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Field Correlation of Soil Liquefaction with SPT and Grain Size

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SYNOPSIS Two earthquakes of magnitudes 6.7 and 7.4 that occurred in 1978 off the Pacific coast of Miyagi Prefecture, Japan, provided field liquefaction data for a fairly wide range of peak ground surface acceleration from 100 to 290 gal. The range of SPT N-values was also fairly wide because special efforts were made to collect non-liquefaction data in addition to liquefaction data. Dynamic shear stress ratios adjusted for earthquake magnitudes and effective overburden pressures are plotted against N-values adjusted for effective overburden pressures. The field data are compared with two methods proposed recently, one by Seed and the other by Iwasaki et al, after a critical review of the methods and the SPT's in the U.S. and Japan. The method by Seed tended to underestimate the resistance to liquefaction for small N-values, particularly for silty sands; whereas the method by Iwasaki et al tended to underestimate the resistance to liquefaction for large N-values.

INTRODUCTION

The need for predicting the dynamic behavior of medium dense to dense sands, either naturally dense or stabilized sands, has increased as aseismic design of important facilities began to call for strong ground motions which would exceed the range covered by past case histories. A straightforward approach in which undrained cyclic tests are conducted on undisturbed soil samples suffers from the difficulty of obtaining high quality undisturbed samples of dense sands. Although it is feasible to obtain such samples by freezing sand in situ (Yoshimi et al, 1977), the method is expensive — particularly so if variability of soil calls for many samples. There is strong need, therefore, for a simple and inexpensive method, e.g., a field correlation technique based on the standard penetration test (SPT) results. The existing methods of that type which will be discussed in the following section lack field data for dense sands subjected to strong ground motions, and their reliability suffers from lack of adequate standardization of the SPT method. The object of this paper is to present some field data of liquefaction behavior of loose to dense sands during strong earthquakes, and to relate them with the SPT results and grain size.

turbed samples of saturated sands. The method, hereinafter abbreviated as the I+T method, has recently been adopted in at least two Japanese design manuals (Japan Road Association, 1980; MITI, 1980).

In this section the two methods introduced above will be compared and discussed. For both methods the dynamic shear stress ratio during earthquakes is given by essentially the same expression as follows:

$$\frac{\tau_d}{\sigma'_0} = C \frac{\alpha_{max}}{g} \frac{\sigma_0}{\sigma'_0} r_d \quad (1)$$

in which τ_d = shear stress induced by an earthquake, α_{max} = peak horizontal acceleration at the ground surface, g = gravitational acceleration, σ_0 = initial total vertical stress, σ'_0 = initial effective vertical stress, r_d = stress reduction factor having a value of one at the ground surface, and C = factor to relate the average shear stress amplitude to the peak value.

Concerning the evaluation of liquefaction resistance, on the other hand, there are substantial differences between the two methods as shown below:

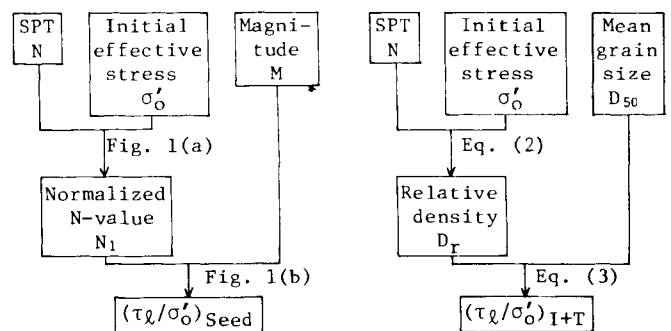
REVIEW OF EXISTING CRITERIA OF SOIL LIQUEFACTION BASED ON SPT RESULTS

Seed (1979) proposed a practical method based on SPT results for evaluating the liquefaction potential of sands for level ground conditions. The method is based on field behavior of sands during earthquakes and large-scale laboratory test results (DeAlba et al, 1976), and is included in a publication by the Applied Technology Council, Palo Alto, California (1978).

Iwasaki, Tatsuoka et al (1978) proposed another method for the same purpose based on numerous undrained cyclic triaxial test results on undis-

The Seed Method

The Iwasaki-Tatsuoka Method



The relative density is expressed by

$$D_r = 21 \sqrt{\frac{N}{\sigma'_0 (\text{kgf/cm}^2) + 0.7}} \quad (2)$$

which is a metric equivalent of the formula proposed by Meyerhof (1957). The liquefaction resistance according to the Iwasaki-Tatsuoka method takes the following form when the factor C in Eq. (1) is assigned a value of 0.65:

$$\left(\frac{\tau_d}{\sigma'_0}\right)_{I+T} = 0.0573 \left[\sqrt{\frac{N}{\sigma'_0 (\text{kgf/cm}^2) + 0.7}} - f(D_{50}) \right] \quad (3)$$

in which

$$f(D_{50}) = \begin{cases} 2.55 \log \frac{D_{50} (\text{mm})}{0.35} & \text{for } D_{50} = 0.04 \sim 0.6 \text{ mm} \\ 0.567 & \text{for } D_{50} = 0.6 \sim 1.5 \text{ mm} \end{cases} \quad (4)$$

Eq. (4) takes into account the effect of fines content on the SPT N-value, i.e., for the same strength N tends to decrease as the sand contains more fines. Note that the relative density is used only as an intermediate parameter for reducing the test data to the form of Eq. (3).

Because the Iwasaki-Tatsuoka method is based on the test data on samples of normally consolidated sands of alluvial deposits or fills, its applicability is limited to the following range (Tatsuoka et al, 1978):

$$\begin{aligned} 0.2 \leq \sigma'_0 &\leq 1.7 \text{ kgf/cm}^2 \\ 15 \leq D_r &\leq 80 \% \\ 0.1 \leq (\tau_d/\sigma'_0)_{I+T} &\leq 0.26 \end{aligned} \quad (5)$$

The factor of safety against liquefaction FL for each method may be defined by

$$FL_{\text{Seed}} = (\tau_d/\sigma'_0)_{\text{Seed}} / (\tau_d/\sigma'_0) \quad (6)$$

$$FL_{I+T} = (\tau_d/\sigma'_0)_{I+T} / (\tau_d/\sigma'_0) \quad (7)$$

Because Fig. 1 has been prepared for application in the U.S.A., the penetration resistance values are those to be obtained according to the current U.S. practice. Seed cautioned that Fig. 1 should be applicable for penetration resistance values determined by using a rope and drum method to operate the hammer and drilling mud to stabilize the hole, and that the N-values

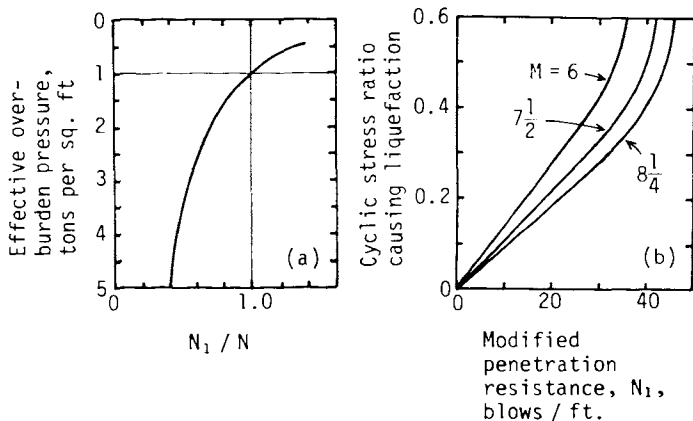


Fig. 1 Charts for the Seed Method (Applied Technology Council, 1978)

determined by the rope and drum method might be about 80 percent greater than those determined by a free-fall method (Seed, 1979).

On the other hand, the Iwasaki-Tatsuoka method is based on the penetration resistance values obtained in Japan according to the Method of Penetration Test for Soils, JIS (Japan Industrial Standards) A 1219-1961, that requires free-fall of the hammer. Although the trip monkey method is being used, the rope and drum method is also accepted in current practice because it is generally believed that either method produces about the same N-values. Fig. 2 shows the results of comparative field tests (Kanto Soil Investigators Association, 1976; Sunami, 1962) for sands, silty sands, sandy silts, and gravelly sands to a depth of 15 m. The data show statistically that the N-value by the rope and drum method is greater by 2.7 than that by the trip monkey method, not by 80 percent as Seed suggested for the U.S. data.

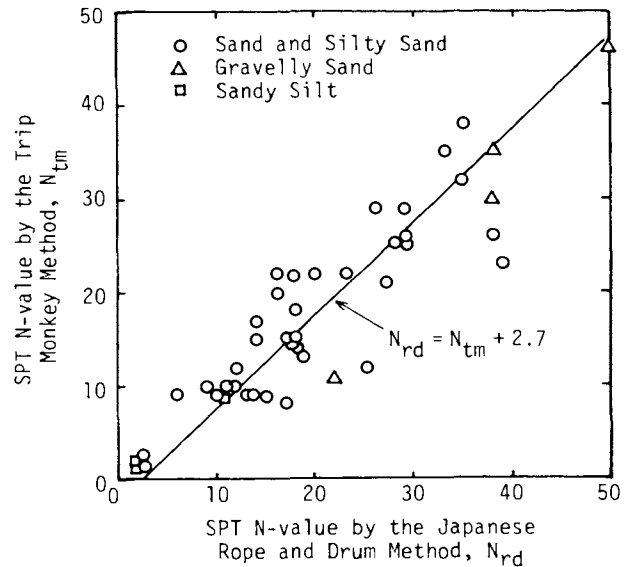


Fig. 2 Results of Comparative SPT Tests for Depths to 15 m (Plotted from data by Kanto Soil Investigators Association, 1976, and by Sunami, 1962)

It seems worthwhile at this stage to compare the U.S. and Japanese SPT's, particularly with respect to the rope and drum method. Both methods use essentially the same sampler-rod assembly and driving method as shown in Fig. 3 and Table I. However, there is a considerable difference in the diameter of the rope and the drum (cathead). The age and the number of turns of a rope have been shown to affect the impact energy delivered to the rod (Kovacs, 1977). But, reports on possible effects of the diameter of the rope and drum have not come to the authors' notice. It is conceivable that the size of the rope and drum may have a significant effect on the SPT result, and may account for a major portion of the difference between the Japanese and U.S. penetration resistance values determined with the rope and drum method. Further studies will be necessary to clarify that point. In the mean time, the SPT results will be classified into the following two groups:

N_A : Blows per foot by the U.S. rope and drum method
 N_J : Blows per 30 cm by the trip monkey method or the Japanese rope and drum method

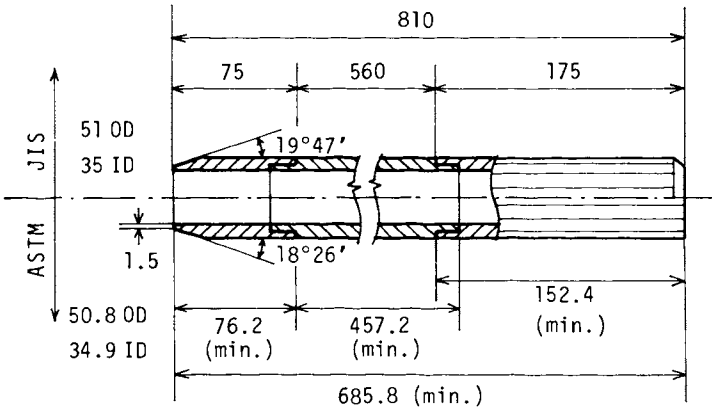


Fig. 3 Dimensions in mm of Standard Split Barrel Sampler for JIS A 1219 and ASTM D1586

Table I. Comparison between Japanese and U.S. SPT Methods

	Japan	U.S.A.
Hammer weight, kgf	63.5	63.5(140 lb)
Fall height, cm	75	76.2(30 in.)
Drill rod diameter, mm	40.5 or 42	41.2(min.)
Seating drive, cm	15	15.24(6 in.)
Effective penetration, cm	30	30.48(12 in.)
Hole diameter, cm	6.5~15	5.7~15.2
Driving method	Trip monkey or rope & drum	Rope & drum
Rope diameter, mm	13~16	19~25 a, b
Drum diameter, cm	≒13	15~30 b, c

a: Kovacs et al (1977), b: Heidengren (1980)
 c: Schmertmann (1977), estimated from photograph

Figs. 4 and 5 show the factors of safety for two soil profiles. For the loose, medium sand of Fig. 4 subjected to a peak acceleration of 0.165 g resembling the conditions in Niigata during the Niigata earthquake of 1964, both methods predict about the same factor of safety to a depth of 10 m, provided that N_A is used for the Seed method and N_J for the Iwasaki and Tatsuoka method. That seems reasonable because both methods have been checked against the case history of that earthquake. For the denser and coarser sand of Fig. 5 subjected to stronger ground motions, on the other hand, the methods give considerably different results, i.e., the Iwasaki and Tatsuoka method predicts liquefaction while the Seed method does not. The difference in the factor of safety is quite substantial and pertinent to the theme of the paper.

Fig. 6 has been prepared to compare the two methods in more general terms. The Iwasaki-Tatsuoka method gives greater strength than the Seed method for looser and/or finer sands, whereas the Seed method predicts greater strength when the soil is denser and/or coarser. The

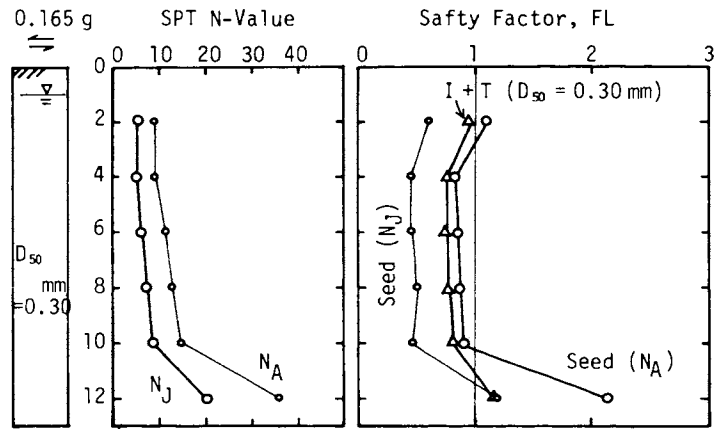


Fig. 4 Methods by Seed and I+T Compared for Soil Profile Similar to Niigata

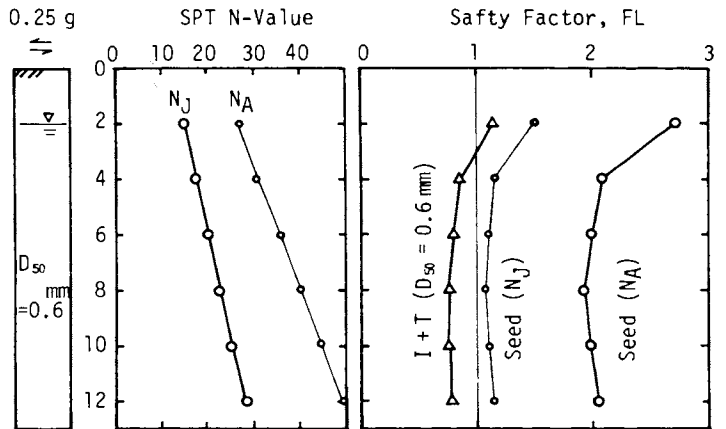


Fig. 5 Methods by Seed and I+T Compared for Dense Sand Deposit

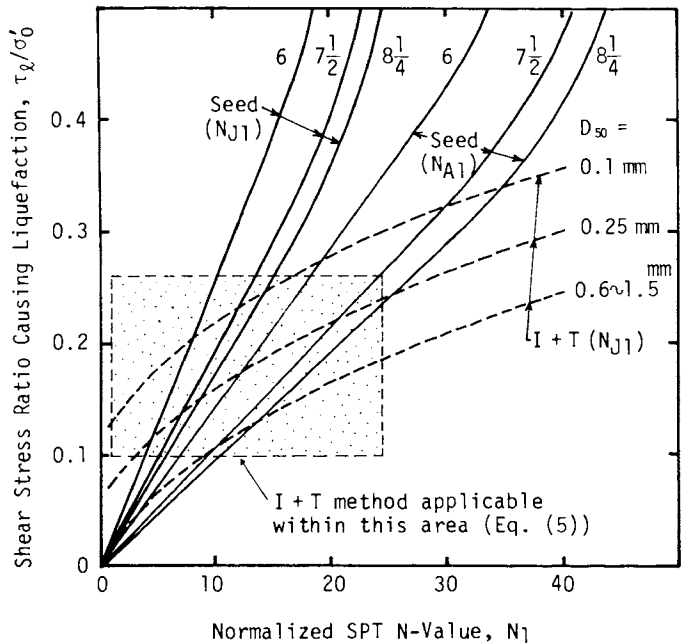


Fig. 6 Comparison between the Seed Method and the Iwasaki-Tatsuoka Method

earthquake magnitude is included in the Seed method probably because both M6 and M8-plus earthquakes can be important in the U.S.A., i.e., an M6 earthquake can be destructive at a short distance from inland faults such as the San Andreas fault known to cause earthquakes, while M8-plus earthquakes can occur off the coast of Alaska. On the other hand, the major concern to the Japanese engineer is M7.5 to M8 earthquakes occurring off the coast, and that probably is the reason for not including M as a variable in the Iwasaki-Tatsuoka method.

The curves by Seed are characterized by the fact that they pass through the origin and that their slope increases as the N-value exceeds a certain limit. The latter characteristic reflects the concept of limiting shear strain potential which is related to positive dilatancy of dense sand. On the other hand, the I+T curves do not necessarily pass through the origin, and their slope decreases with an increase in the N-value reflecting the fact that the first term in Eq. (3) is proportional to the square root of N. It is conceivable that the conservative estimate of the resistance at high N-values might be attributed to sample disturbance or the difficulty of applying high enough shear stress in the extension phase of the cyclic triaxial test. The deviation between the Seed and I+T curves for dense sand is too large to ignore, and has motivated the authors to initiate the present study. What follows is some of their preliminary findings of field behavior of sands during strong earthquakes.

RECENT OBSERVATIONS OF LIQUEFACTION OF SANDS

Two earthquakes occurred off the coast of Miyagi Prefecture in northern Japan within a four-month period in 1978. The dates, the magnitudes, the epicentral locations, and the focal depths of the earthquakes were as follows:

- Feb. 20, 1978, M6.7, 38°45'N, 142°12'E, 50 km
- Jun. 12, 1978, M7.4, 38°09'N, 142°10'E, 40 km

Fig. 7(a) shows the peak horizontal accelerations at the ground surface recorded with strong-motion instruments during the earthquakes. The peak horizontal accelerations at some other locations have been estimated from various field observations including those of overturned tombstones. Both the measured and estimated accelerations are shown in Fig. 7(b), (c), covering a wide range between 100 and 290 gal. In order to facilitate comparison of liquefaction behaviors during different earthquakes, the factor C in Eq. (1) is adjusted in such a way that the equation will give an equivalent shear stress ratio which would cause liquefaction in 20 cycles, as follows:

$$C = 0.65 (N_{\ell} / 20)^{0.2} \tag{8}$$

in which N_{ℓ} = number of cycles of equivalent uniform shear stresses having an amplitude of 0.65 times the peak value. Eq. (8) is based on the assumption that the relationship between the dynamic shear stress and the number of cycles on a log-log graph is a straight line having a slope of -0.20. The assumption is compatible with the results of undrained cyclic triaxial tests on undisturbed sands conducted by Tatsuoka et al (1980).

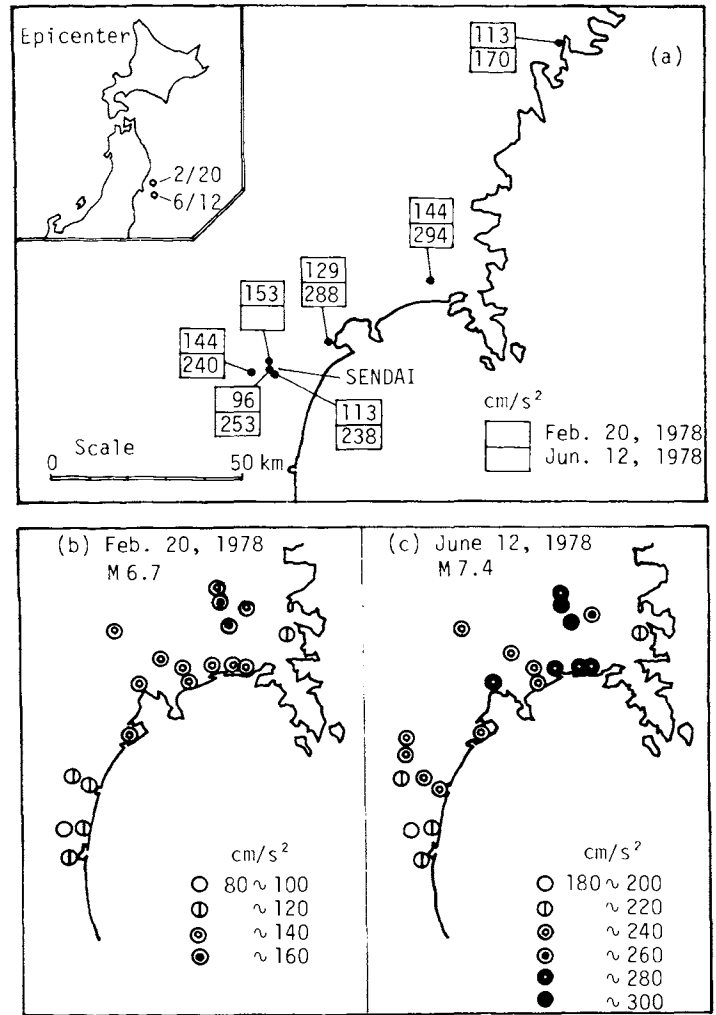


Fig. 7 Peak Horizontal Accelerations at the Ground Surface During the Miyagiken-oki Earthquakes of 1978

On the basis of the relationship between N_{ℓ} and earthquake magnitude, M, proposed by Seed (1979), the value of C may be related to M as shown in Table II and Fig. 8. When the expression for r_d by Iwasaki et al (1978) is incorporated, Eq. (1) becomes

$$\frac{T_d}{\sigma'_0} = C \frac{\alpha_{max}}{g} \frac{\sigma'_0}{\sigma'_0} (1 - 0.015z) \tag{9}$$

in which z = depth in m. The N-value, N_{ℓ} ,

Table II. Values of C for Eq. (9)

M	N_{ℓ}	C
5 ~ 6	5	0.49
7 ~ 7 1/2	15	0.61
8 ~ 8 1/4	25	0.68

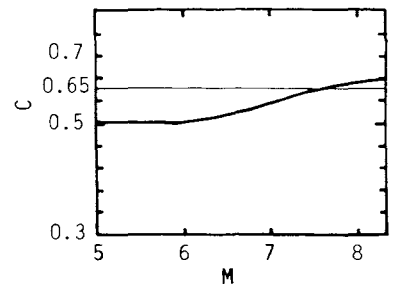


Fig. 8 Values of C for Eq. (9)

normalized for $\sigma'_0 = 1 \text{ kgf/cm}^2$, N_{J1} , may be approximated by

$$N_{J1} = \frac{2N_j}{\sigma'_0 (\text{kgf/cm}^2) + 1}, \quad \sigma'_0 < 3 \text{ kgf/cm}^2 \quad (10)$$

which is equivalent to Fig. 1(a).

The field data and the results of calculation for the liquefied sites are shown in Table III, and the relationship between τ_d/σ'_0 and N_{J1} is plotted in Fig. 9 for both liquefied and non-liquefied sites. The data include the sites where liquefaction did not occur during either earthquake and those where liquefaction occurred only during the June earthquake. Efforts were made to collect as many non-liquefaction data as possible in addition to liquefaction data (Tohno and Yasuda, 1978, Iwasaki et al, 1978, Tsuchida et al, 1979, Ishihara et al, 1980).

All the data for $0.25 < D_{50} \leq 1.5 \text{ mm}$ are plotted together in Fig. 9(a) because the grain size does not seem to affect the relative position of liquefaction and non-liquefaction data. The solid curves in Figs. 9(a) and 9(b) show the lower bound for sites where liquefaction occurred. The lower bound curve in Fig. 9(b) is significantly higher than that in Fig. 9(a), indicating that the grain size influenced the liquefaction resistance of sand at a given N-value, as Tatsuoka et al (1978) had shown, although the grain size appears to have little effect when D_{50} exceeds 0.25 mm.

The chain-dotted lines labeled S and the broken lines labeled I+T in Fig. 9 show the liquefaction resistance by the Seed method (Fig. 1(b)) and the Iwasaki-Tatsuoka method (Eq. (3)), respectively. As for the Seed method, only the curves for $M = 7 \frac{1}{2}$ are shown because the data points correspond to $N_g = 20$ according to Eq. (8) and Table II. The I+T curves are shown here without regard to the limits of applicability as indicated in Fig. 6.

The lower bound curve in Fig. 9(b) is not very far from either the Seed curve or the I+T curve, except at very low N-values where it is considerably higher than the Seed curve. With respect to Figs. 9(a) and 9(b) the solid circles at higher N-values probably represent a cyclic mobility type behavior which might be more difficult to detect than liquefaction of loose sands as observed in Niigata during the Niigata earthquake of 1964. It is conceivable that a line separating data of destructive behavior and non-destructive behavior might be a bit closer to the upper left corner than the lower bound curve shown.

As far as the data in Fig. 9 are concerned, the Iwasaki-Tatsuoka method tends to underestimate the soil resistance for large N-values, whereas the Seed method tends to underestimate the soil resistance for small N-values, particularly for silty sands.

CONCLUDING REMARKS

The existing methods for evaluating liquefaction potential of sand deposits have limited range of applicability, either in terms of SPT N-values or grain size. The standard penetration tests on which the methods are based

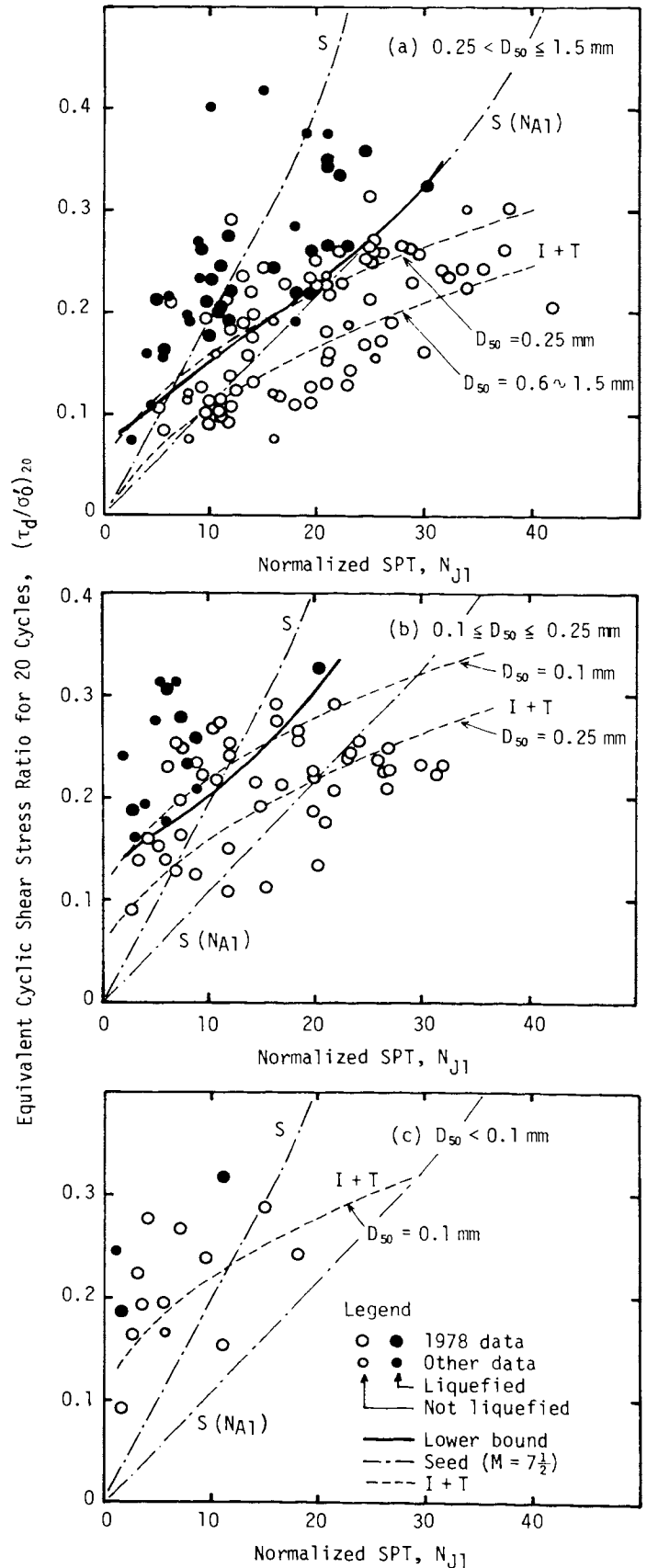


Fig. 9 Relationship among Field Liquefaction Behavior, SPT Results, and Grain Size

involve ambiguities which may cause considerable variation in the N-values. Careful attention to the above is necessary for proper use of the methods.

There is need for more field liquefaction data for dense sands during strong earthquakes, and an international cooperative test program for correlating the SPT results should be beneficial for making better use of field liquefaction data.

Table III. Soil and Seismic Data for Sites Liquefied during the Miyagiken-oki Earthquake of June, 1978

Site	Depth (m)	Water Table (m)	σ'_0 (kgf/cm ²)	N _J	N _{J1}	α_{max} (g)	$\frac{\tau_d}{\sigma'_0}$	D ₅₀ (mm)
1	3.3	0.0	0.34	13	19	0.18	0.22	1.4
2	2.3	0.8	0.28	7	11	0.21	0.20	0.4
	4.3		0.46	16	22		0.34	0.3
3	2.3	0.8	0.28	7	11	0.21	0.20	0.4
4	1.3	0.1	0.13	13	23	0.21	0.27	0.3*
5	3.3	0.8	0.45	2	3	0.21	0.19	0.15*
6	1.3	0.0	0.13	12	21	0.21	0.27	0.6*
	3.3		0.33	13	20		0.26	0.6*
7	6.3	1.0	0.68	10	12	0.21	0.22	1.0
8	2.3	1.8	0.38	4	6	0.23	0.16	0.6*
	3.3		0.48	1	1		0.19	0.03*
9	3.3	0.8	0.39	7	10	0.23	0.23	0.4
	5.3		0.59	13	16		0.24	0.4
10	2.3	1.7	0.38	7	10	0.24	0.17	0.3
	4.3		0.57	4	5		0.21	0.4
11	3.3	1.3	0.43	13	18	0.24	0.22	0.6
12	3.3	0.3	0.36	8	12	0.24	0.27	1.0
13	2.0	0.0	0.18	18	31	0.24	0.32	0.4*
14	3.2	0.3	0.32	14	21	0.28	0.35	0.4*
15	6.3	4.3	0.85	9	10	0.29	0.21	0.3
16	6.3	2.4	0.72	8	9	0.29	0.26	0.4
17	2.0	1.7	0.37	8	12	0.28	0.19	0.4
18	3.3	0.8	0.35	4	6	0.27	0.31	0.15*
19	4.0	1.0	0.48	5	7	0.28	0.28	0.17
20	6.2	1.3	0.84	8	9	0.25	0.26	0.15*
21	2.3	1.5	0.30	5	8	0.29	0.23	0.15*
	6.3		0.72	9	10		0.30	0.07*
22	3.3	0.0	0.31	16	25	0.28	0.36	0.4
	5.3		0.51	16	21		0.34	0.4
23	5.0	2.0	0.65	9	11	0.28	0.25	0.4
24	5.3	0.6	0.47	15	21	0.27	0.32	0.1

* Estimated from Soil Type

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