

# Estimation of cyclic strength of sand from self-boring pressuremeter tests

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**ABSTRACT:** The angle of dilatancy is easily estimated from drained self-boring pressuremeter test (SBPMT) data. The angle of dilatancy is found to correlate quite well with the normalized and energy corrected blow count,  $(N_1)_{60}$ , measured in a standard penetration test (SPT) for world wide data. Using the correlation self-boring pressuremeter can be used as a screening tool for identifying deposits susceptible to cyclic liquefaction.

## 1 INTRODUCTION

The state of packing has a significant influence on the volumetric behavior of granular deposits and is therefore a very important index for liquefaction resistance of the material. Vaid et al. (1981) demonstrated that the dilation angle at large strain,  $v$ , from laboratory simple shear data can be correlated to the state of packing. Based on this observation it was suggested that  $v$  can also be used as an index for resistance of granular soils against cyclic liquefaction. Since the dilation angle at large strain can also be estimated from back analysis of SBPMT, it appears that self-boring pressuremeter can also be used as a screening tool for identifying liquefiable deposits.

Examination of world wide data (Table 1 provides a summary of the study sites) indicates that the value of  $v$  estimated from SBPMT using a very simple isotropic linear elastic perfectly plastic stress strain relationship due to Carter et al. (1986) correlates rather well with  $(N_1)_{60}$ . Using the correlation a chart between cyclic strength of granular deposits and the value of large strain dilation angle estimated from SBPMT is proposed. The proposed chart is validated using two recent earthquake case history.

It should be noted that index tools such as SPT and piezocone are in use for a number of years and it is not the objective of this paper to suggest that SBPMT is a

better alternative. It needs to be recognized however that SBPMT provides stress deformation data over a wide range of deformation and can in principle be used to calibrate a stress-strain relationship. One such procedure is already developed by Roy (1997) for monotonic loading. If a calibration procedure can be developed for cyclic loading, the calibrated stress-strain model can be used in an elaborate deformation analysis for those deposits perceived to be susceptible to cyclic liquefaction without the necessity to undertake an expensive laboratory testing program.

The study undertaken here is expected to show that the conclusions drawn from analysis of SBPMT are consistent with the inference from tests such as SPT at the elementary level. However, due to the reasons mentioned above, SBPMT data can be used in a more comprehensive manner as and when practical procedures for calibration of a realistic stress-strain model using SBPMT data becomes available.

## 2 BACK ANALYSIS OF SBPMT

For isotropic linear elastic perfectly plastic Mohr-Coulomb material without cohesion governed by Rowe's dilatancy, Carter et al. (1986) derived the following relationship between the cavity strain,  $\epsilon_0$  (radial deformation at cavity wall divided by the

**Table 1.** Site particulars

Site	F.C %	D <sub>50</sub> mm	φ <sub>CV</sub>	Reference
Cell 24	7-12	0.20	28°	Campanella et al., 1995
J-Pit	7-12	0.20	28°	Iravani et al., 1995
Massey	2	0.14	32°	In-situ testing group, 1995 <sup>a</sup>
KIDD # 2	7	0.14	32°	In-situ testing group, 1995 <sup>a</sup>
LL Dam	7-9	0.14	34°	Bigger and Robertson, 1996
Treasure Island	15	0.10	30°	Pass, 1994
Nagoya		0.10	30°	Koga et al., 1994
Kobe	10-40	0.10	30°	Unpublished
Tokyo Bay	30	0.15 - 0.2	30°	Sawada and Sugawara (1995); Ishihara et al. (1987)
South Prospero	0-30	0.18 - 0.5	32°	Ghionna et al., 1995

- Note: 1. F.C= percent (by weight passing # 200 US sieve)  
 2. φ<sub>CV</sub> (constant volume friction angle) relates to the effective stress friction angle, φ', and v by K<sub>s</sub> = K<sub>sv</sub> × K<sub>CV</sub>, where  
 $K_s = (1 - \sin \phi') / (1 + \sin \phi')$   
 $K_{sv} = (1 - \sin v) / (1 + \sin v)$  and  
 $K_{CV} = (1 - \sin \phi_{CV}) / (1 + \sin \phi_{CV})$

original cavity radius), and effective cavity pressure (gas pressure within the inflatable section of the probe minus the ambient pore water pressure), P':

$$\epsilon_\theta = \frac{\sigma'_h \sin \phi'}{2G} \left[ \left( \frac{P'}{\sigma'_R} \right)^{Z/K_s - 1} X/Z - \left( \frac{P'}{\sigma'_R} - 1 \right) Y/K_s + 1 \right] \quad (1)$$

where  $X = 2\{1 + \Omega / (K_{as} - K_s + 1)\}$ ,  $Y = 2\Omega / (K_{as} - K_s + 1)$ ,  $Z = 1 + K_{as}$ ,  $\Omega = (1 - \mu)(K_{as}K_s + 1) - \mu(K_{as} + K_s)$ ,  $\sigma'_R = \sigma'_h(1 - \sin \phi')$ , and  $\sigma'_h =$  effective horizontal geostatic stress. The model uses a single valued shear modulus, G, and Poisson's ratio, μ, over the entire volume of deforming soil surrounding the cavity. This stress-strain model is based on small strain assumption and pertains to uncemented deposits. As is evident from Eq. (1), the model parameters include average values of the shear modulus and Poisson's ratio representative of the entire soil mass, the peak angle of internal friction and the dilation angle.

Using G to be approximately equal to 0.7 times the unload reload modulus for 20% unloading at  $\epsilon_\theta \approx 5\%$ , and  $\mu = 0.25$ , very reasonable values of the strength parameter φ' can be derived for many types of sand (da Cunha, 1994, Hughes et al., 1994). Analysis of a self-boring pressuremeter cavity expansion response essentially involves varying φ', v and σ'\_h until a reasonable match is obtained between the response predicted by Eq. (3) and that observed SBPMT. In the following it is examined whether the angle of dilatancy estimated following the procedure described above can be used as an index for liquefaction resistance.

The stress-strain relationship used in this study does not capture the stress path and fabric dependency in soil behavior. Hence, the results of the back analysis are only applicable if the problem geometry is similar to that in a cylindrical cavity expansion, i.e., plane strain extension. However, noting the fact that at large deformation the fabric effects tend to vanish, the value of the large strain dilation angle estimated from back analysis of SBPMT appears to be generally applicable in a plane strain problem. In a critical application, the data can in principle be analyzed using a constitutive model capable of accounting for stress path and fabric dependency to avoid this limitation.

### 3 RELATIONSHIP BETWEEN v AND (N<sub>1</sub>)<sub>60</sub>

Vaid et al. (1981) identified a correlation between the value of the dilation angle at shear strain of 10 % and (N<sub>1</sub>)<sub>60</sub> proceeding as follows. A linear relationship between v<sub>1</sub> (the value of the dilation angle normalized for an effective vertical stress of 1 atmosphere pressure) and relative density, D<sub>R</sub>, from laboratory simple shear experiments on reconstituted Ottawa Sand samples was first postulated. The stress level

correction for the dilation angle was approximated by  $v-v_1=2.5^\circ$ . Then utilizing a linear relationship between the relative density and  $\log(N_1)$  that is not specifically developed for Ottawa sand, a linear relationship between  $\log(N_1)$  and  $v_1$  was proposed. The symbol,  $N_1$ , is used to denote SPT blow count normalized for 100 kPa effective vertical stress. Since  $N_1$  is a reasonable index of liquefaction resistance (Seed, 1979), Vaid et al. (1980) suggest a correlation between the large strain dilation angle and liquefaction potential based on the relationship they identified between  $N_1$  and  $v_1$ . Except for the following approximations in this approach, the procedure can be readily adapted for SBPMT.

- The scheme for stress normalization for the dilation angle is approximate.
- Although a relationship between  $v_1$  and  $D_r$  for Ottawa Sand was used, to develop a relationship between  $v_1$  and  $N_1$  a global correlation between  $N_1$  and  $D_r$  was utilized. Unless the sands for which the correlation between  $N_1$  and  $D_r$  is developed are of the same compressibility as Ottawa sand, its use may lead to ambiguity (see e.g., Vaid et al., 1985).
- The correlation proposed by Vaid et al. does not use energy corrected SPT blow count. Since energy delivered to the drill rods while conducting an SPT can vary over a wide margin depending on testing equipment and procedure, energy correction to SPT blow count is at present perceived to be of minimum necessity for ensuring accuracy.

A direct correlation between an estimate of dilation angle from SBPMT and  $(N_1)_{60}$  can largely resolve these problems. In the simple isotropic elastic perfectly plastic stress strain relationship used in this study to back analyze SBPMT,  $v$  remains constant after failure, prior to which there is no relevance of this parameter. It is the constant post-failure value of  $v$  that is used in what follows as an index of resistance to cyclic liquefaction. Since the dilation angle derived from SBPMT is only used here as an index for soil liquefaction resistance, the fact that the stress strain relationship does not account for variation of  $v$  with strain in a realistic manner should not be viewed as an approximation.

To obtain  $v_1$  from  $v$  determined from back-analysis of SBPMT, the curvature in the Mohr-Coulomb failure envelope needs to be accounted for. For a large number of cohesionless soils, the difference between  $\phi'$  and  $\phi_{cv}$  decreases to zero as the effective mean

normal stress increases from 1 atmosphere to 100 atmosphere (Byrne et al., 1987; and Vesic and Clough, 1968). This observation is utilized in this study to normalize the dilation angle for the effective vertical stress.

To explore the possibility of developing a relationship between  $v_1$  and  $(N_1)_{60}$  the statistical behavior of these variables is first examined. Figure 1 shows the cumulative frequency distributions of  $v_1$  and  $(N_1)_{60}$  for in-situ test data from eleven sand sites. The vertical scale of the plot is such that a normally distributed data set will plot on a straight line. The linearity of the cumulative frequency distribution of the log-transformed variables indicates a log-normal distribution of  $v_1$  and  $(N_1)_{60}$ . Thus, a correlation between  $\log(v_1)$  and  $\log[(N_1)_{60}]$  can be postulated. Linear regression of  $\log(v_1)$  and  $\log[(N_1)_{60}]$  yields the following relationship

$$\log v_1 = 0.57 \log (N_1)_{60} + 0.25 \quad (2)$$

The value of the coefficient of determination,  $R^2$ , for this relationship is 0.82. Eq. (2) pertains to non-plastic cohesionless materials and the correlation does not depend on the fines content. Data used in the development of Eq. (2) and the correlation are plotted in Figure 2.

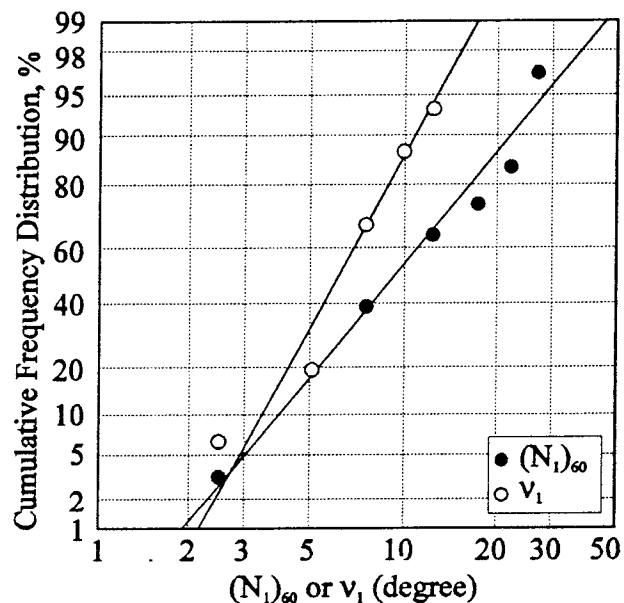


Figure 1. Cumulative frequency distribution

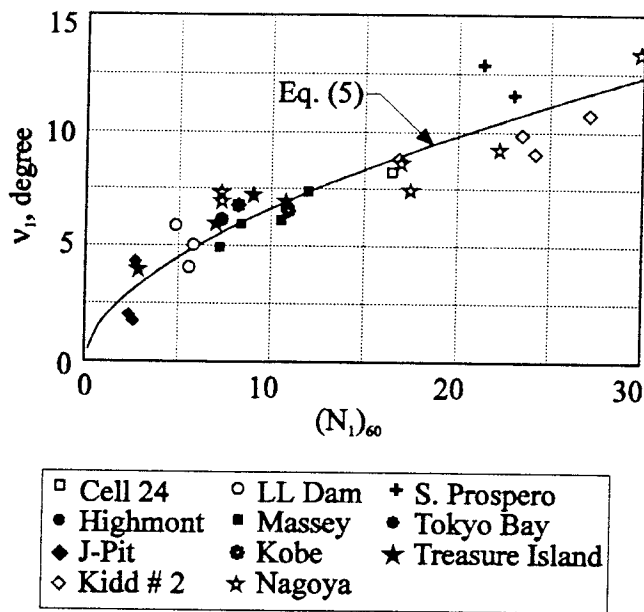


Figure 2. Correlation between  $(N_1)_{60}$  and  $v_1$

#### 4 LIQUEFACTION POTENTIAL FROM SBPMT

Seed et al. (1985) proposed a chart relating  $(N_1)_{60}$  with the cyclic stress ratio needed to trigger liquefaction, that essentially embodies the current state of practice for identifying non-plastic or low-plasticity liquefiable deposits from SPT. A modification to the chart has been proposed recently by the National Center for Earthquake Engineering Research (NCEER), which introduces a cut-off for the critical stress ratio axis at  $\tau/\sigma_v' = 0.05$  (Finn, 1996).

Using Eq. (2), the NCEER chart has been replotted as shown in Figure 3 with  $v_1$  as the index for liquefaction resistance instead of  $(N_1)_{60}$ . Figure 3 can be used to evaluate the liquefaction potential of cohesionless soils from self-boring pressuremeter data.

#### 5 VALIDATION

Widespread liquefaction have been reported at Kobe in the magnitude 7.2 Hyogoken Nambu event of January 17, 1995. Although liquefaction was reported at the north-northwestern and southeastern areas of Treasure Island near San Francisco, the deposit at other areas performed reasonably well during the magnitude 7.1 Loma Prieta event of October 17, 1989 (Hryciw et al., 1991). SBPMTs at a site in Kobe and a location in

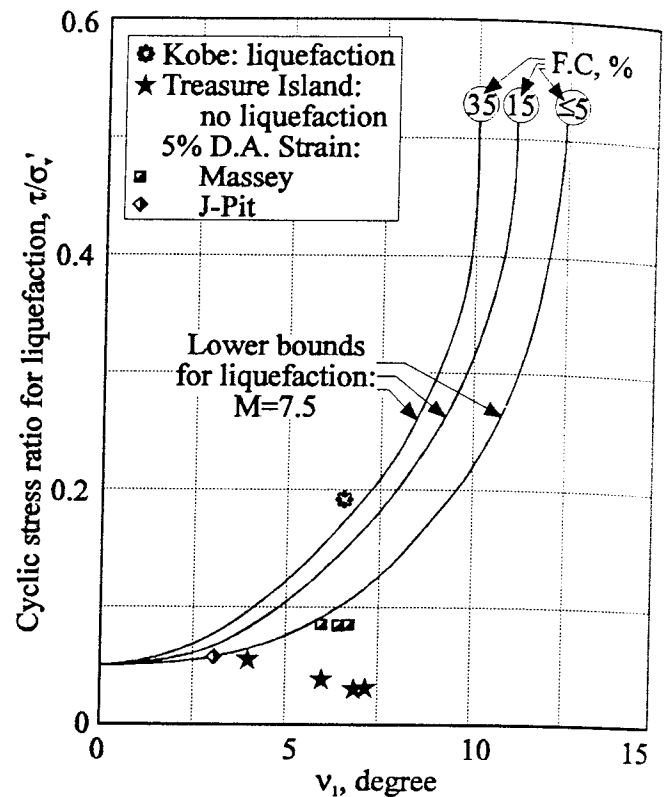


Figure 3. Liquefaction potential from  $v_1$  (D.A.: double amplitude)

Treasure Island that did not liquefy during the Loma Prieta earthquake are used to validate the proposed chart (Figure 3). Laboratory cyclic simple shear test data on samples extracted by ground freezing from Massey Tunnel and J-Pit (Vaid et al., 1996) are also used to check the accuracy of the proposed procedure. The observed field performance of the deposits in Kobe and Treasure Island and the cyclic simple shear data are superposed to the proposed chart (Figure 3). A reasonable performance of the chart is apparent from the comparison.

The above exercise should not be construed as a suggestion that SBPMT is a better screening tool for identifying deposits susceptible to cyclic liquefaction than SPT. However, as mentioned earlier, SBPMT data pertain to stress-strain measurement over a large range of strain at a given depth. In contrast, index measurement such as SPT  $(N_1)_{60}$  is essentially a single measurement pertaining to a certain average value of strain in the surrounding soil. A potential therefore exists of calibrating a realistic stress strain relationship from SBPMT data. A calibration procedure has already been developed for monotonic loading by Roy

(1997) using SBPMT. The approach can be used in principle for cyclic loading. A stress strain relationship calibrated in this manner can be used to derive a precise estimate of deformation of the deposit during an earthquake. A similar use for in-situ index measurements cannot be envisaged.

## 6 CONCLUSIONS

A relationship has been identified between the angle of dilatancy estimated from inverse modeling of the self-boring pressuremeter data and standard penetration test blow count using data from eleven sand sites. Using this correlation, a chart has been proposed to assess the liquefaction resistance of cohesionless deposits from self-boring pressuremeter tests. Laboratory test data on frozen samples from two sites in Western Canada, field performance of a site in Kobe during the Hyogoken Nambu event of 1995 and field performance at Treasure Island near San Francisco during the 1989 Loma Prieta event were used to validate the procedure.

It is evident from the results that the inference drawn from SBPMT data are consistent with the observations in SPT at several sand sites world wide. SBPMT is thus as good a screening tool for identifying deposits susceptible to cyclic liquefaction as SPT. However, since in an SBPMT stress strain data are measured over a wide range of deformation at a given depth, there is a potential to develop a procedure for calibration of a realistic stress strain relationship from SBPMT. The calibrated model can be used to estimate deformation response of the deposit for important structures on soils susceptible to liquefaction if needed.

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