International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1995 - Third International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

06 Apr 1995, 10:30 am - 12:30 pm

Determination of Liquefaction Potential Using Dielectric Concept

A. Kaya
Lehigh University, USA

H. Y. Fang
Lehigh University, USA

Recommended Citation

Kaya, A. and Fang, H. Y., "Determination of Liquefaction Potential Using Dielectric Concept" (1995). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 26.
https://scholarsmine.mst.edu/icrageesd/03icrageesd/session03/26

Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
April 2-7, 1995; Volume III, St. Louis, Missouri

Determination of Liquefaction Potential Using Dielectric Concept

Paper No. 3.54

A. Kaya and H.Y. Fang
Lehigh University
USA

SYNOPSIS: In this paper existing insitu test methods to determine possible liquefaction potential of a site are discussed briefly with their advantages and limitations. Then, resistivity method is presented and showed how both resistivity and dielectric constant can be coped to determine insitu properties of soils such as cementation factor and porosity without disturbing the soil structure by means of Time Domain Reflectometry (TDR). A procedure is also presented to obtain both resistivity and dielectric constant of granular soils in the field. It is concluded that the proposed method and procedure is superior to the existing methods.

I. Introduction

Significant causes of damage on structures during earthquakes is liquefaction of saturated granular soils. Due to liquefaction of granular soils, some structures simply sink into the ground without damaging the entire structure while others can be partially or totally damaged resulting in economic and life losses. Both economic and life losses can be minimized, if not prevented, by adequate engineering design. To prevent the losses due to liquefaction of soil, the liquefaction potential of a site should be investigated thoroughly. Engineers do not have any direct way of determining the liquefaction potential of a given site although there are indirect ways of doing so.

Investigation of potential of liquefaction in high seismic areas has become an everyday practice of geotechnical engineering. To investigate liquefaction potential of a site, engineering properties of soil are needed, thus determination of engineering properties of soils in the laboratory and in the field is significantly important for adequate design of civil engineering structures. Because each test method offers advantages both field and laboratory tests should be carried out in order to properly evaluate site conditions for design purposes. The details of laboratory and field test methods are well presented in the literature (Baldi et al., 1985, Robertson and Campanella, 1985 and 1986).

The factors affecting liquefaction potential of a site are, among others, principal stress differences internal friction angle of soil and insitu void ratio. However, as mentioned above, there is no direct way of evaluating these parameters in the field. Thus, several approximations and similarities have been established to determine the liquefaction potential, for example, the cyclic triaxial test.

The shear resistance of granular soils is given by Coulomb's equation

$$\tau = \sigma_n \tan \phi \qquad (1)$$

where σ_n is the compressive stress normal to shear plane and ϕ is the friction angle. From Eq. 1, everything else being the same, the internal friction angle of granular soil determines the shear strength. Batschinski formulated the internal friction angle of granular materials as

$$\tan \phi = \frac{C}{e - e_{\min}} \qquad (2)$$

where C is a constant, e is insitu void ratio and e_{min} is the minimum void ratio of soil.

Winterkorn and Fang (1970) and Winterkorn (1970) evaluated the constant, C, and concluded the following: (1) Eq 2. gives a good reproduction of experimental data obtained within the same range of confining pressure, and (2) the constant C remains relatively constant with the type of test (for details see Winterkorn and Fang, 1970). Thus, it is fair to conclude that determination of insitu void ratio plays a critical role in evaluating the shear strength of granular soils, and it should be determined for engineering designs without destruction of the soil structure.

It is also well known that some of the engineering properties of soils have been related with relative density which is

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \qquad (3)$$

where e_{max} and e_{min} are maximum and minimum void ratio of a given soil, respectively. To determine the relative density of a given soil, insitu void ratio, e, is needed.

For example, Figure 1 presents relationship between ground surface acceleration, a, and stress factor A as a function of relative density. From the figure, it is fair to state that relative density of a soil can be an indication of liquefaction potential. However, it should be kept in mind that determination of the relative density is very subjective because determination of insitu void ratio is impossible with the current state of art and there is no agreement among researchers how to define e_{min} and e_{max} either. It is the purpose of this paper to define how to obtain insitu void ratio without disturbing the soil structure.

In this paper only the well established insitu test methods: Standard Penetration Test, SPT, Cone Penetration Test, CPT, Dilamoter Test, DMT, Resistivity Method, will be briefly discussed, then a procedure will be presented to cope resistivity method with dielectric constant concept to determine insitu soil parameters without disturbing the soil structure.

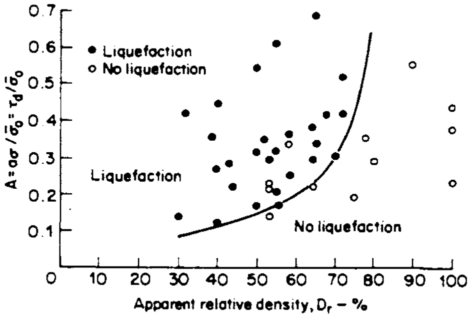

Figure 1. Presents liquefaction data from field studies by Christian and Swinger (1975). After Fang (1991).

II. Insitu Test Methods

II-1 Standard Penetration Test (SPT)

Standard Penetration Test method is based upon the idea of relating the strength of soil with penetration resistance which is obtained by dropping a hammer weighing 63.6 kg drive weight onto the drill rods from a height of 75 cm. The number of blows, N, necessary to produce a penetration resistance of 30 cm (45 cm in total but the first 15 cm are discounted) are related with the engineering properties of soils.

The advantages of SPT are that it is easy to perform, easily available, inexpensive and large databases and numerous correlations of soil properties and empirical foundation design methods have been developed. Some of the disadvantages of the method are that the results are subjective and performing procedures differ from one country to another, thus there is no unique database, disturbance of soils is unavoidable, and the testing profile is not continuous.

It should be pointed out that corrections applied to SPT measurements are controversial and need to be investigated. For a detailed discussion about the corrections and their basis see Skempton (1986) and Rinne (1987).

II. 2 Cone Penetration Test (CPT)

The most common and reliable test used to evaluate the liquefaction potential of soils is CPT. In its simplest form, the apparatus consists of a 60° cone with a base area of 10 cm^2. The cone is pushed by a rod at a rate of 2 cm s^{-1}; the cone resistance q is the force required to advance the cone by the area. Then, the cone resistance and side resistance are related to the properties of soil.

The advantages of this method are that the test is very rapid, a continuous soil profile is recorded and widely available, and a reasonable database has been established. The disadvantages of the method are that no sample is obtainable; it is not suitable for very dense and cemented soils; and it is relatively expensive and not easily available. In recent work, Reyna (1991) and Agrawal (1992) reported that CPT is superior to SPT to evaluate liquefaction potential.

II. 3 Dilatometer Test (DMT)

The DMT test method was developed by Marchetti in the 1970s, and since then the method has been accepted and widely applied as an insitu test method. The dilatometer itself is a flat blade 1.4 cm in thickness, 9.5 cm in wide and 22 cm in long. A flexible stainless steel membrane, 6 cm in diameter, is located on the center and flush on one side of the blade. In general, the test is performed by pushing the blade to the desired depth with a penetration rate of 2 cm s^{-1}, then, the membrane is inflated 1 mm (0.1 cm), in general, with high pressure nitrogen gas. During the tests, two readings are taken. For more details, see Schmertmann (1986).

The advantages of the test are that it is simple and rapid, can be performed in a relatively variety of soils, reduces the shear and volumetric strain associated with other penetration tests, and also the lateral earth pressure at rest, K_o can be estimated. The limitations of the method are a limited database, not widely available, and limited applications to cemented and dense soils.

Although there are considerable databases about evaluation of liquefaction potential of granular soils, it is the opinion of the authors that in estimating soil parameters, liquefaction potential will remain controversial depending on the approach, philosophy, and judgment of the geoscientists or engineers.

II.3 Electrical Method

Several researchers Arumoli et al., (1985), Arulanandan (1991), Bellotti et al., (1994) have suggested that it is possible to determine liquefaction zones of granular soils subjected to earthquakes by means of resistivity methods, because when an electrical field is applied to a soil- water system, the electrical current is mostly transmitted by water: the higher the water content, the lower the resistivity of the soil-water system. From this statement, the loose soils with higher void ratios will have high electrical conductivity, thus void ratio of soils can be determined from resistivity measurements. However, it should be noted that there are also other factors affecting the resistivity of soil-water system besides water content including soil texture, namely long particle axis and shape of particles, soluble salts, temperature, density and the frequency at which the measurements are conducted.

III. Resistivity and Dielectric Constant

Arulanandan (1991) and Thevanayagam (1993) suggested the use of the dielectric constant of the medium besides the resistivity of the system. Dielectric constant is comparable with the permeability of magnetic materials and is a measure for the ease with which a material can be polarized in an electric field. When the space between two parallel plates of condenser is completely filled with non-conducting material, the capacitance C of the condenser is increased to C'. The dielectric constant is defined by the ratio C' to C.

The dielectric constant of soil is between three and six depending on particle orientation whereas that of water is about 80 at 22 °C. These large variations in the dielectric constant give an opportunity to determine the water content of the soil water system. However, the determination of both resistivity and dielectric constant suggested by previous researchers is almost impossible without disturbing the soil structure. Thus, the suggested methods did not find a large ground of applications. However, it can become very practical to

It is clear from the presentation that TDR can be a part of the insitu test methods to determine the possible liquefaction potential of a given site. During the test, a probe as in Figure 3 can be inserted into soil to a desired depth, and both dielectric constant and resistivity can be computed by means of Eqs. 4 and 12, respectively. Porosity of fully saturated soil will be equal to that of water content which can be determined from Eq. 11. Knowing insitu void ratio (or porosity) and resistivity of the medium, cementation factor, m, can be computed from Eq. 6.

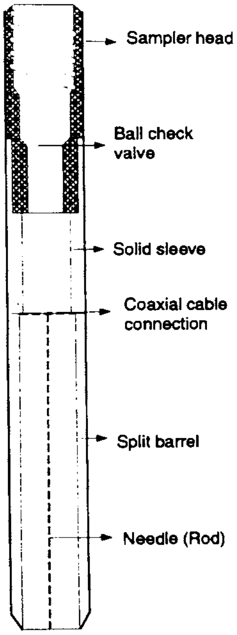

Figure 3. Proposed probe for TDR use

It is clear from the proposed procedure, insitu soil parameters such as porosity and cementation factor can be easily determined without disturbing the soil structure. To draw solid conclusions, further research is needed, however the proposed methods and procedures present the following advantages over existing methods: (1) Insitu void ratio is readily available, (2) The parameters that define the soil fabric and cementation are obtainable, (3) Continuous soil profile is obtainable, (4) Can be performed easily, and 5. Inexpensive.

IV. Summary and Conclusions

To investigate possible liquefaction potential of a given site in an earthquake zone, engineering properties of soils need to be determined both in the field and the laboratory. However, it is difficult, if not impossible, to determine the insitu soil parameters because during field investigations soil structure is disturbed. For example, one of the most important parameters is porosity which cannot be determined by existing insitu methods. However, with the proposed method which combines both dielectric and resistivity concept together to determine both insitu porosity and cementation factor, there is good possibility.

Determination of both insitu porosity and cementation factor will enable both researchers and engineers better understanding of engineering parameters of soils, thus enabling the development of better design methods.

V. References

Agrawal, G., 1992, "Geotechnical Data Analysis: Prediction and Modeling Using a Neural-Fuzzy Methodology" Ph.D. Dissertation, Purdue University, August 1992, 104p.

Archei, G.E., 1942, "The Electric Resistivity Logs as an Aid in Determining some Reservoir Characteristics." Trans. AIME, 146, 54-61.

Arulanandan, K., 1991, "Dielectric Method for Prediction of Porosity of Saturated Soil." J. Geotech. Engr., ASCE, Vol. 117, pp. 319-330.

Arumoli, K., Arulanandan, K., and Seed, H.B., 1985, "A New Method for Evaluating Liquefaction Potential." J. of Geotech. Engrg., ASCE, Vol. 111, pp. 95-114.

Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., and Pasqualini, E., 1985, "Penetration Resistance and Liquefaction of Sands." Proc. of the 11th Int. Conf. on Soil Mechanics and Foundation Engineering, A. A. Belkama, Rotterdam.

Bellotti, R., Benoit, J., and Marabito, P., 1993, "A Self-Boring Electrical Resistivity Probe for Sands" in press.

Dalton, F.N., and van Genuchten, M.T., "1986, "The Time-Domain Reflectometry Method for Measuring Soil water Content and Salinity." Geoderma, Vol. 38, pp. 237-250.

Fang, H.Y., Foundation Engineering Handbook, van Nostrand Reinhold, 923 p.

Fellner-Feldeeg, H., 1969, The measurement of Dielectrics in the Time Domain." J. Phys. Chem., Vol. 73, pp.616-623.

Kaya, A., 1993, The Application of TDR to Geotechnical Engineering" Interim Report to School of Civil Engineering, Purdue University, W. Lafayette, IN, 47907.

Kaya, A., Lovell, C.W., and Altschaeffl, G.A., 1994,"The Effective use of in Geotechnical Engineering." Symposium and Workshop on Time Domain Reflectometry, Northwestern University, IL., pp.398-407.

Kulhawy, F.H., and Mayne, P.W., 1990, "Manual on Estimating Soil Properties for Foundation Design" Final Report, Project 1493-6, EL-6800, Electric Power Research Institute, Palo Alto, CA.

Marchetti, S., 1982, "Detection of Liquefiable San Layers by means of Quasi-Static Penetration Test." Proc. of the 2nd European Symposium on Penetration Testing, ESOPT II, Amsterdam, The Netherlands, 2, pp. 689-695.

Reyna, F.A.M. (1991), "In-situ Tests for Liquefactin Potential Evaluation-application to California Data including Data from the 1989 Loma Prieta earthquake", Ph.D. Dissertation, Purdue University, December 1991, 502 p.

Rinne, E.E., 1987, Assessing the Effects of Potential Liquefaction: A Practicing Engineer's Perspective" in Soil Dynamics and Liquefaction, A.S. Cakmak, Ed., pp.245-251.

Robertson, P.K., and Campanella, R.G., 1985, "Liquefaction Potential of Sands Using the CPT, Research ReportR69-15, Dept. of Civil Eng., Massachusetts Institute of Technology, Cambridge, Mass.

Robertson, P.K., and Campanella, R.G., 1986, "Estimating Liquefaction Potential of Sands Using the Flat-Plate Dilatometer, Geotechnical Testing Journal, Vol. 9, pp. 38-40.

Topp, G.C., Davis, J.L., and Annan, P.A., 1980, "Electromagnetic Determination of Soil-Water content using TDR: Measurements in Coaxial Transmission Lines," Water Resour. Res., Vol. 16, pp. 574-582.

Schmertmann, J.H., "Suggested Method for Performing the Flat Dilatometer Test" Geotechnical Testing Journal, GTJODJ, Vol. 9, pp. 93-101.

Thevanayagam, S., 1993, "Electrical Response of Two-Phase Soil: Theory and Applications." Geotechnical Engin. J., ASCE, Vol. 119, pp. 1250-1275.

Winterkorn, H.F., and Fang, H.Y., 1970, "Mechanical Resistance Properties of Ocean Floors and Beaches in the Light of the Theory of Macromeritic Dusseldorf, Vol. 2, pp. 43-46.

Winterkorn, H.F., (1970), Analogies Between Macromeritic and Molecular Liquids Mechanical Properties of Sand and Gravel Assemblies, Chemical Dynamics, Henry Eyring Presentation Book, pp. 751-766, Wiley-Interscience, New York.

determine both the dielectric constant and the resistivity of soil-water system by Time Domain Reflectometry (TDR) in the field without disturbing the soil structure as will be presented in the following paragraphs.

Time Domain Reflectometry (TDR), originally designed to detect faults in cables and has been used in agronomy to determine water content of soils. The procedure was developed based on the idea of Fellner-Feldeeg (1969) to obtain dielectric constant of different chemical liquids. Advantages and limitations of applications of TDR method to geotechnical engineering have been discussed by Kaya (1993) and Kaya et al., (1994). The TDR applications require coaxial cable conditions, however, close approximation of coaxial conditions may be applicable for most geotechnical problems.

The resistivity of soil-water system is given as (Archei, 1942):

$$\rho_o = F \rho_w \tag{4}$$

where ρ_o, is the resistivity of the medium, F is the formation factor, and ρ_w is the resistivity of the porewater. It is well established that formation factor is function of both cementation and porosity and given as:

$$F = n^{-m} \tag{5}$$

where n is porosity and m is cementation factor ranges from 1.3 to 2.2 depending on cementation and stress history. Figure 2 presents formation factor, F, of different soils as a function of porosity. It should be pointed out that in the Figure, F_V stands for vertical formation factor and F_H stands for horizontal formation factor. As can be seen from the Figure, there is an almost inverse linear relationship between porosity, n, and formation factor, F. It is also clear from the figure that there is not much variation between horizontal and vertical formation factors for a given porosity. Thus, it is fair to conclude that with the measured average formation factor by TDR will give a good representative of insitu porosity of soil in the field.

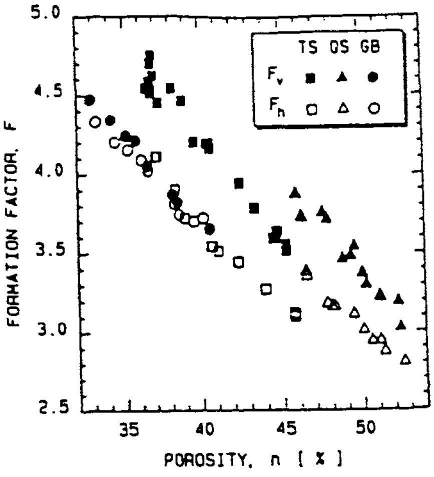

Figure 2. Presents formation factor as a function of porosity (After Bellotti et al.).

To determine cementation factor, m, combining Eq. 4 and Eq. 5 we obtain

$$m = \frac{\log (\rho_o)}{\log (\rho_w\, n)} \tag{6}$$

Thus, to determine the parameters that characterize the soil texture and anisotropy, both insitu porosity and cementation factor are needed. It will be presented how these two parameters can be determined by TDR in the following paragraph.

It should be mentioned that dielectric constant has both a real and imaginary part and is given as

$$\epsilon = \epsilon' + i\, [\epsilon'' + \frac{\sigma_{dc}}{\omega\, \epsilon_o}] \tag{7}$$

where ϵ is the dielectric constant, ϵ' is the real part of the dielectric constant, ϵ'' is the imaginary part of dielectric loss, σ_{dc} is the zero-frequency conductivity, ω is the angular frequency, ϵ_o is free space permittivity, i is $(1)^{-1/2}$. At MHz and GHz range imaginary part of the dielectric constant becomes negligible which is the case of TDR system.

The TDR system obtains only the real part of the dielectric constant of a soil-water system by measuring the transit time of an electromagnetic pulse launched along a pair of rods of known length embedded in the soil-water system. If we measure the transit time, t, of electromagnetic wave:

$$v = \frac{2\, l}{t} \tag{8}$$

where l is the length of the rod (since the electromagnetic wave will go along the rod and will be reflected back, the travel distance is twice the length of the rods). From electromagnetic theory, the velocity can be expressed in terms of the dielectric constant of the medium and the velocity of the light in space, $c = 3x10^8\ m\ s^{-1}$.

$$v = \frac{c}{\sqrt{\epsilon}} \tag{9}$$

Combining Eq. 8 and 9, we obtain

$$\epsilon_a = (\frac{c\, t}{2\, l})^2 \tag{10}$$

As the length of the probe is known and the travel time of the electromagnetic wave is read out from TDR oscilloscope, then the apparent dielectric constant, ϵ_a can be computed in Eq. 10. Topp et al., (1980) showed that ϵ_a, can be related with the water content of soil-water system with the following relationship:

$$\theta_v = -5.3 + 2.92\ \epsilon_a - 5.5x10^{-2}\ \epsilon_a^2 + 4.3x10^{-4}\ \epsilon_a^3$$

where θ_v is volumetric water content. From the known volume of the probe porosity of soil may be computed (n = Volume of water / total volume for fully saturated soils).

So far determination of dielectric constant of soil water system by TDR is defined. However, as it is mentioned above, it is also possible to determine the resistivity of the system

$$\rho_o = \frac{120\ l\ \pi}{\sqrt{\epsilon}} \ln (\frac{V_R}{V_T}) \tag{12}$$

where V_T is transmitted voltage and V_R is reflected voltage.