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Dilation Angle and Liquefaction Potential

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SYNOPSIS Most of our understanding of the liquefaction phenomenon has come from laboratory tests. It would be desirable to express liquefaction resistance in terms of a parameter which can be measured both in the laboratory and in the field. It is proposed that the dilation angle or expansion rate of the sand is such a parameter. It is readily measured in the laboratory from drained simple shear or triaxial tests and in the field from self boring pressuremeter tests. Based on laboratory tests on Ottawa sand a chart is presented for estimating the liquefaction resistance of saturated sands in terms of dilation angle in addition to the usual parameters relative density and blow count. When the chart was used in conjunction with pressuremeter tests, a conservative estimate of liquefaction resistance of a hydraulic fill dam was obtained.

INTRODUCTION

Cyclic loading of saturated sands under conditions of no drainage results in a marked reduction of its strength or resistance. This strength loss is associated with a rise in porewater pressure, and if this rise should cause the effective stress to drop to zero, the strength will be zero, and the sand is said to have liquefied. Such strength loss and liquefaction resulted in major damage during the Alaska, Niigata and San Fernando earthquakes.

Laboratory cyclic load tests indicate that the relative density of the sand is an important parameter controlling its resistance to liquefaction. In the field it is difficult to measure relative density and it is common practice to infer the relative density and liquefaction resistance of sand from penetration tests. The most commonly used relationship between penetration resistance and relative density is the one proposed by Gibbs and Holtz (1957). More recently Seed et al. (1975) have proposed that the penetration resistance corrected or normalized to 1 T/ft^2 be used directly as a measure of liquefaction resistance. Penetration resistance tests cannot be performed on small laboratory samples and thus cannot be correlated directly with laboratory cyclic load test behaviour. It would be desirable to have a single parameter describing the initial state of the sand which could be obtained in both the laboratory and the field and which would give a measure of liquefaction resistance. It is proposed herein that the dilation angle or expansion rate of the sand during shear is such a measurement. It can readily be obtained in the laboratory from drained triaxial or simple shear tests and in the field it can be obtained from self boring pressuremeter tests as described by Hughes et al. (1977).

A liquefaction resistance chart similar to that proposed by Seed (1976) but based on dilation angle rather than corrected blow count is presented. From this chart an estimate of the field liquefaction resistance of saturated sands can be obtained from dilation angles measured from self boring pressuremeter tests.

DILATION ANGLE AND RELATIVE DENSITY

An idealized shear behavior of sand at constant confining stress σ_3' in drained triaxial compression is shown in Fig. 1. Over a considerable range of strain, both initially loose and dense samples undergo volume expansion (dilation), and at very large shear strains tend to approach an ultimate strength and void ratio. However, the rate of volume expansion with shear strain is larger for the dense than for the loose sand. The dilation rate of sand is characterized by the dilation angle ν, which is the inverse sine of the slope of volume expansion curves in Fig. 1 (Hansen, 1958), i.e.

$$\sin \nu = \frac{dv}{d\gamma} \qquad (1)$$

If triaxial compression tests were carried out using a higher value of confining pressure, results similar to Fig. 1 will be obtained; but, at a given initial void ratio (or relative density D_r), increase in σ_3' will result in a decrease in ν and also the ultimate void ratio. The dilation angle ν is thus a function both of relative density and confining pressure.

The shear behavior of sand under drained simple shear conditions at constant vertical confining stress σ_{vo}' is also similar to that under the triaxial conditions. The results of such tests on Ottawa sand C-109 are shown in Fig. 2 for a range of relative densities. It may be seen that for each relative density the slope of vol-

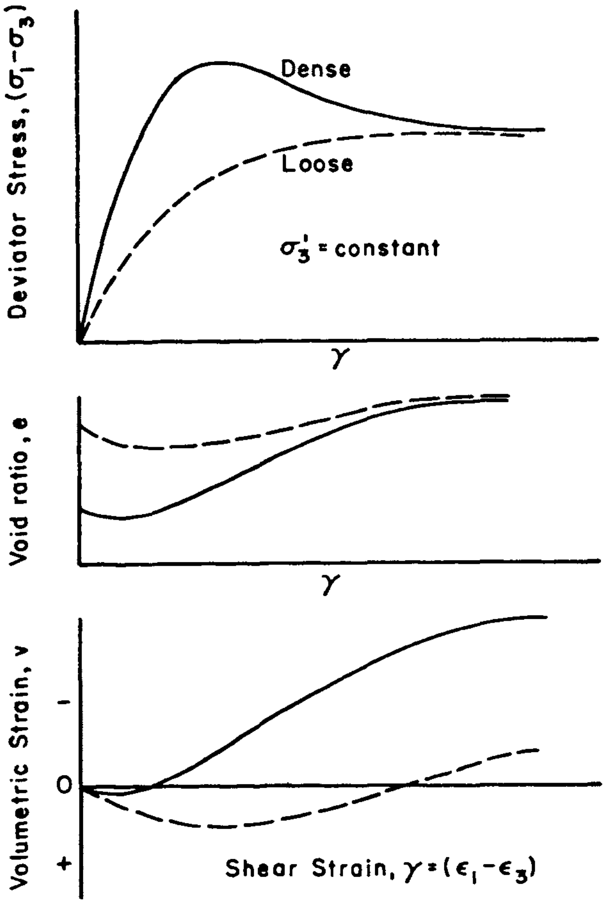


Fig. 1. Idealised behaviour of sand in drained triaxial compression

umetric strain versus shear strain curve, and hence ν, is essentially constant over a wide range of shear strain. A notable feature of the behavior in simple shear, however, is the relative flatness of the stress-strain curve for dense sand in contrast to a peak followed by a reduction in strength under the triaxial conditions (Fig. 1). This implies that under simple shear conditions, the sand deforms at a constant stress ratio with the result that the dilation angle ν also remains constant over a considerable strain range.

It is clear from the results shown in Fig. 2, that the dilation angle ν of sand is closely related to its relative density. The value of ν was computed at a shear strain $\gamma = 10\%$, and is shown plotted against the corresponding relative density in Fig. 3. A linear relationship was obtained for the sand tested. This relationship, however, applies for a vertical confining stress of 200 kPa. As pointed out earlier, the dilation angle also depends on the level of confining stress. The variation of dilation angle with relative density and vertical confining pressure for Leighton Buzzard sand is shown in Fig. 4, and is based on a comprehensive series of simple shear tests by Cole (1967). It is clear that for this sand also a linear relationship exists between ν and D_r at each confining pressure (Fig. 4a). Furthermore, at each relative density, ν decreases linearly with confining pressure and the slope of the straight line is essentially independent of relative density (Fig. 4b). The dilation angle ν_1 at a confining pressure of

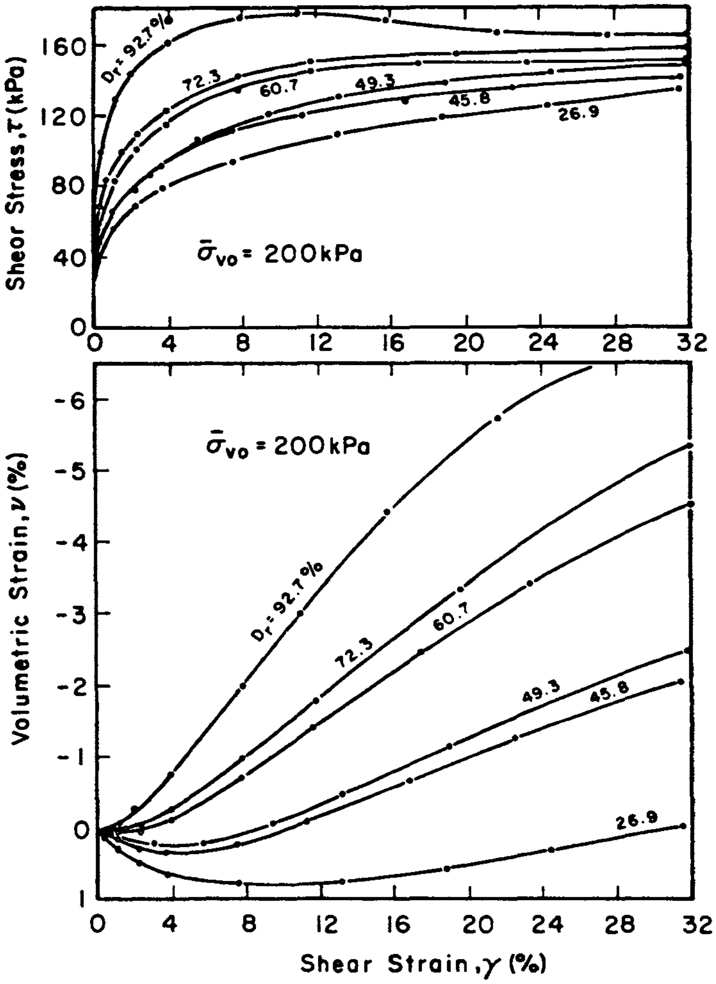


Fig. 2. Stress-strain behaviour of Ottawa Sand in drained simple shear

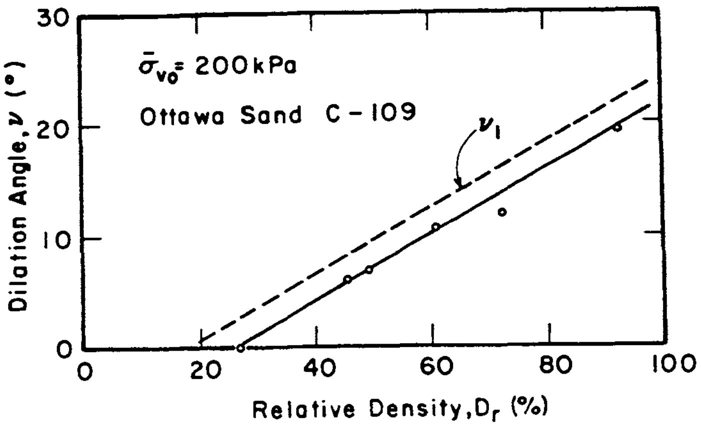


Fig. 3. Relationship between dilation angle and relative density

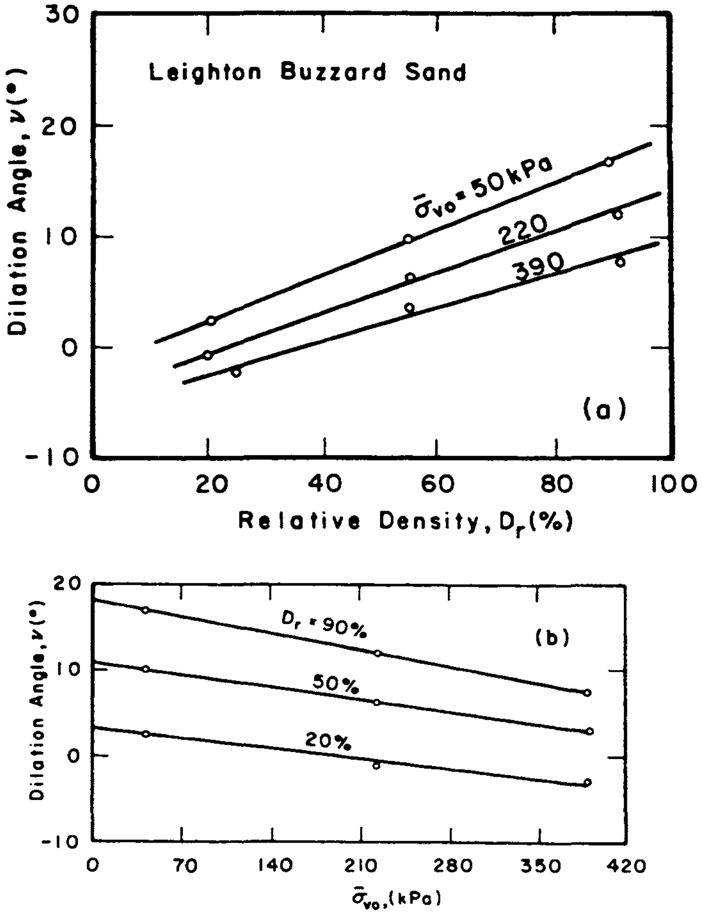


Fig. 4. Dependence of dilation angle on relative density and confining pressure (Data from Cole, 1967)

1 T/ft^2 (100 kPa) is about 2 1/2 degrees higher than at 2 T/ft^2 (200 kPa). If it is assumed that Ottawa sand behaves in a manner similar to Leighton Buzzard sand with respect to the dependence of ν on confining pressure, a linear relationship between dilation angle corrected to a confining pressure of 1 T/ft^2 (100 kPa) and relative density will be obtained. This is shown dotted in Fig. 3.

ANALYSIS PROCEDURE

The liquefaction resistance of saturated sand as obtained from laboratory tests has been expressed as a function of relative density by many researchers including Seed (1976) and Finn and Vaid (1978). By performing drained static simple shear tests on the same sand over a range of relative densities and observing the volume change characteristics, its dilation angle as a function of relative density can be obtained. This allows the liquefaction resistance to be expressed in terms of dilation angle and thus by obtaining in situ measurements of dilation angles from self boring pressuremeter tests, an estimate of the in situ liquefaction resistance of saturated sand is obtained.

LIQUEFACTION RESISTANCE, RELATIVE DENSITY AND DILATION ANGLE

The liquefaction resistance of Ottawa sand as obtained from constant volume cyclic simple shear tests is shown in Fig. 5.

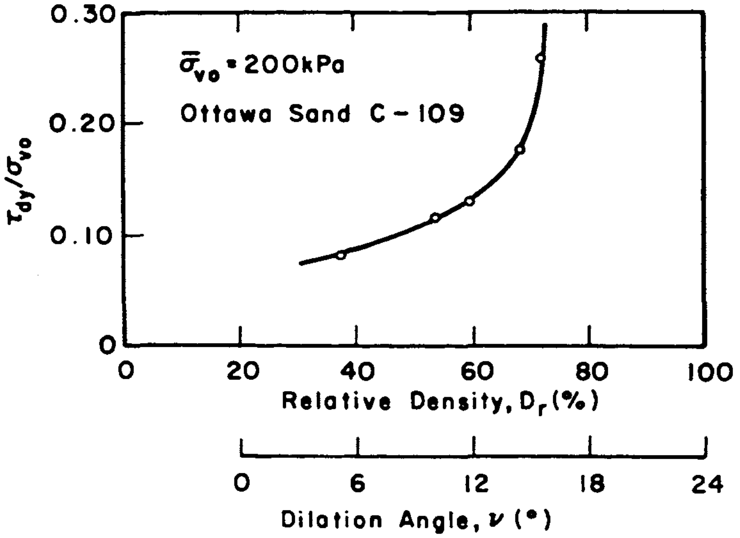
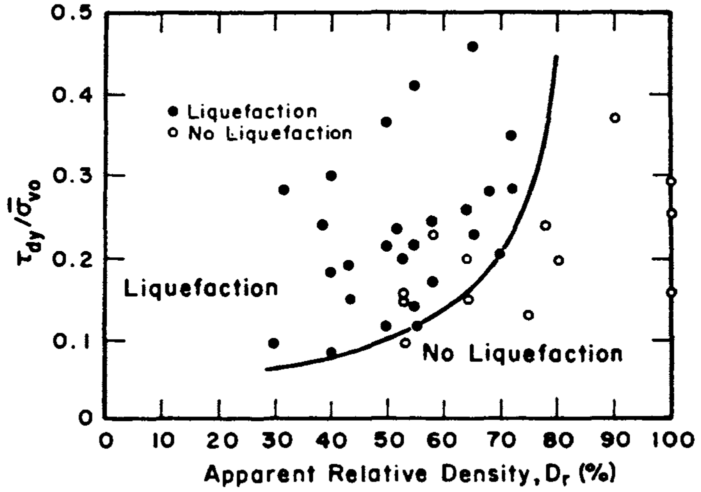


Fig. 5. Resistance to liquefaction as a function of relative density and dilation angle.

Here the cyclic stress ratio, τ_{dy}/σ'_{vo}, to cause liquefaction or 10 percent double amplitude shear strain in 10 cycles is shown as a function of relative density. It may be seen that the liquefaction resistance increases with increasing relative density and very markedly so for relative densities in excess of about 70 percent. These results are in close agreement with the analyses of field records of liquefaction resistance shown in Fig. 6, which is based on data presented by Christian and Swiger (1975). This field experience was analysed by examining sites that had been subjected to earthquakes and which were underlain by granular deposits. Liquefaction had occurred at some of these sites and not at others. The equivalent stress ratio, τ_{dy}/σ'_{vo} was computed from the earthquake acceleration level, and the relative density was inferred from the blow count based on Gibbs and Holtz (1957) correlation. The field liquefaction resistance curve represents the lower limit at which liquefaction was observed to occur. The equivalent uniform stress ratio was taken as 0.65 times the maximum value as suggested by Seed (1976).

Since from Fig. 3 the dilation angle corrected to a normal pressure of 1 T/ft^2 (100 kPa) is uniquely related to the relative density, the liquefaction resistance can also be related to the dilation angle. This is shown in Fig. 5 by an added scale for dilation angle ν, besides the relative density scale. This figure is thought to give a low or conservative estimate of the liquefaction resistance of saturated medium sands. Thus by obtaining the dilation angle in the field as described by Hughes et al. (1977) a conservative estimate of liquefaction



Based on Data by Christian and Swiger, 1975

Fig. 6. Analysis of field records of sites where liquefaction did and did not occur.

resistance is obtained.

The chart shown in Fig. 5 was used to estimate the liquefaction resistance of a dam in British Columbia. This dam was constructed by the hydraulic fill method and the core is comprised of non plastic silt. Dilation angles measured from self boring pressuremeter tests and corrected to an effective confining stress of 1 T/ft^2 were in the range of 0 to 5°. From Fig. 5 this material could be expected to have a dynamic resistance ratio of about 0.08. Laboratory cyclic load tests on undisturbed samples obtained from locations close to the site for pressuremeter tests, indicate that the dynamic resistance ratio is 0.10, and thus the chart gives a reasonable but conservative estimate of liquefaction resistance for this case.

RELATIVE DENSITY, BLOW COUNT AND LIQUEFACTION RESISTANCE

The most commonly used relationship between relative density, blow count and confining pressure is that proposed by Gibbs and Holtz (1957). For a confining pressure of 1 T/ft^2, the relationship is as shown in Fig. 7. Using this relationship combined with the liquefaction resistance versus relative density curve of Fig. 5, the liquefaction resistance in terms of blow count normalized to 1 T/ft^2 is obtained. This is shown by the solid line in Fig. 8. Field experience presented by Seed (1976) together with his liquefaction resistance curve (dashed line) is also shown on this figure and are seen to be in very close agreement with the solid line for N_1 values less than about 20.

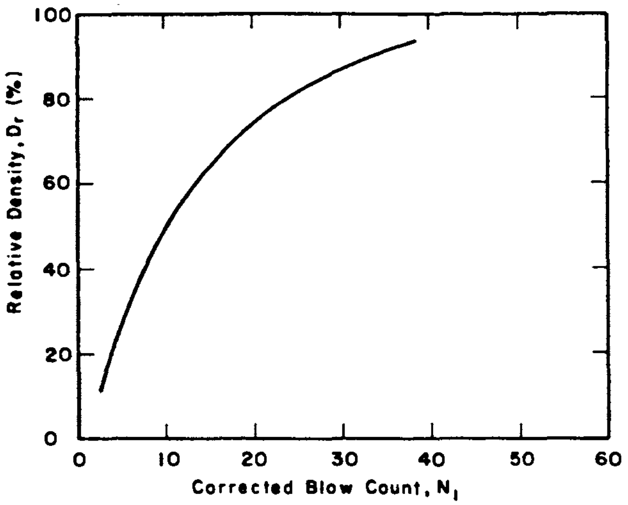


Fig. 7. Relationship between blow count corrected to 1T/ft^2 and relative density (After Gibbs and Holtz, 1957)

Liquefaction resistance can be correlated with relative density, corrected dilation angle or corrected blow count and a chart showing liquefaction resistance in terms of these 3 parameters is shown in Fig. 9. It indicates that liquefaction is not likely to occur regardless of the stress level provided the relative density is in excess of 75 percent, the corrected dilation angle is greater than 16°, or the corrected blow count exceeds 20. Such a conclusion seems apparent from analyses of field records of liquefaction by Seed (Fig. 8), Christian and Swiger (Fig. 6) and Castro (1975).

CONCLUSIONS

Dilation angle or expansion rate of sand during shear has been shown to be uniquely related to its relative density and confining pressure. Its resistance to liquefaction can therefore be expressed in terms of dilation angle in addition to the usual blow count. Laboratory test results on Ottawa sand have been used to illustrate such a correlation. In the field, the dilation angle can be measured by the self boring pressuremeter. Such measurements were performed on a hydraulic fill dam and its liquefaction resistance predicted by the established correlation. A reasonable agreement was obtained between the predictions and the results of liquefaction tests on undisturbed samples.

ACKNOWLEDGEMENTS

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REFERENCES

Castro, G. (1975), "Liquefaction and Cyclic Mobility of Saturated Sands," Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, GT6, pp. 551-569.

Christian, J.T. and Swiger, W.F. (1975), "Statistics of Liquefaction and SPT Results."

Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, GT11, pp. 1135-1150.

Cole, E.R.L. (1967), "The Behavior of Soils in the Simple Shear Apparatus," Ph.D. Thesis, Cambridge University, England.

Finn, W.D.L. and Vaid, Y.P. (1978), "Constant Volume Cyclic Simple Shear Testing", Proceedings 2nd International Conference on Microzonation for Safer Construction, San Francisco, U.S.A., Vol. 2, pp. 839-851.

Gibbs, H.J. and Holtz, W.G. (1957), "Research on Determining the Density of Sands by Spoon Penetration Testing," Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering," Vol. 1, London, England, pp. 35-39.

Hansen, B. (1958), "Line Ruptures Regarded as Narrow Rupture Zones; Basic Equation Based on Kinematic Considerations," Proceedings, Brussels Conference on Earth Pressure Problems, Vol. 1, pp. 39-48.

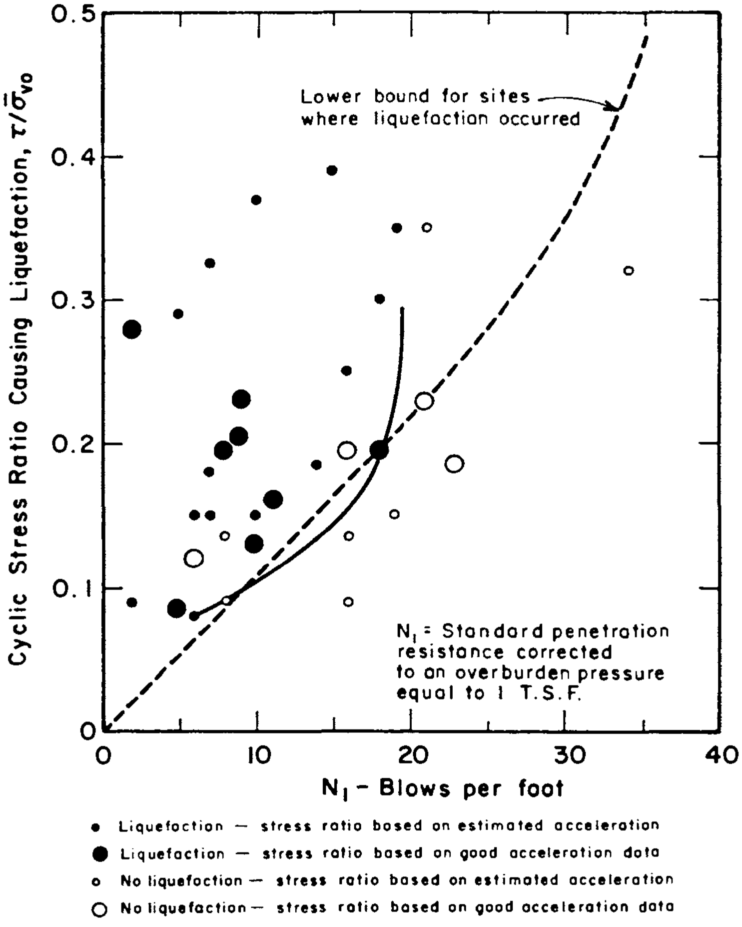

Fig. 8. Correlation between stress ratio causing liquefaction in the field and penetration resistance of sand (After Seed et al. 1975)

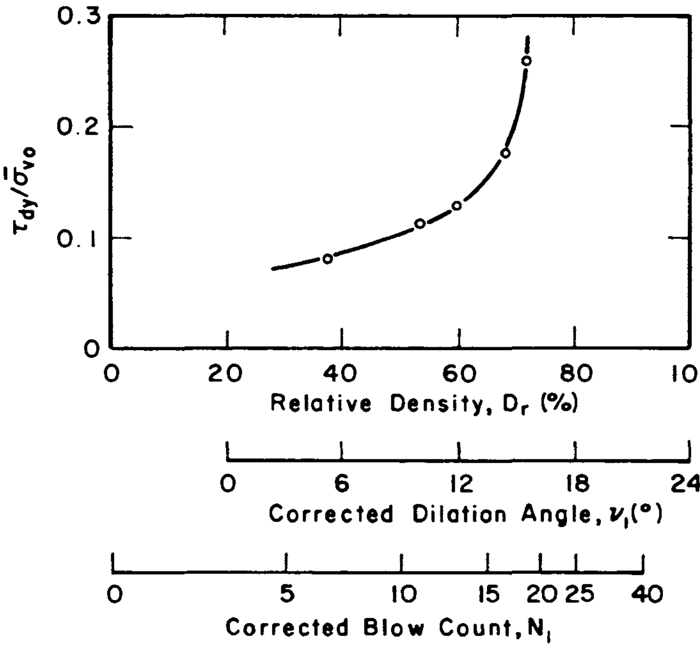

Fig. 9. Resistance to liquefaction of sand as a function of relative density, dilation angle or penetration resistance.

Hughes, J.M.O., Wroth, C.P. and Windle, D. (1977), "Pressuremeter Tests in Sand," Geotechniques, Vol. 27, No. 4, pp. 455-477.

Seed, H.B. (1976), "Evaluation of Soil Liquefaction Effects on Level Ground During Earthquakes," State-of-the-Art Paper, ASCE, National Convention, Philadelphia.

Seed, H.B., Mori, K. and Chan, C.K. (1975), "Influence of Seismic History on the Liquefaction Characteristics of Sands," Earthquake Engineering Research Centre, Report No. EERC 75-25, University of California, Berkeley.