J. agric. Engng Res. (1981) **26**, 541–549

The Response of Tensiometers Embedded in Saturated Soil Peds of Low Hydraulic Conductivity

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The effective time response of a tensiometer embedded in soil of low hydraulic conductivity (e.g. clay) is greater than that measured in free water. Theoretical analysis, based on simplifying mathematical and physical assumptions, is developed to estimate this influence of the soil, and shows that for a typical rapid response tensiometer (e.g. a pressure-transducer type), a time constant of 0·5 s in a loam can lengthen to one of 10 min in a very heavy clay. Experiments indicate that the theory probably underestimates the true value.

To increase the response time in soils of low conductivity, it is necessary to increase the gauge sensitivity (i.e. the change in pressure per unit change in volume of fluid entering the gauge), rather than change the cup conductance, which has negligible effect.

In practice, the available choice of design parameters is limited, and the analysis is of more practical use for assessing the potential of a given system for a given purpose, and for interpreting the significance of observations.

1. Introduction

Tensiometers have been used for many decades, but only in more recent years have their time response characteristics become of practical concern. It is generally recognized that a tensiometer inevitably has a finite response time, arising from the time taken to transfer water through the cup as the manometer level changes or as the transducer diaphragm deforms, and that this should be made as small as possible. However, the response time in soil is longer than that in water, because of the influence of the water transport properties of the soil, and it is perhaps not so fully appreciated just how much longer. Thus a tensiometer with a time response constant in water of 1 s or less, which would certainly be fast enough for most field experiments, may actually perform *in situ* with a time response of minutes or hours and the resulting lag could be severely limiting in many field recording systems in use today.

A particular example of practical interest in which this lag could prove significant is that of a tensiometer embedded in a clay ped to follow the pore-water pressure changes before and during the flow of water through the cracks and fissures surrounding it. This installation could form part of a drain flow investigation in which the tensiometers were simply required to register the presence of water in the fissures surrounding the peds. Theoretically, if the ped is saturated and non-swelling, the pore-water pressure attains equilibrium with that of the surrounding water effectively instantaneously, but the tensiometer may fail to register this equilibrium before the water has drained away, even though the time response constant of the tensiometer is less than 1 s. Furthermore, slow changes registered by the tensiometer might be interpreted as indicating a slow uptake of water, with swelling, whereas in fact the soil-water content was actually constant and only the soil-water pressure was changing.

It is thus desirable to be able to estimate the magnitude of the *in situ* response time constants of tensiometers, to aid the design of rapid recording tensiometer systems on the one hand, and to help the interpretation of field readings on the other. The present study considers this problem with particular reference to the example described in the previous paragraph.

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Received 9 June 1981; accepted in revised form 8 September 1981

0021-8634/81/060541+09 $02.00/0

To avoid possible confusion, the tensiometer time response constant, as normally understood (and conventionally measured in water), will be referred to as the "instrument" time response constant, to distinguish it from that measured in the soil, already referred to above as the *in situ* value.

2. Theory

Consider a winter field situation in which the soil profile may be assumed to be divided by a network of fissures and cracks into distinct saturated peds, with a tensiometer embedded in one such ped [see *Fig. 1 (left)*]. At some time, water flows through the fissures by natural drainage, thus exposing the pore water in the peds to a new (higher) water pressure. We will examine the particular sequence of events in which the tensiometer is initially in equilibrium with the pore-water pressure in the ped, and, at some instant, water flows in the fissures, exposing the ped to a new water pressure, which we will assume remains constant thereafter.

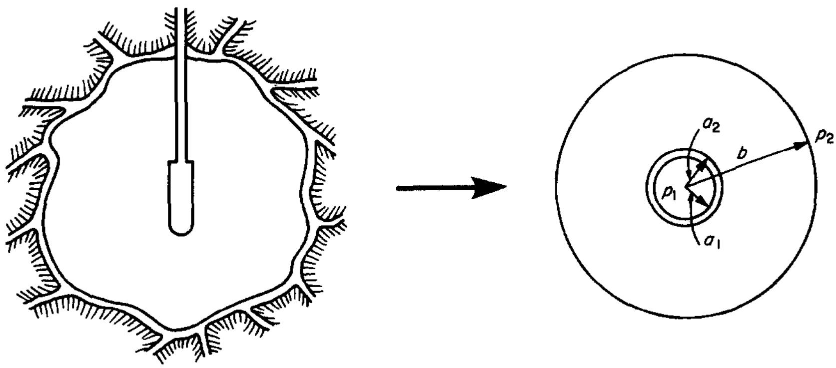

Fig. 1. Geometric simplification of a tensiometer cup in a soil ped

If the ped does not swell, the pore-water pressure equilibrates with the imposed water pressure instantaneously (or at most with the speed of sound). However, for the tensiometer to register the new pore-water pressure, some water, however little, has to enter the cup from the soil, and the rate at which this moves to the cup is controlled by the water transport properties of the soil.

The complete mathematical solution of this problem is formidable, even after making geometrical simplifications, but some progress can be made by introducing various idealizations which in fact lead to values that tend to underestimate the time response constants. Thus the cup and the irregularly shaped ped, *Fig. 1 (left)*, are replaced by a spherical cup at the centre of a spherical ped, *Fig. 1 (right)*. The soil matrix is assumed to remain rigid during the passage of the water to the cup: this is exact for non-swelling soils. The influence of the gravity gradient on the flow of water is ignored: this assists the flow in the upper region, but opposes it in the lower, so that the errors introduced through its neglect will tend to cancel out.

Following the mathematical analysis given by Carslaw and Jaeger[1] for the analogous heat conduction problem, it can readily be shown that the rate of flow of water to the tensiometer is given by

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \frac{4\pi(p_2-p_1)}{\dfrac{1}{K_1}\left(\dfrac{1}{a_1}-\dfrac{1}{a_2}\right)+\dfrac{1}{K_2}\left(\dfrac{1}{a_2}-\dfrac{1}{b}\right)}, \qquad \ldots(1)$$

where p_1 and p_2 are the pressures in the tensiometer and at the surface of the ped, respectively; a_1 and a_2 are the inner and outer radii of the tensiometer cup; K_1 and K_2 are the hydraulic conductivities of the cup wall and of the soil; b is the radius of the ped. But

$$\frac{dq}{dt} = \frac{dq}{dp_1}\frac{dp_1}{dt} = \frac{1}{S}\frac{dp_1}{dt},$$

where S is the gauge sensitivity, defined as the change in pressure registered by the gauge per unit change in volume of fluid entering or leaving it.[2]

Thus Eqn (1) can be written as

$$\tau' \frac{dp_1}{dt} = p_2 - p_1, \qquad \ldots(2)$$

where

$$\tau' = \frac{\frac{1}{K_1}\left(\frac{1}{a_1} - \frac{1}{a_2}\right) + \frac{1}{K_2}\left(\frac{1}{a_2} - \frac{1}{b}\right)}{4\pi S}. \qquad \ldots(3)$$

Hence solving Eqn (2), subject to the condition that the initial pore-water pressure in the ped (and hence in the tensiometer) is $p_1 = p_0$,

$$p_1 - p_2 = (p_0 - p_2)\exp(-t/\tau'). \qquad \ldots(4)$$

Thus the time response function, Eqn (4), is of similar form to that given by Klute and Gardner,[3] but with the time constant given by Eqn (3), now a function of the soil transport properties as well as of the instrument parameters.

The cup conductance, C, defined as the volume of fluid crossing the wall per unit time per unit pressure difference across the wall[2] is given by

$$C = 4\pi a_1 a_2 K_1/(a_2 - a_1),$$

so that Eqn (3) may be written as

$$\tau' = \frac{1}{CS} + \frac{1}{4\pi K_2 S}\left(\frac{b - a_2}{a_2 b}\right). \qquad \ldots(5)$$

Note that $1/CS$ is the instrument time constant,[3] τ. Hence Eqn (4), with τ' given by Eqn (5), gives an estimate of the effect of the soil on the time response of the tensiometer.

When the ped size is large, so that $b/a_2 \gg 1$, Eqn (5) reduces to

$$\tau' = \frac{1}{CS} + \frac{1}{4\pi a S K}, \qquad \ldots(6)$$

where a is the radius of the cup and K is the hydraulic conductivity of the soil.

In general, the time response function cannot be expressed in a form such as Eqn (4) in which all the soil and instrumental parameters are combined in the time constant τ'. The simplification is a result of assuming that the water content remains constant at all points with time.[4]

3. Experimental details

Results from various laboratory experiments are reported, in which time constants have been measured using various tensiometer systems, to demonstrate the influence of the soil on the response time. An experiment is also described which substantiates the statement that soil-water pressure changes may be instantaneous in a confined swelling soil, even though a tensiometer appears to indicate otherwise.

3.1. *Tensiometers*

Two types of tensiometer systems were used:

(1) a nominal 1·0 cm dia disc "cup" connected via a 2-way tap to either of 2 pressure transducers of different sensitivities;

(2) a commercial 4·0×1·0 cm dia cylindrical tensiometer cup connected to a nominal 2·5 mm dia water manometer.

The cup conductances, obtained from steady state flow measurements made directly on these components, were of the order of 10^{-5} cm^3 s^{-1} mbar^{-1} for the "disc" cup and 10^{-4} cm^3 s^{-1} mbar^{-1} for the cylindrical cup. The sensitivity of the water manometer was 17·7 mbar/cm^3, calculated from a measurement of the cross-sectional area of the manometer. The sensitivities of the pressure transducers, including the connection tubes, were of the order of 10^3 and 10^2 mbar/cm^3, respectively, as calculated from measurements of the time constants of the cup/transducer system, with the cup in water; it is very difficult to obtain independent measurements of the sensitivity of such sensitive devices. However, the ratio of the sensitivities is more easily determined by allowing the transducers to share different initial pressures set up in them, and was found to be 20 : 1. The time constants of the tensiometers, with the cups in water, measured during different phases of the experimentation as appropriate, were of the order of 14 and 184 s, respectively for the pressure transducer systems, and 300 s for the water manometer systems.

The experience of many measurements of the separate instrument parameters, and of the time constants of complete systems, shows that it is virtually impossible to specify a very accurate time constant for a given instrument. On many occasions, 2 different but reproducible values were obtained for the time constant depending on the direction of flow through the cup. Furthermore, the cup conductance always fell during steady continuous flow measurements of it, sometimes halving over a period of 1 h, and decreasing by an order of magnitude or more over a period of days. Such occurrences represent extreme conditions, not representative of actual field conditions but do emphasize the variability of the cup conductance.

3.2. *Interpretation of response of tensiometers in confined saturated swelling soils*

This experiment was designed specifically to demonstrate that a slowly changing tensiometer reading does not necessarily reflect the actual pressure changes in the soil-water. The experiment also shows that the water pressure in a confined saturated swelling soil changes effectively instantaneously following a change in the pressure in the water supply that communicates with the soil-water.

Fig. 2 is a schematic diagram of the essential features of the hydraulic circuit. As much as possible of the connecting tubing was of stiff nylon, but that connecting transducer (B) to the

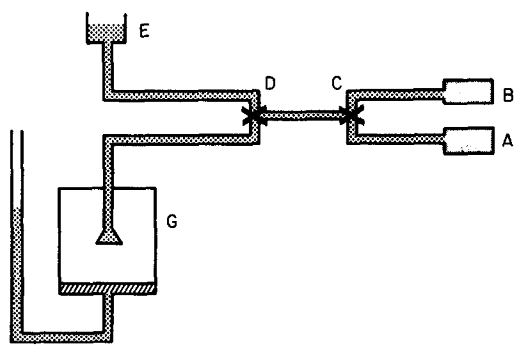

Fig. 2. Hydraulic circuit of experimental apparatus. A, B pressure transducers; C, D 2-way taps, E, F moveable water heads; G soil cell

2-way tap (C) was of rubber pressure tubing in order to reduce its sensitivity. Thus transducers (A) and (B) had significantly different sensitivities. Only the head of water (E) connected to the 2-way tap (D), and the water supply (F) connected to the base of the soil cell (G), were moved during the experiment. The cell (G) contained saturated kaolinite clay in communication through a supporting filter with the water supply (F) whose pressure was controlled externally by raising and lowering the manometer. Each transducer was calibrated separately by switching to the head of water (E) which could be raised or lowered. The calibrations drifted and therefore had to be checked frequently. The pressure in either transducer was perturbed for the time response measurements also by switching to (E). Unfortunately, turning the taps tended to "pump" water, so that although the pressure in the transducer was known from its voltage output reading, it was not always possible to set up in the transducer a prescribed water pressure.

The experimental arrangement thus allowed one either

(a) to change the soil-water pressure, and follow the changes on 1 of 2 pressure transducers or
(b) to change the water pressure in a pressure transducer and subsequently to allow the perturbed transducer to come into equilibrium with a constant soil-water pressure.

Thus the time response for a cup in soil to a step change in soil-water pressure could be obtained by imposing a step change in pressure in the transducer.

Curve (1) in *Fig. 3* gives the tensiometer readings observed for transducer (B) when the soil-water pressure was changed by adjusting the level of the supply water (F) as rapidly as possible. Such a response suggests a very slow approach of the soil-water pressure to the new imposed pressure, contrary to the expected instantaneous equilibration. Curve (2) gives the change in the

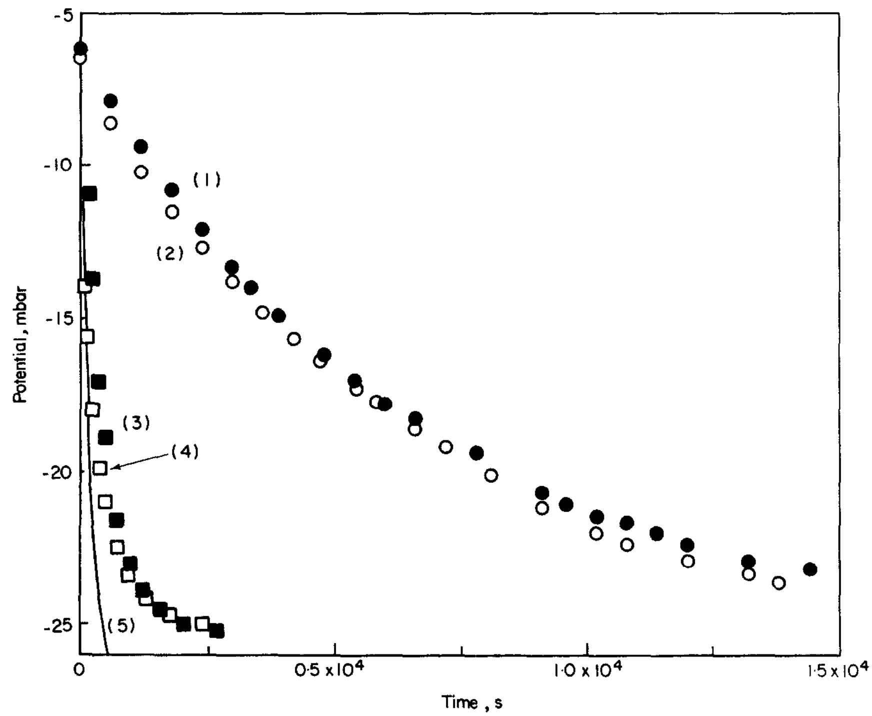

Fig. 3. Time response curves. (1) in situ "slow" tensiometer response to clay water-pressure change; (2) in situ "slow" tensiometer response to transducer pressure change; (3) and (4) as (1) and (2) but for "fast" tensiometer; (5) "slow" tensiometer response in water. Note that the corresponding "fast" tensiometer response is virtually indistinguishable from the vertical axis

transducer output reading when the transducer pressure had been suitably perturbed via the 2-way tap and subsequently allowed to equilibrate with the soil-water pressure in cell G, while the water external to the soil cell remained at constant pressure. The curves are very similar, and indeed might have been even closer had it been possible to adjust the perturbed transducer more precisely. Curves (3) and (4) in *Fig. 3* represent similar measurements made using the more sensitive pressure transducer (A), duplicating as closely as possible the conditions corresponding to Curves (1) and (2) respectively. Curve (3) again suggests a slow approach of the soil-water pressure to the new imposed pressure, and although it is faster this time than before, an instantaneous result would have been expected (as in 1) if the response of the tensiometers had been sufficiently rapid to follow the actual soil-water pressures. The readings for Curve (2) given by transducer (B) would therefore wrongly be interpreted as indicating a slow change in the pore-water pressure. Curves (3) and (4) are similar, as were curves (1) and (2).

Thus the tensiometer experienced the same pressure changes at the cup wall in all four experiments. Since in two experiments [Curves (2) and (4)] the tensiometer experienced an imposed step change in pressure, it may be concluded that it likewise experienced a step change in the soil-water pressure in the other two experiments [Curves (1) and (3)]. In other words, the soil-water pressure had in fact changed instantaneously in response to the rapid change imposed in the supply water level, and the delayed response was due to soil conductivity limiting the rate of transfer of water into the tensiometer cell.

TABLE I

Measured soil tensiometer parameters; and measured and calculated *in situ* constants, τ'

Experiment number	*1*	*2*	*3*	*4*	*5*	*6*
Soil*	*a*	*a*	*b*	*c*	*d*	*e*
K, cm/s	4×10^{-7}	4×10^{-7}	8×10^{-3}†	1×10^{-5}	—	3×10^{-6}†
Tensiometer‡	*f1*	*f2*	*g1*	*g2*	*g3*	*g1*
Radius a, cm	0·2	0·2	1·2	1·2	1·2	1·2
Sensitivity, mbar/cm^3	3×10^2	4×10^3	18	18	18	18
τ, s (instrument)	14	180	270	340	540	270
τ', (calculated), s	3×10^2	4×10^3	3×10^2	7×10^2	—	2×10^3
τ', (measured), s	4×10^2	8×10^3	3×10^2	6×10^3	1×10^3	6×10^3

* *a*, Kaolinite; saturated, *b*, Kimmeridge clay; loosely packed; saturated, *c*, As *b*, but partially drained, *d*, Kimmeridge clay; packed; saturated, *e*, Kimmeridge clay; re-packed; saturated

† Measured directly on the soil containing the tensiometer

‡ *f1*, Disc "cup"/pressure transducer A, *f2*, Disc "cup"/pressure transducer B, *g1*, Cylindrical cup 1/water manometer, *g2*, Cylindrical cup 2/water manometer, *g3*, Nominally *g1*, but dirty and partially dried out from earlier experiment: effectively a different cup

3.3. *The influence of the soil on the tensiometer time constant*

Results are given in Table 1 from a number of laboratory experiments in which the time constants of several different types of tensiometers embedded in clays have been measured. The data for the experiments designated 1 and 2 are derived from those described in section 3.2; those for experiments 3–6 were obtained from measurements made on tensiometers consisting of water manometers connected to cylindrical cups embedded in pots of repacked Kimmeridge Clay soil. (The loosely packed sample would be similar to a loose tilth.) The hydraulic conductivity values marked † were measured on the soil in which the tensiometer was actually embedded: the other values were obtained on separate samples packed as similarly as possible to the soil in which the particular tensiometer was embedded.

The influence of the soil on the instrument time constant is clearly demonstrated in Table I, and also in *Fig. 3* where response curves for tensiometer systems (A) and (B) in both water and soil are given.

None of the experimental arrangements correspond exactly to the geometry of a spherical tensiometer in a spherical body of soil (as assumed in the theory). However, in view of the large variation obtained in the measurements, attributed to the cup conductance changing, and the various physical assumptions included in the theory, a high order of agreement between measurements and theoretical predictions would not be expected. The results in Table I have therefore been used to compare the measured *in situ* time constants, τ', with values calculated using Eqn (6), which are also included in Table I. The value of the radius, a, in Eqn (6) has been replaced by an equivalent radius, calculated using shape factor tables[5,6] although a suitable value could probably have been estimated.

Experiments 1 and 2 can be examined further. The transducers were connected to the same cup in the same soil, and the experiments were conducted with soil-water conditions as similar as was feasible. A theoretical consequence of this is that

$$\tau_2'/\tau_1' = \tau_2/\tau_1 = S_1/S_2,$$

where the subscripts refer to the experiment numbers. Moreover, this expression is independent of the value assumed for a (or for $4\pi a$). The values of τ_2'/τ_1' and τ_2/τ_1 from Table I are 18 and 13, respectively, whereas the value of S_1/S_2 is 20 (obtained from the pressure transducer sharing experiment. Thus, given the variability of the conductance the data are as consistent as can be expected.

The overall conclusion from Table I is that the calculated values do appear to underestimate the experimental values. However, the observed underestimation may not be due entirely to simplifying assumptions made in deriving the theory, because of confounding effects of the variability of the cup conductance, and errors in measuring the hydraulic conductivity appropriate to the soil condition.

4. Response of a typical field tensiometer in a saturated ped

The tensiometer cups used in the experiments described in section 3 were small laboratory types, not typical of those used in the field. This section therefore examines the response of a typical field pressure-transducer tensiometer system.

To estimate the magnitude of the effect of the soil on the response of field tensiometers specific cases must be considered. In general, cups are not spherical, but are cylindrical with hemispherical tips. However, for the purposes of these calculations the cup can be replaced by an equivalent spherical one as described in section 3.3. The dimensions of commercially available cups appear to be typically in the ranges: length 5·0–5·5 cm; radius 0·5–1·2 cm; wall thickness 0·2 cm; conductance 1×10^{-4} to 5×10^{-4} cm^3 s^{-1} mbar^{-1}. Pressure transducers used in rapid recording systems are typically of the 1–2 bar type [see, for example, References (7–9)], and sensitivities of similar types lie in the range 4×10^3 to 1×10^4 mbar/cm^3. Hence the following set of data can be considered representative, and will be used in the calculations: $C = 2\times10^{-4}$ cm^3 s^{-1} mbar^{-1}; $S = 1\times10^4$ mbar/cm^3; $a_1 = 1{\cdot}0$ cm; $a_2 = 1{\cdot}2$ cm. The instrument time constant, $1/CS$, is thus 0·5 s.

The *in situ* time constants, calculated for a range of hydraulic conductivities for a 10 cm radius ped, are listed in Table II. As a rough guide, a hydraulic conductivity of 10^{-3} cm/s might apply to a light loam, and that of 10^{-8} cm/s to a heavy clay. The values are actually those measured in the ped, not those obtained by field measurements, which include contributions from the cracks and fissures around the ped. Furthermore, the time constant, τ, does not represent the time required to attain equilibrium with the applied pressure; in fact the equilibrium is only 95% complete by 3τ, and 99% by $4{\cdot}6\tau$. Table II shows that the specified tensiometer, not atypical, would be virtually useless for following rapid changes in the heaviest soils, and would not respond rapidly enough in field scanning systems that allow only a fraction of a minute for scanning each tensiometer.

TABLE II

Theoretical values of time constants for a representative tensiometer in soils of various hydraulic conductivities

K, cm/s	*τ, s*
10^{-3}	0·5
10^{-4}	0·6
10^{-5}	1×10^{0}
10^{-6}	6×10^{0}
10^{-7}	6×10^{1}
10^{-8}	6×10^{2}

5. Discussion

In general, the time response of a tensiometer installed in a soil will depend both on the instrument parameters and on the transport properties of the soil. The interaction is mathematically very complex because the soil acts as a distributed capacity and as a distributed resistance, both of which depend on the water content. It is therefore impossible to obtain general expressions for characterizing the dynamic response of a tensiometer in soil. However, certain specific cases can be analysed, as in the present paper, to show quite clearly the significant lengthening effect that soil can have on the time response behaviour of a tensiometer, and the time constants given in Table II are almost certainly underestimates.

Eqn (5) shows that the tensiometer with the shortest instrument response time does not necessarily have the shortest *in situ* value. When the soil is dominating the dynamic behaviour, the sensitivity, S, of the pressure gauge is the relevant parameter, not the combination CS. Indeed, it can probably be argued that this is a general result, since in the limit when the gauge sensitivity is infinite, no water moves so that the resistive properties of the cup (and soil) become irrelevant.

In view of the complexity of the general field situation, it is clearly desirable to measure the response *in situ*, especially if values given in Eqn (4), which applies to the saturated state, indicate that the soil has a dominating effect. This measurement should be made at the driest state likely. The response function will not conform in general to an equation of the form given by Eqn (4), so it is not possible in general to define an *in situ* time constant, τ. Nevertheless, it might be useful, for comparison purposes, to define an effective *in situ* time constant given by

$$\tau = (\text{Measured time to attain } 99\% \text{ of full response})/4{\cdot}6.$$

6. Conclusion

The soil can have a significant lengthening effect on the time response behaviour of a tensiometer, which cannot be ignored in many practical situations. Cases that will cause particular problems are those in which the tensiometer is used in heavy soils, especially to follow fairly rapid changes, particularly where many tensiometers are connected to a single transducer through a fluid scanning switching system, sampling the cups in quick succession. It is also evident that although the response characteristics of manometer tensiometers can be improved in various ways, such as by decreasing the bore diameter of the manometer tube, such tensiometers cannot be used to follow pressure changes in heavy soils. Pressure-transducer tensiometers are then essential.

It is recommended that the response should be measured for the driest state likely *in situ*, especially if values given in Eqn (4), which applies to the saturated state, indicate that the soil has a dominating effect.

In practice, the available choice of design parameters is limited. Hence the analysis is probably of more use for assessing the potential of a given system for a given purpose, and for interpreting the value of observations, rather than for designing systems.

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