefficients J_p *and* J_s

The driving of the SPT sampler gives us a field test for the driving of a pile. Both involve hammer impact on a one-dimensional rod system to produce a pulsed or cyclic penetration of either pile or sampler into the soil, with the penetration behavior controlled by the stress wave traverses in the pile or sampling rods and the dynamic resistance response of the soil. Many investigators have shown the validity of using the one-dimensional wave equation to analyze real pile-driving problems. Others, notably Adam [*21*] and McLean et al [*22*], have recognized that we can also model the SPT behavior with the wave equation. Gallet [*20*] also did so and had the advantage of having dynamic SPT field data against which to adjust and validate his wave equation model for the SPT. After so doing, and demonstrating that the soil quake generated at the SPT sampler represented a negligible quantity, he could solve the SPT penetration problem with the wave equation and evaluate J_p and J_s. Gallet determined these damping coefficients for a number of SPT blows and obtained values within the range of values usually assumed in pile-driving analyses. The method looks viable.

The J damping coefficients represent major variables in the pile-driving simulation using the wave equation method. More-accurate, site-specific values of J might prove very useful in many applications. In principle, one can estimate these from the SPT using only the ordinary SPT data and the stress wave recorded by a dynamic load cell placed in the string of rods. This load cell should be close to the anvil, but at least 5 rod diameters below it, to allow the wave to recover from the effects of the area reduction from anvil to rods. It can usually be placed above ground level for convenience, as shown in Fig. 1*a* and 1*b*.

Correlation with Factor of Safety Against Liquefaction

We now know from field experience, and in some cases from controlled laboratory research [*2*], that all the variables we know of that increase the safety factor against liquefaction occurring also increase dynamic SPT or quasi-static cone penetration resistance. Table 1*a* summarizes these variables.

The results from the University of Florida research on the dynamics of the SPT can provide additional qualitative arguments to support the possible applicability of the dynamic SPT for the prediction of dynamic liquefaction behavior. Table 1*b* lists these additional arguments. The

TABLE 1*a*—*Qualitative comparison of soil penetration resistance with resistance to liquefaction.*

	Effect on	
Factor (after Seed [2])	*N*-Value	Liquefaction Factor of Safety
1. Greater relative density	+	+
2. Greater depth (vertical efficiency stress)	+	+
3. Greater horizontal efficiency stresses (OCR or roller compaction)	+	+
4. Cementation, aging phenomena	+	+
5. Vibration prestraining	+	+
	(+ denotes increase)	

TABLE 1*b*—*Some additional dynamic advantages of the SPT for evaluating liquefaction.*

6. Dynamic test to model dynamic behavior.
   (*a*) Rapid penetration: average 1.2 m/s (4 ft/s), 90 percent in 200/*N* ms
   (*b*) Pulsed penetration: decays with frequency 8000/depth (ft) Hz
7. Essentially undrained.
8. High percentage shear wave energy

Metric conversion: 1 ft = 0.3048 m.

SPT produces a pulsed sampler penetration and decaying cycles of loading. The penetration occurs very quickly and must be essentially undrained in all but very coarse soils. The sampler also introduces primarily shear strains into the soil—to match the primarily shear wave propagation assumed to occur under earthquake loading.

Considering the great qualitative similarity between penetration resistance and factor of safety against liquefaction, plus the dynamic and cyclic penetration of the SPT sampler and the dynamic and cyclic production of the liquefaction phenomenon, it seems quite reasonable to expect at least some useful degree of correlation between the SPT *N*-value and the factor of safety against liquefaction.

Correlation with Shear Wave Velocity

The shear wave velocity depends on the shear modulus, which in turn depends on the dynamic stress-strain properties of the soil and the level of strain in the traveling shear waves. Because the SPT sampler penetration involves primarily dynamic soil shear behavior, at the failure reference level of shear strain and modulus one can argue that it would be reasonable to expect a correlation between *N*-values and shear wave velocities at the other reference level of very low strain and maximum modulus.

Figure 2 shows an example from a research site in Florida that indicates such a correlation may exist—at least for a specific site. These data come from Heller [23].

The research site consisted of fine sands, above the water table. Figure 2 shows shear wave velocity profiles with depth using different determination methods and the average N-value profile as determined by Waterways Experiment Station equipment and personnel. It appears we can say that, approximately, V_s (ft/s) = 50 N at this site. The author understands that

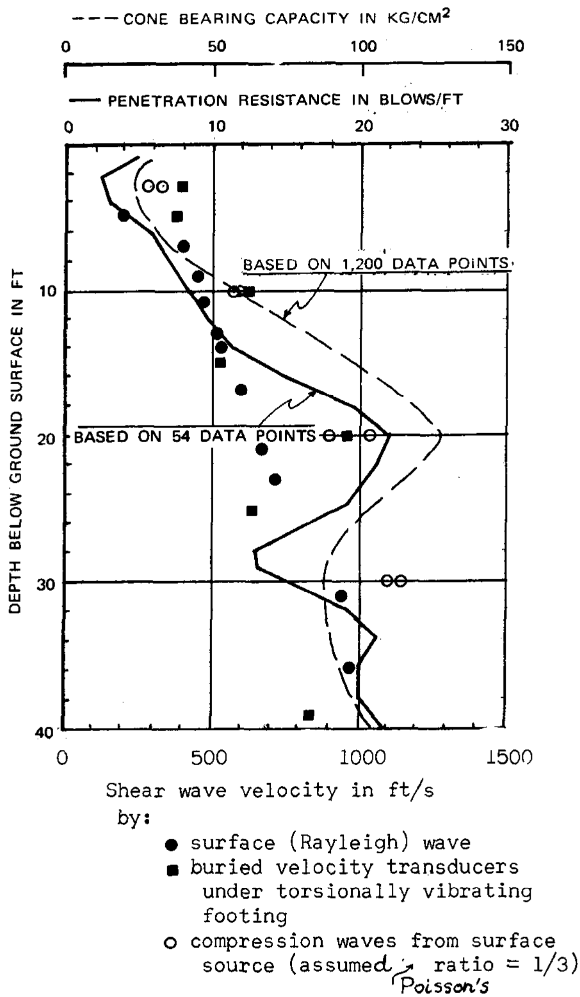


FIG. 2—*Correlation between SPT blowcount, CPT bearing capacity and shear wave velocity in a fine sand above the water table at a site in Northwest Florida (from Heller* [23]) *(1 kg = 2.2 lb; 1 cm² = 0.16 in.²; 1 ft/s = 0.3 m/s).*

the Waterways Experiment Station currently has an active project to more thoroughly explore the possibility of a more general correlation between V_s and N.

As a matter of general interest, Figure 2 also includes the average q_c profile from a large number of Begemann friction-cone penetration tests at the same site. It seems that one could also develop a site correlation between V_s and the static cone bearing capacity, q_c.

First Need to Restandardize the SPT

From only the previous section of this paper the reader would perhaps reach an optimistic conclusion about the possible use of SPT N-value data to make useful quantitative predictions of those dynamic soil properties discussed, and perhaps of others not discussed. Unfortunately, the SPT, as practiced in the United States under ASTM Method D 1586, suffers from a perhaps fatal or near-fatal flaw. Practicing engineers know all too well that the test and its N-values have a poor reproducibility and great variability between different operators and equipment. Many investigators, as mentioned earlier, have pointed out this major flaw and given one or more reasons to help explain it. See Schmertmann [*24*] for a broader discussion of the variability problem.

One need not look far to see why in practice we have such great variability in the test. The author has attempted in Table 2 to organize his digest of the literature and personal opinions as to the causes and magnitude of this variability. He believes that the major causes fall into two categories: variability in the energy that actually enters the sampling rods and travels to the sampler in the form of the first compression wave, and variability in the effective stress conditions at the bottom of the borehole during drilling and sampling.

As Table 2 indicates, these causes can produce major effects which can easily change N by 100 percent. Note that this would also change the factor of safety against liquefaction by 100 percent when using the SPT field method for evaluating the factor of safety. The author considers this an unacceptable situation. The present system negates almost any rational use of the SPT as a quantitative design tool in dynamic as well as in static problems. If we want to use the SPT to its potential for design in problems involving dynamic soil behavior, we must first establish and enforce logical standards for the performance of the SPT. The author offers the following suggestions.

Standardize Energy Entering Rods

The various works cited earlier have shown convincingly that the energy delivered by the drop weight system presents a major variable in deter-

TABLE 2—*Some factors in the variability of standard penetration test* N.

Cause		Estimated % by Which Cause Can Change N
Basic	Detailed	
Effective stresses at bottom of borehole (sands)	1. use drilling mud versus casing and water	+100%
	2. use hollow-stem auger versus casing and water and allow head imbalance	±100%
	3. Small-diameter hole (3 in.) versus large diameter (18 in.)	50%
Dynamic energy reaching sampler (All Soils)	4. 2 to 3 turn rope-cathead versus free drop	+100%
	5. Large versus small anvil	+50%
	6. Length of rods	
	Less than 10 ft	+50%
	30 to 80 ft	0%
	more than 100 ft	+10%
	7. Variations in height drop	±10%
	8. A-rods versus NW-rods	±10%
Sampler design	9. Larger ID for liners, but no liners	−10% (sands) −30% (insensitive clays)
Penetration interval	10. $N_{0\text{ to }12\text{ in.}}$ instead $N_{6\text{ to }18\text{ in.}}$	−15% (sands) −30% (insensitive clays)
	11. $N_{12\text{ to }24\text{ in.}}$ versus $N_{6\text{ to }18\text{ in.}}$	+15% (sands) +30% (insensitive clays)

Metric conversions: 1 ft = 0.3048 m; 1 in. = 2.54 cm.

mining N. The work at the University of Florida has shown convincingly that N varies inversely with the compression wave energy that actually enters the sampling rods. We must develop a standard system that introduces a specified compression wave energy into the rods, and that is repeatable all day long in normal operation. It seems obvious that this requires a mechanized drop system that remains independent of operator techniques. With such a system the engineer can adjust the drop height to obtain a fixed amount of compression wave energy, E_i, as determined by appropriate integration of the force-time wave pulse measured by a load cell placed in the rod system a short distance below the hammer. Figure 1 illustrates how researchers at the University of Florida have measured E_i.

Of course, the idea of using a mechanized hammer drop system did not originate here. Some countries have already adopted a mechanized free-drop system as their standard. The paper by Kovacs et al [*13*] strongly supports the idea of using a mechanized drop system in the United States and details the impact velocity calibration results from such a system presently marketed by a national U.S. distributor.

The author already has some experience with trying to calibrate SPT rigs using the common rope-cathead hammer drop system so as to introduce a standard amount of wave energy delivered into the rods. However, even under the somewhat artificial, especially attentive conditions of a field calibration at a university site, the University of Florida researchers found [*19*] a ratio of high/low E_i energy delivered from blow to blow by the same operator using his own rig that varied from 1.53 to 1.10, and averaged 1.28 for 10 rigs when considering a random sampling of 5 blows. The author believes that any rig using a rope-cathead hammer drop system remains too operator-dependent to permit its use under a standardized SPT test procedure intended to produce N-values for quantitative design.

Need to Use Drilling Mud

In the author's opinion, as a practical matter the use of rotary drilling methods with the hole continuously filled with drilling mud to the surface offers the only present way to assure that the effective stress conditions in the sampling zone immediately below the borehole remain as little disturbed as possible by the borehole.

Possible Dual-Standard SPT

In recognition of the practical difficulties of suddenly adopting a much more rigorous standard for the SPT, involving new equipment with unfamiliar dynamic calibration and possibly unfamiliar drilling techniques, perhaps the profession should again consider a transition period with a dual standard. Chairman Frank Steiger of the SPT task committee for ASTM Committee D-18.02 already proposed a dual standard several years ago.

An SPT performed to say a "Class B" standard would use a calibrated, fully mechanized hammer drop system, and use only rotary drilling and drilling mud. This class would serve for testing in which the engineer intended to use the N-values for important quantitative design, or for research and establishing correlations intended for other than local use. "Class A" SPT work would fall under the continued present standard and allow the great local variability to accommodate local equipment, preferences and correlations.

Conclusions

1. The profession now has an important new insight into the statics and dynamics of the standard penetration test. Any full understanding of the SPT must include stress wave analysis.

2. A properly standardized SPT has a reasonable, already partly demon-

strated potential for quantitative correlations with a factor of safety against liquefaction, with the J damping coefficients in pile-driving problems, and perhaps with high- and low-strain shear wave velocity.

3. The profession needs to establish and enforce an alternative ASTM Method D 1586 standard that requires a mechanized hammer drop, a calibrated energy content in the first compression wave in the rods, and the use of rotary drilling in a hole kept continuously full with drilling mud.

Acknowledgments

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