INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

PENETROMETER METHOD FOR DETERMINING SOIL PARAMETERS

DETERMINATION DES PARAMETRES DU SOL PAR LA METHODE DU PENETROMETRE

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SYNOPSIS A suitable rheological model is chosen to represent the soil deformations under impact loads. The parameters of the model are evaluated from the deceleration history curves of the impact penetrometer. The method is useful for determining the soil properties in situ, especially for remote soils where immediate soil data are required and direct access is not available.

INTRODUCTION

Various methods have been used to determine the soil properties in situ. For example, the standard penetration test, the shear vane, and the Menard pressure meter are used to measure the shear strength of the soil in a bore hole. Some other techniques, such as penetrometer tests, had their origin in the principles of hardness measurement. They were developed to determine the properties of surface soils. Among these, the aerial cone penetrometer was developed for determining the soil properties at a distance. The drawbacks of this method were discussed by Schmid(4) and improvements were made to make it more suitable for practical applications. This paper describes a new penetrometer and analyzes the data and results obtained with it.

IMPACT PENETROMETER TESTS

The penetrometer (Fig. 1) is a hollow, circular, chromium steel cylinder of 75 mm. diameter with a hemi-spherical tip. A cross-section is shown in Fig. 2. An accelerometer is attached by a thread to a small anvil inside the tip such that the axis of the accelerometer and that of the cylinder coincide. The weight of the capsule is 1.573 kg. The accelerometer signal showing the whole history of deceleration is transmitted through an amplifier system to the screen of an oscilloscope, and the resulting trace is photographed by a polaroid camera. With an adjustable time scale the signal can thus be recorded for the best readability. For practical, operational applications the signal may also be stored on a magnetic tape. Also, a triple accelerometer with respective axes mounted along three mutually perpendicular directions at the center of a sphere was suggested for prototype applications if the direction of the penetrometer impact cannot be controlled precisely.

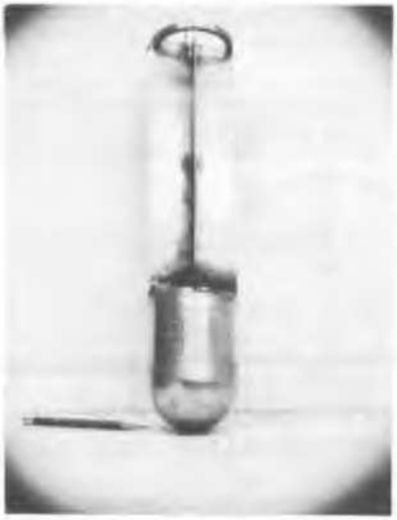


Fig. 1 Princeton Impact Penetrometer

Series of tests, both in the laboratory and in the field, were carried out by Schmid and Hechtl(3)(4) at Princeton in 1963-64. For normal soil conditions, the deceleration history of the impact penetrometer is first, a monotonously rising and then, falling curve which can be approximated by a sine function (Fig. 3).

THEORETICAL ANALYSIS OF SOILS UNDER IMPACT LOADS

1. Rheological Model

According to Winterkorn's macromeritic liquid state theory(6), the constitutive relations for a soil subjected to impact load in a high

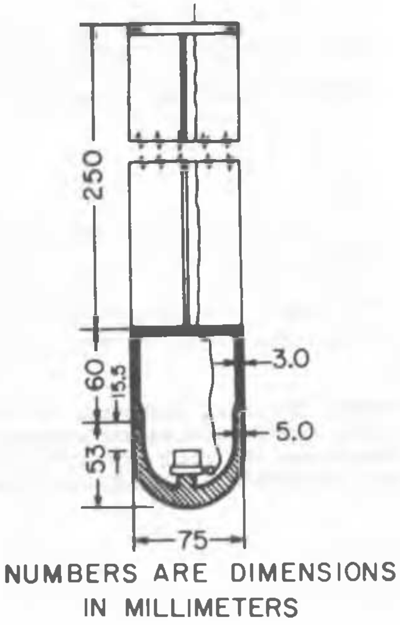


Fig. 2 Section through Princeton Impact Penetrometer

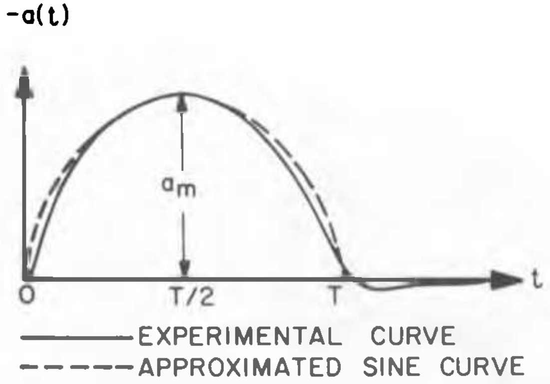


Fig. 3 Deceleration Curve of Impact Penetrometer

energy state are essentially those of a liquid state. Soils, under such load conditions, can be considered to be somewhere between a purely solid and a purely liquid state. Therefore, a generalized, rheological model (Fig. 4) with a combination of an elastic element which takes care of the volumetric behavior and a four-parameter model which represents the deviatoric characteristics, is used to represent soils under impact load. The governing stress-strain relations can be written as follows:

$$\sigma_{kk} = 3K\varepsilon_{kk} \qquad (1)$$

and

$$\ddot{\tau}_{ij} + (\omega_1 + \omega_2 + k\omega_2)\dot{\tau}_{ij} + \omega_1\omega_2\tau_{ij} = G_1(\ddot{\gamma}_{ij} + \omega_2\dot{\gamma}_{ij}) \qquad (2)$$

where:

$$\omega_1 = \frac{G_1}{\eta_1} \qquad (3\text{-}1)$$

$$\omega_2 = \frac{G_2}{\eta_2} \qquad (3\text{-}2)$$

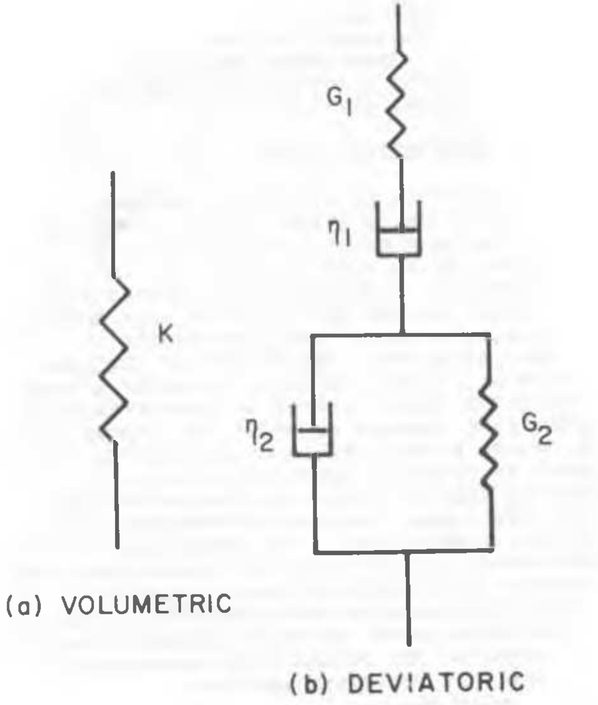
$$k = \frac{G_1}{G_2} \qquad (3\text{-}3)$$

$$\dot{\tau} = \frac{d\tau}{dt} \quad \text{etc.} \qquad (3\text{-}4)$$

In the Laplace transform domain, the stress-strain relations are:

$$\bar{\sigma}_{kk}(s) = 3\bar{K}(s)\,\bar{\varepsilon}_{kk}(s) \qquad (4)$$

$$\bar{\tau}_{ij}(s) = 2\bar{G}(s)\,\bar{\gamma}_{ij}(s) \qquad (5)$$



(a) VOLUMETRIC

(b) DEVIATORIC

Fig. 4 Rheological Soil Models

$$\bar{G}(s) = \frac{G_1}{2} \cdot \frac{s(s+\omega_2)}{s^2 + (\omega_1 + \omega_2 + k\omega_2)s + \omega_1 \omega_2} \tag{6}$$

in which s is the Laplace transform parameter.

2. Viscoelastic Solution of a Sphere on the Half Space

The pressure distribution p underneath the contact area, with radius ρ, of the impact penetrometer on the soil surface is assumed to be a spherical one as shown in Figure 5.

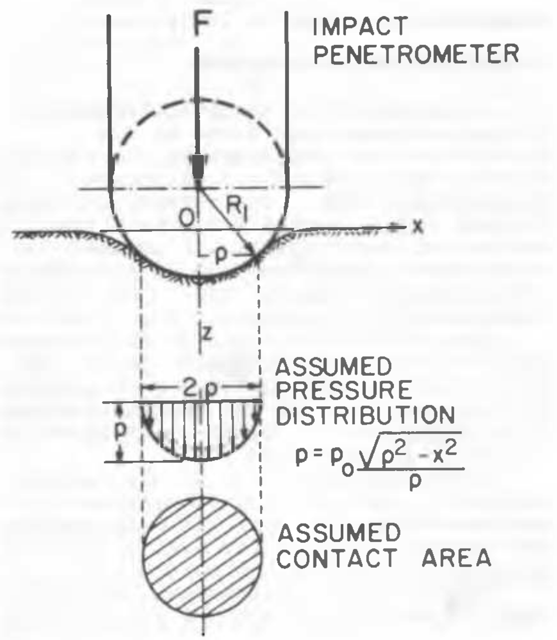


Fig. 5 Impact Penetrometer on the Soil Surface

$$p = p_o \frac{\sqrt{\rho^2 - x^2}}{\rho} \tag{7}$$

The elastic solution (5) can be expressed as

$$w' \rho = \frac{3}{16} \cdot \frac{\lambda + 2\mu}{\mu(\lambda+\mu)} \cdot F \tag{8}$$

$$\rho = \sqrt{w'(R_1 - \frac{w'}{4})} \tag{9}$$

where w′ is the deformation at the tip of the spherical head, λ and μ are Lames constants, and F is the forcing function. Test results of the impact penetrometer show that, for most soils, F essentially may be represented by

$$F = m \cdot a_m \cdot \sin \frac{\pi}{T} t \tag{10}$$

where m designates the mass of the impact penetrometer, t represents time, a_m the maximum amplitude and T the period of the deceleration curve (Fig. 3).

For the problem of a penetrometer impacting on the soil surface, if the impact velocity is small compared to that of the stress wave, the problem may be treated as a quasi-static one, and the method of the elastic-viscoelastic analogy can be applied. The viscoelastic solution is then obtained as:

$$w'(t) \cdot \rho(t) = \frac{3ma_m}{16} \int_0^t \phi(t-\tau) \cdot \sin \frac{\pi\tau}{T} \, d\tau \tag{11}$$

where $\phi(t)$ is the inverse Laplace transform of $\bar{\phi}(s) = (\bar{\lambda} + 2\bar{\mu}) / [\bar{\mu} \cdot (\bar{\lambda} + \bar{\mu})]$
The complexity of equation (11) makes it difficult to evaluate the soil parameters from experimental results. Therefore, simplification of this general solution has to be made by observing the physical characteristics.

Under high energy impact, soils behave essentially like a liquid material and consolidation is relatively small. It appears reasonable then to assume that the deviatoric deformations predominate. This means that the volumetric change is negligible, or $K = \infty$ during impact. This assumption yields $\lambda = \infty$ also, and the solution of equation (11) is then simplified to

$$w'(t) \cdot \rho(t) = \frac{3ma_m}{8} \cdot \Big[C_1 \cdot \sin \frac{\pi t}{T} - (C_2 + C_3) \cdot \cos \frac{\pi t}{T} + C_2 + C_3 \cdot e^{-\frac{G_2 t}{\eta_2}} \Big] \tag{12}$$

where

$$C_1 = \frac{1}{G_1} + \frac{G_2/\eta_2^2}{(\frac{\pi}{T})^2 + (G_2/\eta_2)^2} \tag{13-1}$$

$$C_2 = \frac{T}{\eta_1 \pi} \tag{13-2}$$

$$C_3 = \frac{\pi/T}{\eta_2 \cdot [(\frac{\pi}{T})^2 + (G_2/\eta_2)^2]} \tag{13-3}$$

EVALUATION OF THE SOIL PARAMETERS

The deceleration history (Fig. 3) of the impact penetrometer on the soil surface can be approximated by a sine function

$$a(t) = -a_m \sin\frac{\pi t}{T} \qquad (14)$$

Assuming the final velocity of the penetrometer to be zero without rebound, the deformation w"(t) can be obtained by double integration of equation (14) and has the form:

$$w''(t) = \frac{a_m T}{\pi}\left(t + \frac{T}{\pi}\cdot \sin\frac{\pi t}{T}\right) \qquad (15)$$

In order to evaluate the soil parameters from an impact penetrometer test, the theoretical [equation (12)] and the experimental [equations (9) and (15)] curves were matched. By using the principle of the least square method, soil parameters were obtained for the theoretical curve giving the best fit. Since these soil parameters can have physical significance only for non-negative values, the occurence of negative values were excluded in the process of curve fitting.

The results thus obtained, showed that the four parameter model could be simplified to a Maxwell model (Fig. 6), since G_2 was nearly equal to zero and η_2 could be combined with η_1 to represent a single dashpot.

Fig. 6 Maxwell Model

For the simplified soil model, the equation (12) can be modified as

$$w'(t)\cdot\rho(t) = \frac{3 m a_m}{8}\cdot\left[\frac{1}{G_1}\cdot\sin\frac{\pi t}{T} + \frac{T}{\pi\eta_1}\left(1-\cos\frac{\pi t}{T}\right)\right] \qquad (16)$$

This simplified theoretical curve [equation (16)] was then matched with the experimental curve by using the same approach that was discussed previously. The calculated soil parameters are shown in Table 1.

DISCUSSIONS AND CONCLUSIONS

Soil parameters can be obtained by fitting a theoretical curve to the experimental one representing the variation of the quantity $w'(t)\,\rho(t)$ of impact penetrometer tests. The results actually obtained indicate that the generalised, rheological model originally assumed for the soils under impact load can be simplified to a two-parameter Maxwell model, which still represents the liquid-solid characteristics.

The constants for the model parameters obtained from different tests on one and the same target soil are in very good agreement. This seems to confirm the general validity of using the Maxwell model to represent the soil under impact loads.

Comparing the values of the spring constant G_1 and the dashpot constant η_1 shows that the viscous part of the deformation predominates, because the soil is very much liquefied under the high impact load.

Finally, the experimental, vertical displacements of the soil at the tip of the penetrometer can be compared with the theoretical values by feeding back the soil parameters obtained from the experimental curves.

This paper presents a simple and meaningful rheological model for those dynamic soil problems in which the shear deformations predominate. The parameters of the model can be obtained quickly by a simple impact penetrometer test. The soil responses under different loadings could therefore easily be calculated.

Table 1 Calculated Soil Parameters (Maxwell Model)

Target Material	Remarks	G_1 (psi)	η_1 (psi - sec)
Sandy Princeton clay	Natural soil after two days soaked in heavy rain, $w = 27.42\%$	262.5 264.3 251.4 266.2	0.5885 0.5721 0.5357 0.5436
Princeton red clay	Dry, relatively loose material, $w = 2.65\%$	156.6 201.7 182.8	0.4402 0.4987 0.4587
Silty sand at soil surface	Natural soil	665.3 882.0	0.8938 1.0219
Silty sand, 20" below surface	Natural soil	669.3 626.9 610.0	0.9133 0.8810 0.8287
Sandy silt and clay	Natural soil, dry	1178 1192 1331	1.222 1.234 1.271
Sandy clay	Field recently plowed and disked	150.1 225.9 201.5	0.4093 0.5021 0.4726
Crushed rock ½-1"	Compacted	1709	1.5010
Fine sand	Natural soil	373.6 373.6	0.6466 0.6466
Wax: Cambar M-348 at 31°C	Material used for comparison purposes	155.6 151.1 164.1 161.7	0.4249 0.4111 0.4288 0.4227

REFERENCES

Bland, D. R., 1960, "The Theory of Linear Viscoelasticity," *International Series of Monographs on Pure and Applied Mathematics*, Pergamon Press, Vol. 10, 120 pp.

Föppl, A. & L. Föppl, 1944, *Drang und Zwang*, Band II, Druck und Verlag von R. Oldenbourg, Munchen und Berlin, pp. 218-226.

Hechtl, E.C., June 1964, "Impact Tests on Soils and Their Significance for Trafficability," Ph.D. Dissertation, Princeton University, 135 pp.

Schmid, W. E., January 1966, "The Determination of Soil Properties in Situ by and Impact Penetrometer," *Princeton Soil Engineering Research Series* No. 3, 139 pp.

Tsai, K.W., March 1967, *Strength Response Parameters of Natural Soil Surfaces and Their Application to the Landing Problem of Aircraft*, Ph.D. Dissertation, Princeton University.

Winterkorn, H. F., 1960, *The Scientific Foundation of Soil Engineering*, Princeton University, 463 pp.

SYMBOLS

a	acceleration
a_m	maximum acceleration
C_j	constant
F	force
G	shear modulus
G_1	spring constant
K	bulk modulus
k	$= \frac{G_1}{G_2}$
m	mass
p	pressure
R_1	radius of the spherical head of the impact penetrometer
s	Laplace transform parameter
T	period of the sine function

t	time
w	water content
w'	theoretical vertical displacement
w''	experimental vertical displacement
λ, μ	Lames constants
η_1	dashpot constant
ρ	radius of the contact area
σ_{kk}	volumetric stress tensor
ε_{kk}	volumetric strain tensor
τ_{ij}	deviatoric stress tensor
γ_{ij}	deviatoric strain tensor
ω_1	$= \frac{G_1}{\eta_1}$
ω_2	$= \frac{G_2}{\eta_2}$