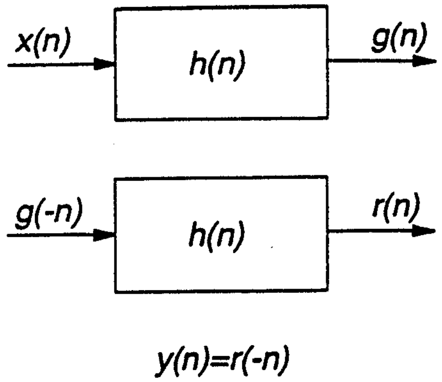

FIG. 14. Diagram of Two-Pass Filtering Process

where $H(e^{j\omega})$ = transfer function of the filter; $H^*(e^{j\omega})$ = conjugation of $H(e^{j\omega})$; ω and ϕ denote the frequency and phase shift, respectively.

Since $|H(e^{j\omega})|$ is normalized to be unity in the passband, $|H(e^{j\omega})|^2$ is also unity in the passband. Thus, the final output has zero-phase shift but still maintains the correct magnitudes.

APPENDIX II. REFERENCES

Lee, V. M., and Trifunac, M. D. (1984). "Current developments in data processing of strong motion accelerogram." *Rep. No. 84-01*, Dept. of Civ. Engrg., Univ. of Southern California, Los Angeles, Calif.

Oppenheim, A. V., and Schafer, R. W. (1975). *Digital signal processing*. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Sunder, S. S. (1981). "Some contributions to strong-motion earthquake signal processing," PhD thesis, Dept. of Civ. Engrg., Massachusetts Inst. of Technol., Cambridge, Mass.

Closure by Koichi Nakagawa,[5] Kenichi Soga,[6] and James K. Mitchell[7]

The writers thank the discusser for his interest in our paper and his important analysis of phase shift. The possibility of an additive phase shift caused by analog filtering was considered early in our experimental program. We increased the gain of the amplifier and examined the possible change of the initial arrival time of traveling waves under the conditions of with and without an analog filter. Although the effect was not examined mathematically, as suggested by the discusser, we found experimentally that the initial arrival times were not significantly affected by the filtering process as shown in Fig. 6(c) and 6(d). The error introduced by the filtering process was found to be less than the error in determining the arrival time used in computing the elastic wave velocities.

It is possible, however, that the shape of the traveling waveform, which contains various frequency components, could be affected by the process. Since our primary interest was to determine the initial arrival time of a traveling wave for elastic wave-velocity measurements and not to examine the shape of the traveling waveform, we did not pursue the issue further.

---

[5] Prof., Dept. of Geosci., Osaka City Univ., Osaka, 558, Japan.

[6] Lect., Cambridge Univ., Engrg. Dept., Cambridge, CB2 1PZ, U.K.; formerly, Grad. Res. Asst., Dept. of Civ. Engrg., Univ. of California at Berkeley, CA.

[7] Via Professor of Civil Engineering, Dept. of Civ. Engrg., Virginia Polytechnic Inst. and State Univ., Blacksburg, VA 24061; formerly, Edward G. Cahill and John R. Cahill Professor of Civil Engineering, Emeritus, Dept. of Civ. Engrg., Univ. of California at Berkeley, CA.

ANALYSIS OF CONE PRESSUREMETER TESTS IN SANDS[a]

Discussion by John A. Howie[4]

1997

INTRODUCTION

The authors have provided valuable insight into the potential use of the cone pressuremeter (CPM) for determination of design parameters in sands. The proposed method of interpretation is based on theory that incorporates the major aspects of the behavior of sands around an expanding cavity. The paper presents data from chamber tests that suggest that the CPM and the proposed method of interpretation can be used to obtain a reasonable estimate of the friction angle and initial state parameter of sands. However, the attempts to use field data are less convincing. The discusser has carried out field testing of two prototype CPM instruments, including the one described in the paper (Howie 1991), and has found that extreme attention to detail is required in the implementation of the pressuremeter expansion test to ensure that differences among test data are due to soil behavior and not to equipment characteristics and test procedures. The discusser fears that failure to recognize these effects and the resulting difficulty of comparing test results obtained with different instruments and test procedures will yield inconsistent conclusions about the ability of the CPM to provide useful data. In addition, the discusser has concerns about the sensitivity of the proposed method of interpretation, particularly at low stress levels, i.e., at shallow depths.

IMPLEMENTATION OF THE METHOD

For site characterization by cone penetration testing (CPT), the instrument and the installation and test procedures have been standardized. At any site, the results should be independent of the operator and the equipment used, i.e., different instruments should give comparable results within the limitations imposed by variability of the site conditions. Sufficient experience exists in many soil deposits to allow the derivation of site stratigraphy and soil engineering properties by existing correlations with tip resistance, friction ratio, dynamic pore pressure ratio, and shear-wave velocity.

For the CPM to be used, it must be clearly shown that the additional complexity of the instrument, test procedure, and methods of interpretation are justified by increases in the amount and quality of the data and/or additional confidence in the results. The proposed general interpretation method requires the input of limit pressure (p_L), shear modulus (G), and cone penetration resistance (q_c), all of which can be obtained from the CPM instrument. However, the results in the paper do not indicate that the CPM is likely to provide sufficient advantage over the procedures based on the CPT to justify the considerable increase in effort to acquire the data. Possible sources of inaccuracy are discussed in the following.

VARIABILITY OF RESULTS DUE TO EQUIPMENT EFFECTS

Pressuremeter Expansion Test

The shape of the pressuremeter expansion curve and the value of unload-reload modulus obtained are sensitive to the

---

[a] August 1996, Vol. 122, No. 8, by H. S. Yu, F. Schnaid, and I. F. Collins (Paper 9353).

[4] Geotech. Engr., 962 West 22nd Ave., Vancouver, British Columbia, V5Z 2A1 Canada.

details of the equipment. The authors identify a correction to limit pressure for instruments with a length to diameter (*L*/*D*) ratio differing from *L*/*D* = 10, but a number of other influences in interpretation of limit pressure and shear modulus must be considered prior to selection of parameters for input to the analysis. For example, Howie (1991) showed that the shape of the expansion curve and especially the initial part of the curve are extremely sensitive to small variations in instrument diameter and/or compressibility of the lantern protecting the membrane. In addition, Fahey and Jewell (1990), Howie (1991), and Houlsby and Schnaid (1994) showed that instrument compliance and hysteresis can have a large effect on the determination of unload-reload modulus obtained. The magnitude of this effect can vary with stress level. As the diameter of the probe becomes smaller, these effects become more critical as strain is calculated relative to the initial diameter of the probe. Standardization of the CPM geometry and of the details of the deflection measurement system would allow research to focus on soil behavior.

Cone Penetration Resistance

For a typical 10-t capacity cone tip, a measurement precision of ±0.5% of full-scale represents about ±490 kPa for a 10-cm^2 cone tip. At shallow depths where both tip resistance and CPM limit pressures will be low, particular attention must be paid to the maintenance of the cone to ensure that representative values are obtained. In a loose soil, such a variation would affect the interpreted value of the state parameter by a considerable amount and could make the difference between classifying the soil as contractive or dilative.

VARIABILITY OF RESULTS DUE TO TEST PROCEDURE AND METHOD OF INTERPRETATION

Limit Pressure

The test data shown in Fig. 11 of the paper were obtained by the discusser early in his investigation of the CPM. A significant factor in these tests was the presence of large amounts of time-dependent deformation during phases of the test when pressure was maintained constant. This becomes more noticeable in pressuremeter tests in which the membrane is expanded to cavity strains in excess of the 10% more common for self-boring PM testing. Additional testing with the Fugro CPM and also with the Seismic CPM developed at the University of British Columbia suggested that the rate of expansion would affect the shape of the expansion curve. Fast strain-controlled tests would result in larger limit pressures than slow strain-controlled or stress-controlled tests. When pressuremeter data are published, it is important that the expansion procedure used be detailed so that rate effects may be considered in the interpretation. The importance of this effect will depend on the characteristics of the soil being tested and on the sensitivity of the method of interpretation.

For tests where a limit pressure is not reached within the expansion capacity of the probe, extrapolation of the data will be required to estimate a limit pressure. The value obtained will be affected by the shape of the initial portion of the curve, which, as noted earlier, can be affected by equipment details. To promote consistency of use of the interpretation procedure, an extrapolation procedure should be agreed on. The *L*/*D* correction proposed by the authors may then be applied to the derived value.

Shear Modulus

Considerable variation in G_{ur} can occur depending on the test procedure followed and the method of interpretation used, e.g., the value obtained varies considerably with the magnitude of unloading used, the stress level from which unloading commences, and whether the modulus value is obtained by a best fit to the data, joining the tips of the loop and so on [see Bellotti et al. (1989); Byrne et al. (1989); Howie (1991); Houlsby and Schnaid (1994)]. A standard method of derivation of *G* from the CPM test is required to allow consistent application of the design approach. Alternatively, G_{max} could be used if the CPM unit incorporated the capability of measuring the shear-wave arrival time.

Cone Penetration Resistance

The development of the proposed method has been based on the results of chamber tests. The method will be more difficult to apply in situ. Withers et al. (1989) presented the variation in tip resistance measured in three CPT soundings conducted within about 1.5 m of each other at McDonald's Farm and noted the difficulty of assigning a tip resistance to a particular depth for comparison with the CPM limit pressure. It is therefore of great importance that the tip resistances and limit pressures are measured in the same sounding so that the measured tip resistance applies to the zone of the expansion test.

Variability of the tip resistance with depth also introduces difficulty of application of the method. What value of tip resistance should be used? It is well known that the zone of soil stressed by the cone tip during penetration varies with the strength and stiffness of the soil being penetrated. Pile design methods based on q_c include empirical methods of selecting an average tip resistance by averaging over some distance ahead and behind the zone of interest. Something similar is required for the CPM to allow consistent application of the design approach. A significant advantage of the CPM is the ability to observe q_c during penetration and to use it to select a suitable location for pressuremeter expansion. Limits could be placed on the acceptable variation in q_c before membrane expansion proceeds.

METHODS OF INTERPRETATION AND PHILOSOPHY OF USE

The discusser believes that a major advantage of the CPM is the ability to measure the response of the soil to a variety of types of loading in a single sounding. As soil responds differently depending on the nature of the loading, the additional loading conditions imposed by the CPM over penetration testing offer the potential for the detection of anomalous or unusual soil conditions, especially in sites for which little previous experience exists such as in frontier exploration. However, very few examples of site profiles obtained with a CPM have yet been published to allow assessment of the potential of the instrument. The paper continues to use field data obtained by CPT and full-displacement (i.e., pressuremeter pushed in behind an uninstrumented cone of the same diameter) or self-boring pressuremeter in adjacent soundings. It is unlikely that research based on comparisons between field CPT and pressuremeter tests in adjacent holes will overcome the effects of site variability except at sites with uniform soil conditions.

Although the proposed method of interpretation has a theoretical basis, it is based on correlations with chamber and laboratory test data and so requires a number of approximations and normalizations in the process, all of which introduce error. Empiricism will inevitably be required to derive representative parameters for input to the interpretation procedure. It would therefore seem advantageous to standardize the equipment and test procedures and proceed to obtain data in a standard way at many different sites as has been done for the CPT. These standardized data can then be subjected to various methods of analysis and a database developed. In addition to the method proposed by the authors, it is likely that methods based on numerical modeling of the entire curve using realistic soil models will provide much useful information.

CONCLUSION

The CPM has the potential to be a very useful tool for site characterization. However, considerable attention must be paid to obtaining consistent expansion curves affected to a known extent by constraints of equipment and test procedure. The ability to observe the soil's response to several loading paths at the same location in the same sounding offers significant advantages over the CPT and may make it possible to detect unusual soil conditions early in a field investigation.

APPENDIX. REFERENCES

Byrne, P. M., Salgado, F. M., and Howie, J. A. (1989). "Relationship between the unload shear modulus from pressuremeter tests and the maximum shear modulus for sand." *The 3rd Int. Symp. on Pressuremeters*, Oxford, England, 231–241.

Fahey, M., and Jewell, R. (1990). "Effect of pressuremeter compliance on measurement of shear modulus." *The 3rd Int. Symp. on Pressuremeters*, Oxford, England, 115–124.

Houlsby, G. T., and Schnaid, F. (1994). "Interpretation of shear moduli from cone pressuremeter tests in sand." *Géotechnique*, London, England, 44(1), 147–164.

Howie, J. A. (1991). "Factors affecting the interpretation and analysis of full-displacement pressuremeter tests in sands," PhD thesis, Dept. of Civ. Engrg., Univ. of British Columbia, Vancouver, Canada.

Closure by H. S. Yu,[5] Member, ASCE, F. Schnaid,[6] and I. F. Collins,[7] Member, ASCE

The writers would like to thank the discusser for his interest in the paper. The discussion covers two main issues: (1) the applicability of the proposed interpretation method to field data; and (2) the advantage of the proposed CPMT method over procedures based on cone penetration testing (CPT). The points raised in the discussion on these two issues are commented on in turn.

APPLICABILITY OF PROPOSED INTERPRETATION METHOD TO FIELD DATA

As stated clearly in the paper, little field cone pressuremeter test data were available at the time when the proposed interpretation method was developed. As a result, the method has been validated mainly with results from both chamber tests of the cone pressuremeter and fields tests of CPT and SBPM. Large calibration chambers are widely used to calibrate and evaluate in-situ tests in sand. With chamber testing, a sample of known material prepared at a particular density in the chamber is tested under strictly controlled boundary conditions. Because calibration chambers are necessarily of limited size for practical reasons, the cone resistance and pressuremeter limit pressure measured in a calibration chamber with the cone pressuremeter may be different from those measured in the field. This difference is very much dependent on the size of the chamber and the type of boundary conditions used in the testing (Yu 1990; Schnaid and Houlsby 1991; Yu and Mitchell 1996). Despite the fact that both the cone resistance and pressuremeter limit pressure depend on the chamber size, recent experimental studies by Schnaid and Houlsby (1992) on the chamber testing of the cone pressuremeter have also showed that the ratio of these two quantities (i.e., the cone resistance over the pressuremeter limit pressure) is largely not affected by the chamber size. It is therefore reasonable to assume that the correlations between soil properties and the ratio of cone resistance to pressuremeter limit pressure established by or validated with chamber testing may be directly applied to field conditions.

In the paper the results of four field cone pressuremeter tests and 28 chamber tests of the cone pressuremeter have been interpreted using the proposed interpretation method. The detailed comparison between the results derived using the new interpretation method agree well with other laboratory and field measurements. In addition, it was pointed out in the paper that the interpretation method developed by the writers has also been successfully used by Ghionna et al. (1995) to interpret the results of 10 field cone pressuremeter tests carried out in Po river sand in Italy. The discusser seems to have overlooked this fact by wrongly stating that the attempts to use field data are less convincing.

To provide additional evidence for the relevance of the proposed interpretation method, the results of some field tests of CPT (for cone resistance) and SBPM (for pressuremeter limit pressure) have also been used in the paper. While it is reasonable to assume that the cone resistance obtained from CPT is directly comparable to that from CPMT, some semiempirical correction factors were used to estimate CPMT limit pressures from the limit pressure values derived from SBPM. The writers agree with the discusser that extreme caution needs to be taken in comparing measured quantities from different instruments with different geometries and installation processes. The discusser stressed a number of factors that would need to be accounted for if data from different instruments are to be compared. The influence of these factors on the interpreted results has already been recognized and fully discussed by the writers in previous publications [e.g., Schnaid (1990); Schnaid and Houlsby (1992); Houlsby and Schnaid (1994)].

ADVANTAGE OF PROPOSED CPMT METHOD OVER PROCEDURES BASED ON CPT

It is well known that although CPT can be used to estimate soil strength parameters from the measured cone resistance, it cannot be used to accurately obtain soil stiffness (Yu and Mitchell 1996). The relative merit of CPMT over CPT has been discussed at length by Houlsby and Nutt (1993). They concluded that in clay the additional confidence in the derived undrained shear strength and the estimation of stiffness obtained from CPMT may not be worth the extra cost involved, but in sand the additional quantitative information provided by CPMT on strength, stiffness, and horizontal stress would amply reward the additional cost.

The new interpretation method proposed in the paper enables state parameter (Been and Jefferies 1985) to be estimated reliably from the results of CPMT, and this should be regarded as a further advantage of CPMT over CPT. Although Been et al. (1987) suggested that CPT may be used to determine the state parameter, more recent theoretical and experimental research (Collins et al. 1992; Sladen 1989) showed that contrary to what was assumed by Been et al. (1987), there is no unique correlation between the cone resistance and the state parameter. In fact, the correlation between the cone resistance and the state parameter is found to be very much dependent on stress level. On the other hand, the studies presented in the paper (both theoretical and experimental) clearly demonstrated that a unique correlation exists between the ratio of cone resistance to pressuremeter limit pressure and the state parameter.

---

[5] Sr. Lect., Dept. of Civ. Engrg. and Surv., The Univ. of Newcastle, NSW 2308, Australia.

[6] Sr. Lect., Departamento de Engenharia Civil, Universidade Federal Do Rio Grande Do Sul, Brazil.

[7] Prof., Dept. of Engrg. Sci., The Univ. of Auckland, New Zealand.

PPENDIX. REFERENCES

en, K., Jefferies, M. G., Crooks, J. H., and Rothenburg, L. (1987). "The cone penetration test in sands. II: General inference of state." *éotechnique*, London, England, 37(3), 285–299.

ulsby, G. T., and Nutt, N. R. F. (1993). "Development of the cone ressuremeter." *Proc., Peter Wroth Memorial Symp.: Predictive Soil ech.*, Thomas Telford, London, England, 359–377.

ulsby, G. T., and Schnaid, F. (1994). "Interpretation of shear moduli rom cone pressuremeter tests in sands." *Géotechnique*, London, Engand, 44(1), 147–164.

den, J. A. (1989). "Problems with interpretation of sand state from cone penetration test." *Géotechnique*, London, England, 39(2), 323–332.

, H. S., and Mitchell, J. K. (1996). "Analysis of cone resistance: a eview of methods." *Civ. Engrg. Res. Rep. No. 142.09.1996*, Univ. of ewcastle, Australia.

DRAINED SAND BEHAVIOR IN AXISYMMETRIC TESTS AT HIGH PRESSURES[a]

Discussion by Eulalio Juárez-Badillo,[3] Fellow, ASCE

The discusser read with great interest the paper that contains ery good experimental data on sand under high pressures. In articular, the discusser has applied the general compressibility quation for soils (Juárez-Badillo 1981) to describe the highressure isotropic compression test on dense Cambria sand Fig. 1) with the following results.

For the first mechanical phrase before the general crushing f particles, the equation is

$$V = \frac{V_o}{1 + \left(\frac{\sigma}{\sigma^*}\right)^{\gamma}} \tag{1}$$

hile for the second mechanical phase where there is, already, generalized crushing of particles, the equation is

$$V = V_1 \left(\frac{\sigma}{\sigma_1}\right)^{-\gamma} \tag{2}$$

here V = volume; V_o = volume under zero pressure; σ = ressure; σ^* = characteristic pressure for $V = V_o/2$; γ = coefficient of compressibility; and (σ_1, V_1) = known point.

The author found the following values for the parameters:

1. For the first mechanical phase of loading: (1) with $\gamma = 0.4$, $V_o = 1{,}000$ and $\sigma^* = 25{,}000$ MPa.
2. For the second mechanical phase of loading: (2) with $\gamma = 0.09$ and $(\sigma_1, V_1) = (70$ MPa, $830)$. It should be observed that between 10 and 25 MPa, there appears to be a transition zone due, surely, to the statement: "Cambria sand is composed of many mineral constituents of varying hardness. Some of the softer components consists of sedimentaric lithic fragments (shale), which crush easily relative to the harder elements that are contained in the sand."
3. For the unloading: (1) with $\gamma = 0.1$, $V_o = 914$ and $\sigma^* = 3 \times 10^{11}$ MPa.

It is interesting that the unloading the high value of $V_o = 914$ compared to the initial value $V_o = 1{,}000$.

The discusser expects the comments of the authors on the application of the aforementioned equations to their Fig. 1.

APPENDIX. REFERENCE

Juárez-Badillo, E. (1981). "General compressibility equation for soils." *Proc., X, Int. Conf. on Soil Mech. and Found. Engrg.*, 1, 171–178.

Closure by Jerry A. Yamamuro[4] and Poul V. Lade[5]

The discusser's interest is focused on one aspect of the paper, namely the isotropic compression test result. He presents two different curve-fitting expressions to model each of the sections before and after the inflection point occurring near 10 MPa of the isotropic compression curve presented in Fig. 1. He also uses the first expression to model the unloading branch of this experiment, but different parameter values are used for unloading. Using the parameter values given in the discussion, the two curve-fitting expressions seem to reproduce the loading and the unloading branches well.

Many different mathematical expressions have been proposed in the literature to model separate aspects of stress-strain behavior of soils. This was especially prevalent in the early days of soil mechanics. Some of these expressions were devised as pure curve fits, with little consideration given to capturing the underlying characteristics and patterns of soil behavior. Such simple models may be used in specific cases, but they have limited applicability to general stress and strain conditions found in most geotechnical engineering projects.

---

[a] February 1996, Vol. 122, No. 2, by Jerry A. Yamamuro and Poul V. Lade (Paper 9733).

[3] Prof., Grad. School of Engrg., Nat. Univ. of Mexico, Tepanco 32, Coyoacán, 04030 México D.F., México.

[4] Asst. Prof., CEE, Box 5710, Clarkson Univ., Potsdam, NY 13699-5710.

[5] Prof., Dept. of Civ. Engrg., Johns Hopkins Univ., Baltimore, MD 21218.

SIGNIFICANCE OF PARTICLE CRUSHING IN GRANULAR MATERIALS[a]

Discussion by Robert W. Day,[4] Fellow, ASCE

The authors have performed a comprehensive study of the crushing of granular particles due to an increase in confining pressure [Figs. 2(a)–2(d)]. The authors state that increasing the mineral hardness decreases the amount of particle crush-

---

[a] April 1996, Vol. 122, No. 4, by Poul V. Lade, Jerry A. Yamamuro, and Paul A. Bopp (Paper 9927).

[4] Chf. Engr., American Geotechnical, 5764 Pacific Ctr. Blvd., Ste. 112, San Diego, CA 92121.