Using time domain reflectometry in triaxial testing

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Abstract: Time domain reflectometry (TDR) can be used to determine the volumetric water content of soils. This note describes the utilization of a TDR mini-probe in triaxial testing. The TDR performance was examined with a series of tests that not only proved its reliability but also resulted in two empirical correlations. Using these correlations, the degree of saturation and volumetric water content during triaxial testing could be determined. The TDR was then put to use in a laboratory program designed at investigating the response of loose gassy sand under static and cyclic loading. Because of the TDR measurements it was possible to determine the degree of saturation and void ratio of the gassy specimens. The TDR mini-probe proved to be accurate, simple to use, and inexpensive to build.

Key words: time domain reflectometry, TDR, triaxial testing, gassy, unsaturated

Introduction

Time domain reflectometry (TDR) has been used extensively in the soil sciences to measure the volumetric water content of soils, both in situ and in the laboratory. However to date the use of TDR in geotechnical engineering has not been commonplace, possibly due to a lack of familiarity with this technique (Benson and Bosscher 1999). TDR has not been used to study the geotechnical properties of gassy soils and to the knowledge of the authors, has not been adapted for use in a triaxial cell. The aim of this paper is to show how with some simple modifications the TDR was successfully used in triaxial testing.

In essence, the TDR works by emitting an electromagnetic step pulse that travels along a transmission line and is reflected by discontinuities in the line. A probe at the end of the line alters the pulse and returns a waveform back to the TDR receiver. From this waveform, the propagation velocity of the pulse through the soil can be calculated. The propagation velocity, v, is indicative of the dielectric constant, which in turn, can be related to the volumetric water content. Factors affecting the measurement of the dielectric constant are temperature, salinity, and density. In this particular program, temperature was not a factor since the temperature fluctuation in the laboratory was within a few degrees, and salinity was not a factor because distilled water was used. The effects of density are discussed later in this paper.

For details on TDR the reader is encouraged to see Dowding and O'Connor (1999) and Benson and Bossher (1999); both are recently presented comprehensive reviews on the theory of TDR and its applications in geotechnical engineering.

Triaxial testing of gassy soils

A gassy soil differs from an unsaturated soil in that it has a large amount of gas dissolved in its pore fluid. This affects its response to loading and unloading (see Sobkowicz and Morgenstern 1984). In a gassy soil, bubbles develop when the moles (or volume) of gas exceeds the maximum moles (or volume) that can be dissolved in the pore liquid at that particular pressure and temperature. This paper is only concerned with soils where the water phase is continuous and the gas phase is discontinuous; in other words where the gas phase forms discrete bubbles. The structure of a coarse-grained gassy soil with discrete bubbles is illustrated in Figure 1.

Specialized triaxial testing was undertaken as a component of a research program with the objective of determining the effect of gas on the static and cyclic liquefaction potential of loose sand (Grozic et al. 1999a, 1999b). Due to the compressibility of the gas, and to a lesser extent to the solubility of the gas in the pore fluid, even when tested undrained a gassy specimen experiences a change in degree of saturation (gas content) and void ratio (density) during shearing. The two most commonly used methods to measure the degree of saturation of gassy soils are; i) measure the volume change from the cell fluid of a standard or double walled triaxial cell, or ii) measure radial changes with a circumference measurement device. After considering accuracy, sample disturbance, simplicity, and cost it was decided to develop a new method to measure the degree of saturation utilizing TDR technology.

Methodology

Equipment

A TDR mini-probe with steel rods was constructed and incorporated into the base of the triaxial cell. A probe length of 40 mm was adopted so it would fit within the specimen and have minimal affect on the strength results. (In triaxial testing stress concentrations occurring within the sample, due to friction between the soil and end restraints, cause the development of an area of limited strain similar to the wedge of soil that develops beneath a footing or a pile. From tests on driven piles, this area can be approximated as a 60° cone of material; thus for a 63 mm diameter triaxial specimen with the given rod spacing a probe length of 40 mm should not affect the strength results.) The diameter across the probe was limited by the soil specimen diameter and by the spatial sensitivity of the probe. A rod spacing of 6.5 mm was chosen which would affect a cylinder of soil approximately 25 mm in diameter (Knight et al. 1994), well within the specimen dimensions. For this study, four wire probes were used, as opposed to the more typical two and three wire TDR probes. The probe geometry is shown in Figure 2 and a photograph of the mini-probe in the base of the triaxial setup is shown in Figure 3.

A Tektronix 1502C TDR unit was used to conduct the experiments. The TDR unit was connected to an IBM computer via an RS-232 cable, which allowed the waveforms to be downloaded in real time. A coaxial cable (50Ω RG58) approximately one meter long was connected to the probe. The cable was passed through the base of the triaxial cell. The waveforms were interpreted using a windows based software program (M-TDR version 1.4) developed at the University of Alberta (Lefebvre 1997).

Specimen preparation

All laboratory specimens were prepared using Ottawa sand, a uniform, medium sand comprised of round to sub-rounded quartz grains. Ottawa sand has a specific gravity of 2.65 and a mean grain size (D_{50}) of 0.34 mm. The maximum and minimum void ratios, determined using ASTM D2049, are 0.82 and 0.50, respectively. The gas selected for use in this program was carbon dioxide (CO_2), a readily available, non-corrosive, and non-flammable gas that is moderately to highly soluble in water.

The laboratory samples were reconstituted using the moist tamping method (Ladd 1978). The specimens were prepared with the first sand layer carefully tamped around the TDR probe. All specimens were approximately 63 mm in diameter and 125 mm in height. The specimens were made gassy by first replacing the pore fluid with gas saturated water and then reducing the back pressure thus forcing gas to come out of solution and form small bubbles. Details of the laboratory materials and procedure can be found in Grozic (1999).

Soil moisture content determination

Although different equations now exist to determine the soil moisture content, the most widely used is still the Topp equation (Topp et al. 1980):

[1] $$K_a = 3.03 + 9.30\theta_v + 146.0\theta_v^2 + 76.7\theta_v^3$$

where K_a is the apparent dielectric constant and θ_v is the volumetric water content defined as the volume of water divided by the total volume.

Accuracy of the TDR method

In order to determine if the TDR method would be appropriate a series of tests were carried out with the aim of comparing the results to the Topp equation. These tests were carried out in the triaxial apparatus using the same equipment and specimen preparation method described above. The only difference was a rigid Plexiglass cylinder (with an inside diameter of 63 mm and a height of 130 mm) was constructed to contain the specimen. This enabled the total volume of the specimen to be calculated. Introducing a known volume of water increased the degree of saturation of the specimens while the cell and back pressures were set at approximately the intended test pressures. TDR readings were taken and compared to the calculated degree of saturation and void ratio.

The results of these tests are presented in Figures 4, 5, and 6. Figure 4 relates the dielectric constant to the volumetric water content for all the tests performed. The test data forms a clear trend with little scatter indicating that the TDR produced reliable, repeatable results. The lack of scatter also suggests that the volumetric water content does not depend on the density. The Topp equation, plotted on Figure 4, is located slightly higher than these test results. However when a polynomial is drawn through the test results obtained from this study, it matches the shape of the Topp equation. In Figure 5 the dielectric constant is plotted against the degree of saturation. This figure illustrates a dependency of the degree of saturation on the void ratio, indicating the effects of density are not negligible. For higher void ratios (i.e. looser specimens) a lower initial degree of saturation is obtained.

These series of tests proved that the TDR gave consistent results. The trend of the volumetric water content compared well with the Topp equation yet was located slightly lower on the chart. It is possible that the difference in location is due to the relatively high void ratios of the specimens. Due to this slightly different location, it was decided to use the trend of the test results (shown in Figure 4) as an empirical correlation instead of the Topp equation. To determine the degree of saturation, the test results from Figure 5 were limited to the range of void ratios expected in the tests; in this program the intent was to construct the specimens as loose as possible with void ratios greater than 0.8. Thus, when the degree of saturation results were limited to these high void ratios the result is a significant reduction of scatter as shown in Figure 6. A polynomial was drawn through the data from Figure 6 and it was used as the empirical correlation to determine degree of saturation.

Application of the TDR method

Determining void ratio and degree of saturation

TDR measurements were taken at the beginning (i.e. after consolidation) and end of the monotonic and cyclic triaxial tests. During monotonic shearing it was even possible to obtain TDR measurements during the test. Although it was possible to obtain TDR measurements during cyclic shearing, the stress conditions changed so quickly during the test that it was too difficult to relate the measurement to a specific stress condition.

After shearing was complete the entire specimen was carefully placed into a pan and weighted for determination of the final moisture content. The volume of water in the specimen was calculated from the moisture content and dry mass of soil. The volumetric water content and degree of saturation for each TDR measurement was determined empirically using the relations shown in Figures 4 and 6. By combining this information with the volume of water, the void ratio could be determined for each point from:

$$[2] \qquad V_V = \frac{V_W}{S_r} \text{ and } V_T = \frac{V_W}{\theta_V}$$

$$V_S = V_T - V_V \text{ and finally } e = \frac{V_V}{V_S}$$

where V_v, V_w, V_S, and V_T are the volumes of voids, water, solids, and total, respectively, S_r is the degree of saturation, and e is the void ratio. Hence, at any point during the monotonic testing and at the beginning and end of cyclic testing the degree of saturation and void ratio was readily calculated from the TDR data.

Triaxial tests with TDR measurements

Over 20 triaxial specimens were subjected to monotonic loading of which 13 gassy test results were obtained. A summary of the gassy tests is presented in Table 1(a). The results of the triaxial tests have been presented in Grozic et al. 1999a. In the monotonic tests the TDR measurements enabled the determination of the initial and final conditions. By taking TDR measurements during shearing, it was also possible to establish the trends or the changes in the specimen response during loading. These differences in specimen response were used to determine the potential for liquefaction of loose gassy sand based on initial degree of saturation and void ratio.

In addition to the monotonic tests, over 15 triaxial specimens were subjected to cyclic loading of which 10 gassy test results were obtained. The gassy test results are summarized in Table 1(b). The initial void ratio of the cyclic specimens were lower than the specified range of the degree of saturation calibration. Therefore, the calibration curve presented in Figure 6 was moved down vertically so that it passed through the data points for the void ratio range from 0.75 to 0.80. (This means that the equation was identical except for the last number or the y intercept). Although the changes in void ratio and degree of saturation were not tracked during cyclic shearing, the initial and final points were used to determine the effect of initial degree of saturation and void ratio on the cyclic resistance.

For a couple tests the degree of saturation calculated at the end of shearing was greater than 100%, which is impossible. A calculated value greater than 100% indicates that using the TDR data to determine the degree of saturation has an accuracy of about a couple percent. It is estimated that the void ratio is also accurate to about the second decimal place.

Limitations

The TDR method of determining degree of saturation was used successfully in this research program. However if TDR is to be used in the triaxial cell for unsaturated soils where the gas phase is continuous, it may be necessary to ensure that a capillary fringe would not develop at the base of the probe.

Summary and conclusions

Although time domain reflectometry (TDR) has been used in the soil sciences for many years, it has not been used extensively by geotechnical engineers, and to the authors' knowledge has not been used in a triaxial cell. A laboratory program with the aim of determining the liquefaction potential of gassy sands required that the initial degree of saturation (gas content) and void ratio (density) be determined. After examining the commonly used methods to determine the degree of saturation of gassy soils, it was decided to develop a new method for measuring the degree of saturation by using a TDR mini-probe in the triaxial specimen.

The accuracy of the TDR mini-probe was examined by performing a series of tests where the saturation and void ratio were known. The results indicated that the TDR produced reliable, repeatable results. Two empirical correlations relating the volumetric water content and degree of saturation to the apparent dielectric constant were obtained. These empirical curves were used during triaxial testing of gassy specimens to determine the degree of saturation and void ratio. Knowing the degree of saturation and void ratio of the gassy specimens enabled recommendations for determining the potential for static liquefaction and the resistance to cyclic liquefaction to be developed. Utilizing a TDR mini-probe in the triaxial cell achieved the required level of accuracy, was inexpensive to build, and simple to use. TDR technology worked well for this application and should be considered a viable tool that has other potential applications in geotechnical engineering.

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Table 1(a) - Summary of gassy monotonic triaxial tests.

Sample	Type	p' initial (kPa)	e* initial	e* final	Sr * initial	Sr * final
8	Gassy	286	0.92	0.86	80%	88%
9	Gassy	295	1.07	0.99	72%	77%
10	Gassy	259	0.99	0.96	91%	95%
13	Gassy	304	0.88	0.78	83%	90%
14	Gassy	302	0.77	0.73	97%	>100%
15	Gassy	313	0.87	0.82	80%	84%
16	Gassy	317	0.88	0.80	82%	87%
17	Gassy	299	0.89	0.83	77%	81%
18	Gassy	296	0.88	0.89	76%	75%
20	Gassy	301	0.87	0.80	86%	92%
21	Gassy	296	0.90	0.86	80%	82%
24	Gassy	284	0.84	0.78	97%	>100%
25	Gassy	272	0.85	0.82	91%	96%

* Void ratio and degree of saturation are calculated from TDR data.

Note: >100% indicates that the calculated S_r was greater than 100%.
p' is the mean normal effective stress defined as $^1/_3\,(\sigma_1 + 2\sigma_3)$ in kPa.
All specimens were tested undrained.

Table 1(b) – Summary of gassy cyclic triaxial tests.

Sample	Type	σ_d' (kPa)	p' initial (kPa)	Period (Sec)	e* initial	e* final	Sr* initial	Sr* final
28	Gassy	70	297	15	0.71	0.70	100%	>100%
32	Gassy	70	294	15	0.72	0.71	99%	>100%
33	Gassy	140	272	30	0.75	0.70	87%	94%
36	Gassy	130	292	26	0.78	0.69	78%	86%
37	Gassy	115	291	24	0.80	0.71	76%	84%
38	Gassy	148	270	30	0.73	0.70	83%	86%
39	Gassy	155	213	31	0.79	0.69	74%	83%
40	Gassy	125	284	24	0.75	0.70	84%	90%
41	Gassy	158	271	31	0.67	0.61	75%	82%
42	Gassy	140	212	27	0.71	0.66	79%	85%

* Void ratio and degree of saturation are calculated from TDR data.

Note: >100% indicates that the calculated S_r was greater than 100%.
σ_d' is the applied effective cyclic stress in kPa.
p' is the mean normal effective stress defined as $^1/_3\,(\sigma_1' + 2\sigma_3')$ in kPa.
All specimens were tested undrained.

Figure 1 – Profile of soil containing gas bubbles much smaller than soil particles (Wheeler 1988).

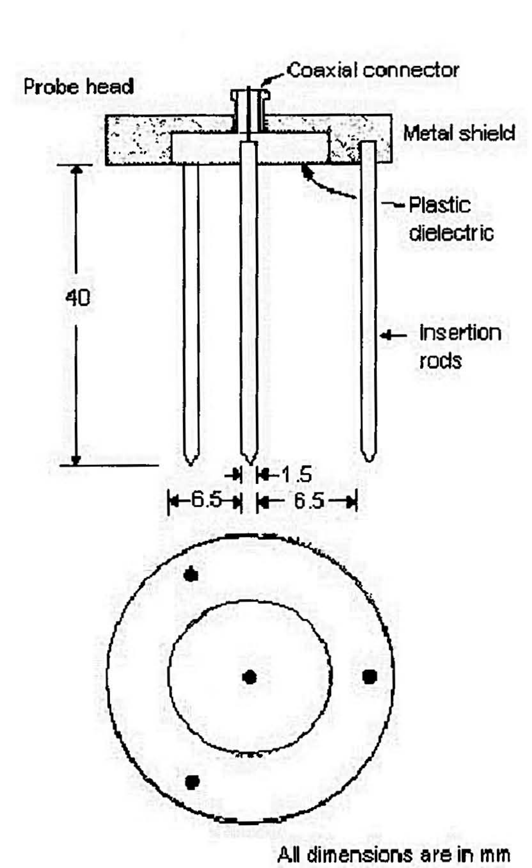
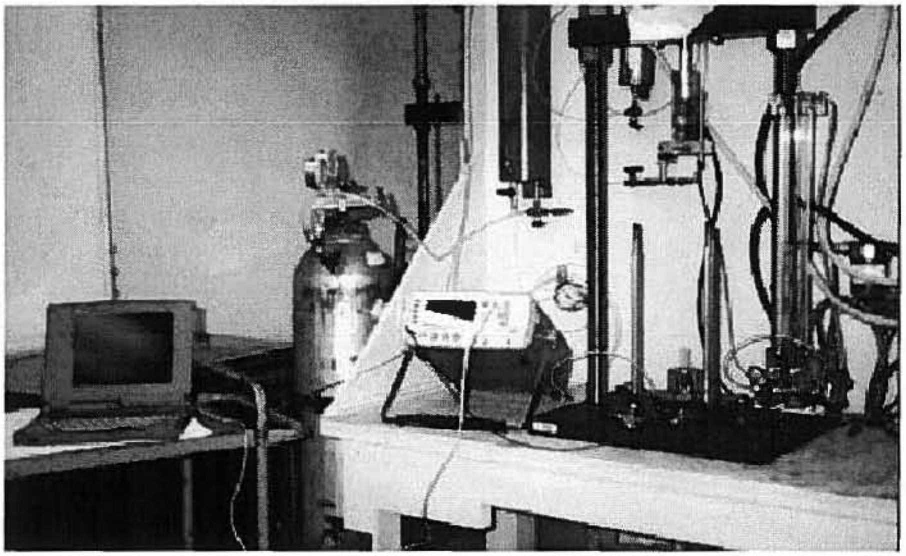
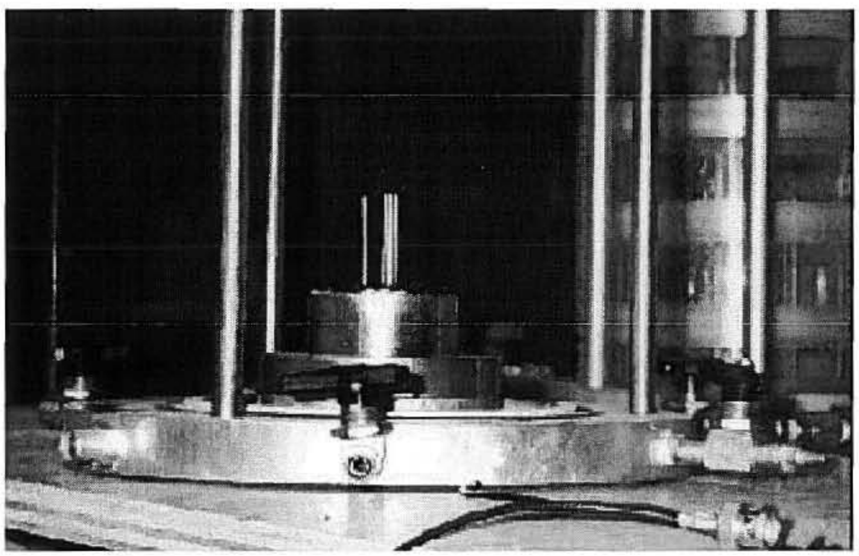


Figure 2 - TDR probe geometry.



(a) TDR setup triaxial tests



(b) TDR probe in triaxial base

Figure 3 – TDR equipment.

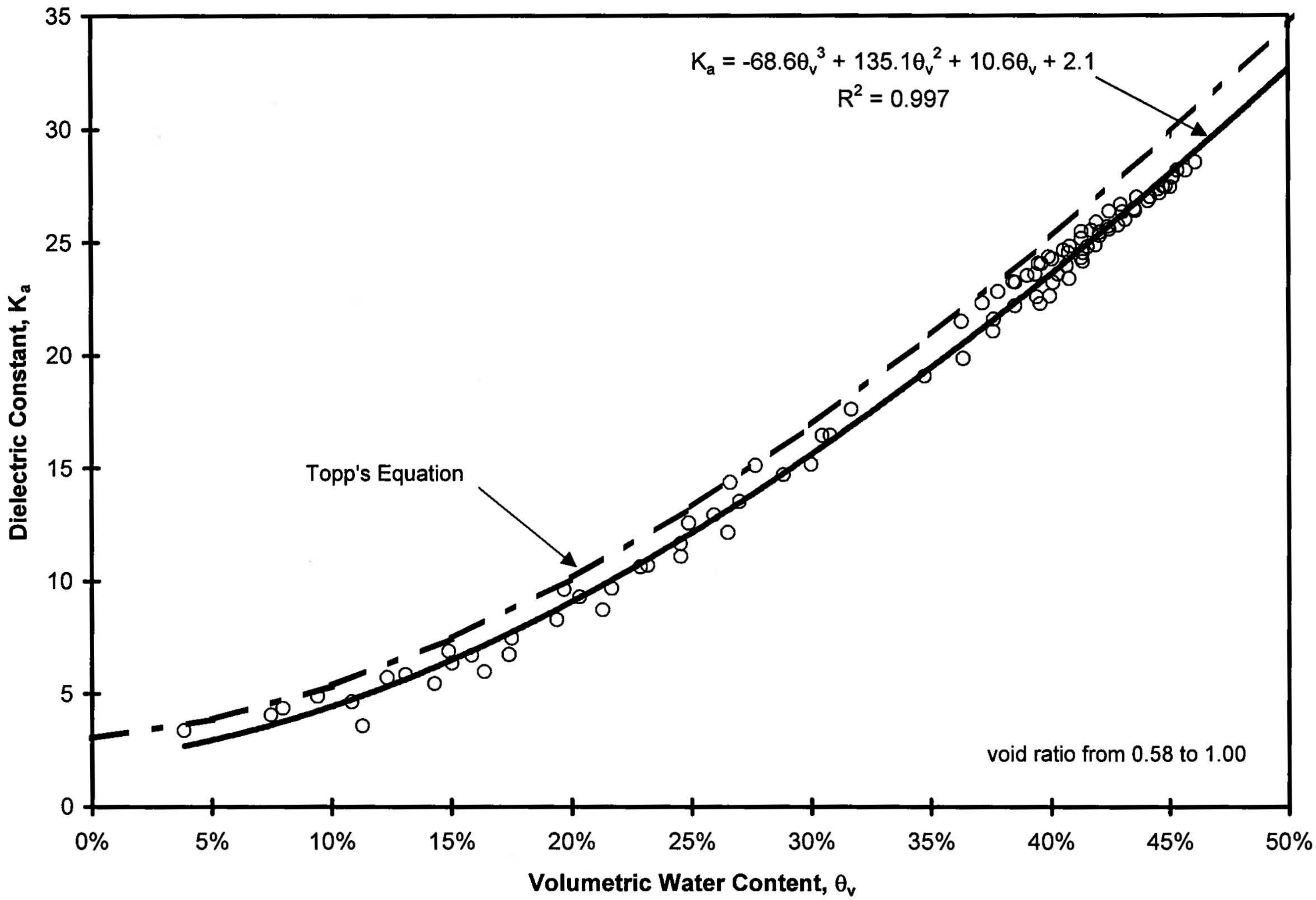


Figure 4 - Apparent dielectric constant versus volumetric water content.

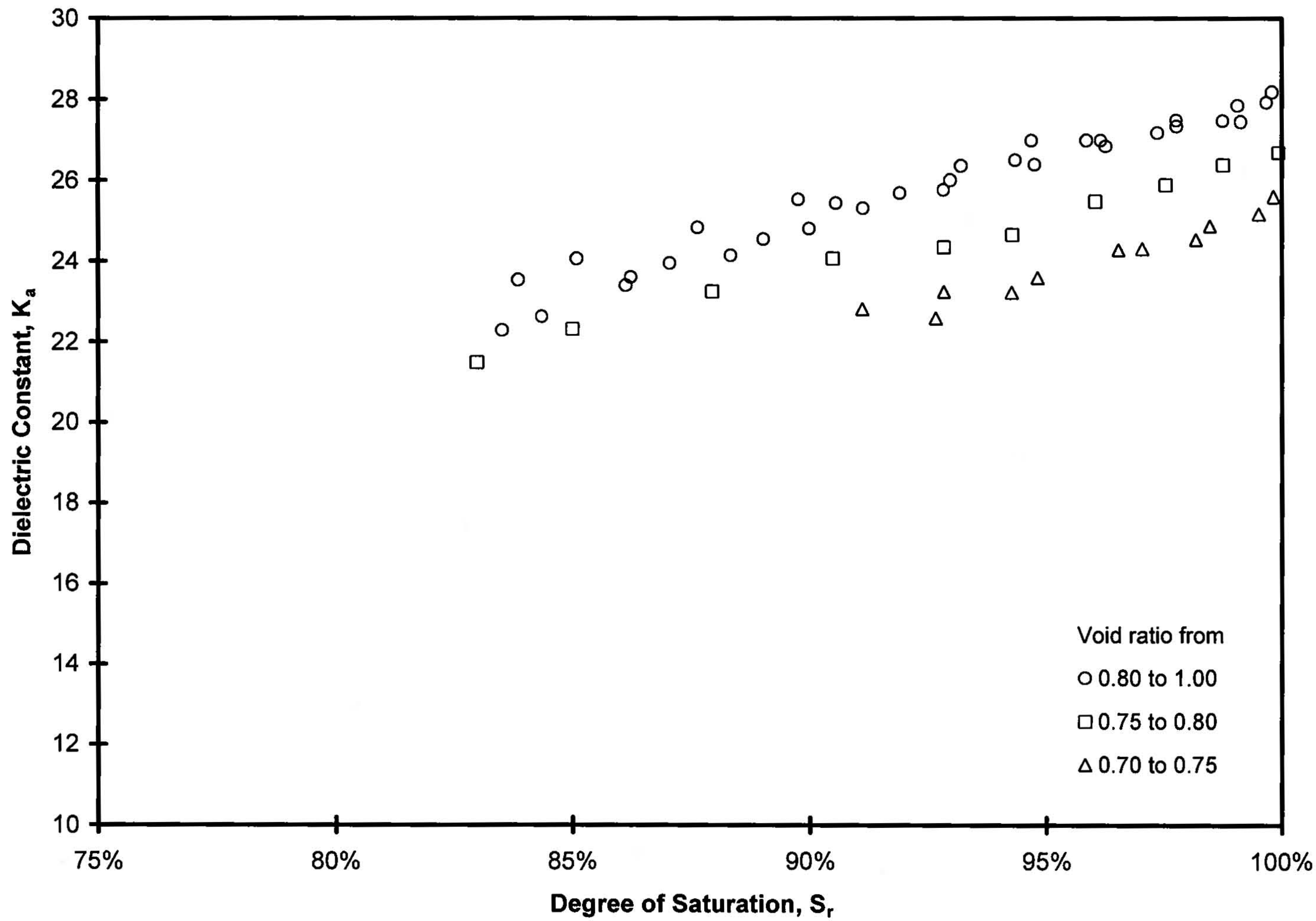


Figure 5 – Apparent dielectric constant versus degree of saturation.

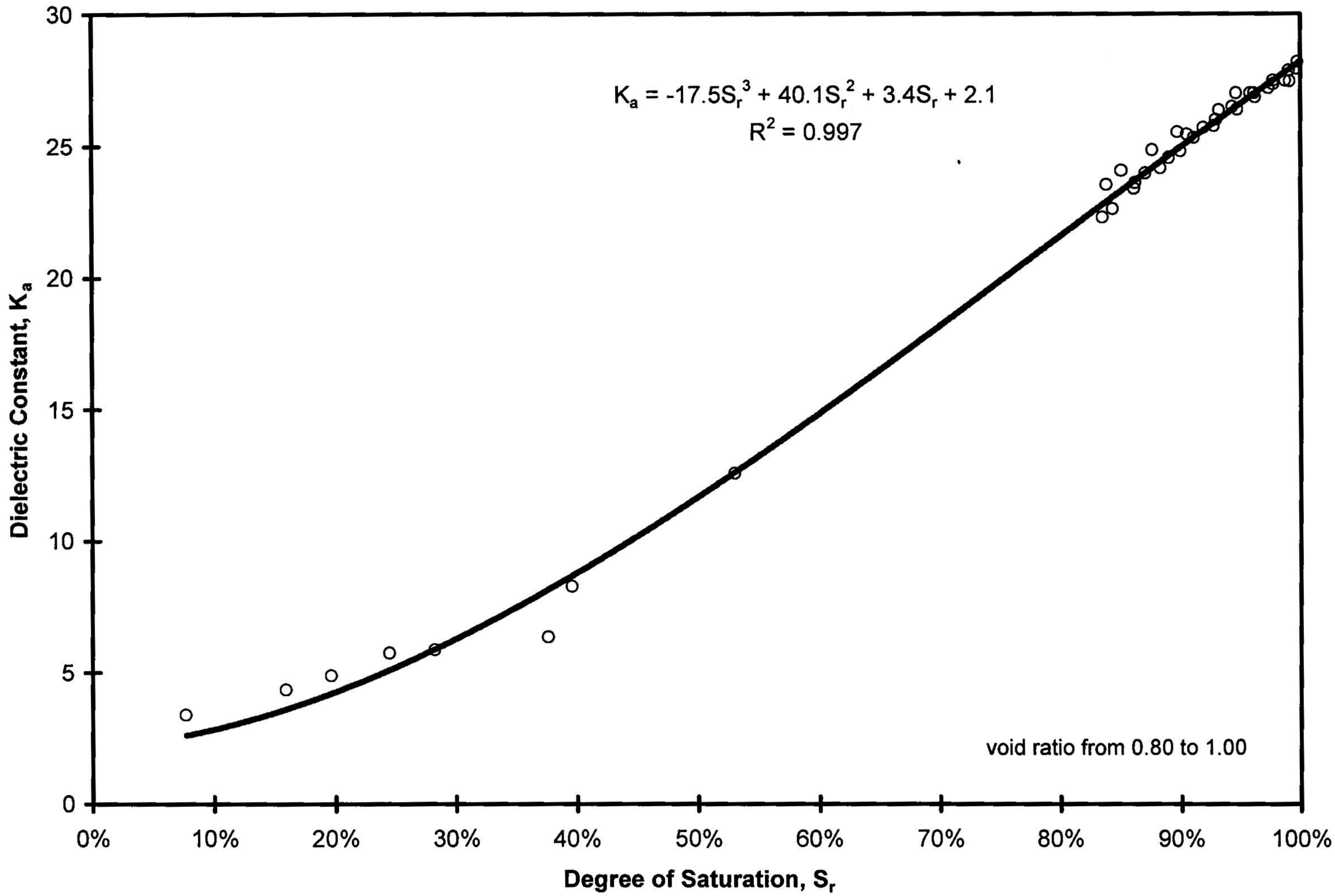


Figure 6 - Apparent dielectric constant versus degree of saturation for void ratios from 0.80 to 1.00.