On the Characterization of Suction in Swelling Clay

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The analysis of wetting and consequent swelling of unsaturated clays requires the specification of water potential in the unsaturated regime. Conventional characterization of water potential in unsaturated soils is done in terms of "retention curves" that specify a relation between suction and water content. In all conceptual models of unsaturated soils, suction is assumed to depend on the geometry of the "water-filled pore space." A first order characterization of this geometry is proposed in terms of water content, void ratio, and initial conditions. Despite this fact, conventional retention curves are presented as a relation between suction and water content, regardless of the void ratio. Moreover, in conventional laboratory techniques for the determination of suction there is no control over the void ratio, and each point on the retention curve corresponds to a different void ratio if swelling soil is tested. The present paper presents a laboratory technique for the determination of suction as a function of water content, void ratio, and initial conditions. Preliminary experimental results show that void ratio may have a substantial effect on suction, particularly in the low suction range. It is also demonstrated that the dependence of suction on void ratio has a significant effect on the analysis of the flow and swelling processes, to the extent that use of conventional suction curves in the analysis may lead to unreasonable results.

Design of structures in swelling soils represents one of the most challenging engineering problems. This problem occurs mainly in unsaturated clay soils in temperate climatic conditions consisting of wet and dry seasons. Generally the process involves migration of water from wet to relatively dry regions in the soil mass. This migration is accompanied by volume changes and, if mechanical constraints are present, a buildup in the state of stress. Thus the problem is a multifield process involving simultaneous changes in void ratio, water content, and stress as a result of a change in the environmental boundary conditions. Migration of water is an indication of spatial variation in the energy level of the soil water. Consequently, one of the preconditions for rational analysis of the swelling process is the establishment of a constitutive law which characterizes the energy state of water in unsaturated clay soils in a way that is meaningful under conditions that exist during a process of constrained swelling. The present work represents an attempt of such characterization. The paper includes the following elements:

1. Discussion of some physical facts relevant for the formulation of a constitutive model of water potential in unsaturated swelling soils;
2. A detailed description of equipment which was built for the purpose of experimental determination of the model;
3. Preliminary experimental results which were obtained for a particular Israeli clay at a given initial condition; and
4. A demonstration of the significance of the present characterization vis-à-vis the classical formulation, which is based on the concept of retention curves.

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THE CONSTITUTIVE MODEL

The essential feature of the swelling process is the simultaneous change of void ratio, water content, and stress. Hence a proper characterization of the energy state of water in an unsaturated swelling clay soil should reflect the dependence of the energy on the parameters that change during the process, namely void ratio, water content, and stress. The following discussion uses the term "water potential" (h) as an abbreviation for the "energy state of water in the soil." When h is negative, it is usually called "suction."

In the classical approach, using the pressure or suction plates procedures [ASTM D3152 (*1*)], retention curves are determined without control of void ratio. In nonswelling soils this feature of the classical procedure is not a limitation, because void ratio does not change during the process. However, when dealing with swelling soils it is important to quantify the dependence of the potential on the void ratio. The existence of such a dependence is implied by all models that relate suction to the "geometry of the pore space" [e.g., Yong and Warkentin (*2*), Bear (*3*), and many others].

In view of this argument, we propose the following constitutive model for the specification of water potential:

$$h = p_a + p_{w0} + p_{w\sigma} + \gamma_w Z - \phi(w,e,I_0) \quad (1)$$

where

h = total water potential,
w = current water content,
e = current void ratio,
I_0 = "initial conditions," including w_0 and e_0 (the initial values of w and e) but also the method of sample preparation (compaction) and other factors of similar nature,
$\phi(w,e,I_0)$ = physico-chemical potential (suction), a term representing the effect of the clay matrix on the energy of the water mechanisms by which such effects take place (include capillary, absorption, osmotic, etc.),
p_a = air pressure (present in an equation defining the potential of water because ϕ includes a capillary component, which is defined relative to the air pressure),

p_{w0} = static component of pore water pressure, related to the depth of the element below water table,
$p_{w\sigma}$ = excess pore water pressure due to external mechanical loading,
Z = elevation,
γ_w = unit weight of water, and
$\gamma_w Z$ = potential energy of the water.

Since the interaction between soil and water depends on the position of water elements relative to the clay particles, the value of ϕ must depend on the geometry of the water-filled pore space. As a first approximation this geometry can be characterized by the void ratio and water content. It is evident, however, that these two scalar variables cannot describe all the details of the pore geometry. Consequently, there may exist two samples with the same e and w but having different ϕ values due to the difference in the "pore size distribution function," or in other words difference in "soil structure." Failure to include such high-order geometrical variables in the constitutive relations manifests itself as a "history dependence," that is, the potential ϕ will show a dependence on the total time history of e and w, rather than the final values of these variables. One of the well-known manifestations of such history dependence is the phenomenon of hysteresis. In the present work we avoid the need to model hysteresis by considering the wetting process only. Other aspects of the history dependence are described in an approximate way by allowing ϕ to depend not only on the current values of w and e but also on the initial conditions, I_0. In other words, we allow different functions $\phi(w,e)$ for samples with different initial conditions, and therefore write $\phi(w,e,I_0)$.

Equation 1 is essentially a constitutive assumption, and as such its validity must be judged on the basis of the correspondence between predictions obtained using this equation and experimental results. In general this equation is not controversial, except perhaps the role of the term $p_{w\sigma}$, representing the effect of external loads on the water potential. Therefore, further discussion of Equation 1 is restricted mainly to this term.

In saturated soils Equation 1 simplifies to

$$h = p_{w0} + p_{w\sigma} + \gamma_w Z \tag{2}$$

corresponding to $p_a = 0$ and $\phi(w_s,e,I_0) = 0$, where w_s is the moisture content at complete saturation. Equation 2 states that the total water potential is the sum of the gravity potential, the static water pressure, and the mechanical potential due to external loading. The existence of $p_{w\sigma}$—generally called excess of pore pressure due to mechanical load—is well known in saturated soils where undrained conditions prevail. However, when the water is allowed to drain, $p_{w\sigma}$ will dissipate with time, with the external load being now supported by the particles (principle of effective stress).

In unsaturated soils, all terms of Equation 1 may exist simultaneously. However, in the case of low degree of saturation, when both the air and the water are continuous, one may argue whether $p_{w\sigma}$ develops or not under load application. If $p_{w\sigma}$ develops it is anticipated that due to the existence of the continuous air phase within the material (corresponding to internal drainage), $p_{w\sigma}$ will certainly dissipate, and may do so at a fast rate. Therefore, for practical purposes and since processes of wetting and swelling are relatively slow, $p_{w\sigma}$ may be assumed to equal zero. This argument breaks down at sufficiently high degree of saturation (90 percent and higher), when the air in the soil exists probably in the form of air bubbles [Barden (*4*)]. At these high degrees of saturation, $p_{w\sigma}$ probably dissipates at a rate similar to or slightly slower than that of a completely saturated soil.

The above discussion suggests that $p_{w\sigma}$ dissipates with time, probably at a faster rate in unsaturated soils than in the completely or almost completely saturated soils. It should be noted that $p_{w\sigma}$ can be attributed to a variety of sources, such as foundations loading, changes in overburden pressure, etc. Due to these external loads, $p_{w\sigma}$ develops and dissipates, resulting in void ratio changes and consequently changes in the water potential. The effect of external load on the water potential is obtained here naturally, in contrast with the approach taken by Philip (*5*), who included a separate "overburden potential" term in Equation 1.

THE PRINCIPLE OF THE PROPOSED TESTING METHOD

In principle the proposed procedure for the determination of the function $\phi(w,e,I_0)$ is similar to the conventional pressure plate test [ASTM D-3152 (*1*)], or Zur's osmotic cell (*6*), except for the fact that the soil sample is enclosed in a rigid cell, hence in a wetting process the volume of the sample and also the void ratio remains constant. In fact, each point of the function $\phi(w,e,I_0) = \phi(w,e=e_0,I_0)$ is determined by running a swell pressure test under controlled suction. The suction is controlled either by the concentration of the osmotic solution or by the magnitude of the externally applied air pressure. Tests of similar type have been performed previously by Kassiff and Ben Shalom (*7*) for the purpose of estimating swelling pressure under controlled suction rather than quantifying the suction function. On the basis of the discussion presented in the previous section, the mechanical pressure (swell pressure) that is developed during such a test has no effect on the results of the measurements, because by its very nature the test is run under "drained" conditions. One of the added advantages of running suction tests at constant volume is that the pore size distribution function (soil structure) remains approximately constant during the test.

More specifically, consider the osmotic version of the test, in which the following procedure is used:

1. A series of soil samples are compacted in a rigid cell to the same initial conditions w_0, e_0.
2. Each sample is allowed to come to equilibrium with an osmotic solution of different concentration. Let h_s be the potential of the water in the solution. During the test p_a is kept equal to atmospheric pressure. The sample is prevented from swelling by the rigid cell, so that the void ratio remains at its initial value, i.e., $e = e_0$.
3. At equilibrium the total water potential of the sample equals h_s, the known potential of the water in the osmotic solution; p_{w0}, $p_{w\sigma}$, and $\gamma_w Z$ are zero; and Equation 1 reduces to $h = -\phi(w,e_0,I_0) = h_s$, or:

$$\phi(w,e_0,I_0) = -h_s \tag{3}$$

4. At the end of the test the water content at equilibrium is determined. Repeating this procedure with a series of sam-

ples, all having the same initial conditions, using different concentrations of the osmotic solution with each sample, results in a function $\phi = \phi(w,e_0,I_0)$, which is a "retention curve" for a condition of constant void ratio.

In a second version of this procedure, the water potential at equilibrium is controlled by applying a known air pressure p_a to the sample rather than the osmotic solution. In this case the water potential at equilibrium equals the energy of free water (i.e., $h = 0$), and p_{w0}, $p_{w\sigma}$, and $\gamma_w Z$ equal zero. Hence Equation 1 reduces to

$$h = p_a - \phi(w,e_0,I_0) = 0 \tag{4.1}$$

or

$$\phi(w,e_0,I_0) = p_a \tag{4.2}$$

EQUIPMENT

The test equipment is composed of a specimen box, a supply system for water or osmotic solution, and an air pressure supply system. The specimen box (Figure 1) is made of stainless steel and it may be considered as rigid. The box consists of two parts:

1. The box body, in which the specimen is compacted (part A). At the bottom of the box there is a porous stone and a connection to air pressure, or (as an alternative) an atmospheric pressure opening.

2. The box cover (part B). Two stainless steel meshes are embedded in this cover, No. 80 on top and under it No. 20. The surface of the top mesh creates a plane with the area of the cover box.

Water or osmotic solution is supplied through two connections at the top of the box cover. This arrangement provides the supply of water or osmotic solution to the stainless steel meshes and through them to the top of the specimen. The osmotic solution (or water) is circulated continuously.

The two parts of the box are separated by semipermeable membrane. The membrane separates the sample from the circulating free water or osmotic solution. When suction is controlled by air pressure, fresh water is supplied, and the semipermeable membrane that is used is pervious to water but impervious to air. When suction is controlled by osmotic solution, the air pressure in the soil specimen is atmospheric, and the semipermeable membrane used is pervious to water but impervious to salt molecules in the solution.

One of the advantages of this arrangement is that water penetrates into the sample on one side, while air leaves the system on the other side. This prevents air from being trapped inside the sample and reduces the time required in order to achieve equilibrium. The principal disadvantage of this testing procedure is that tests can be conducted in a wetting process only. This limitation is due to the fact that it is not possible to prevent shrinkage or to keep the void ratio constant during a drying process.

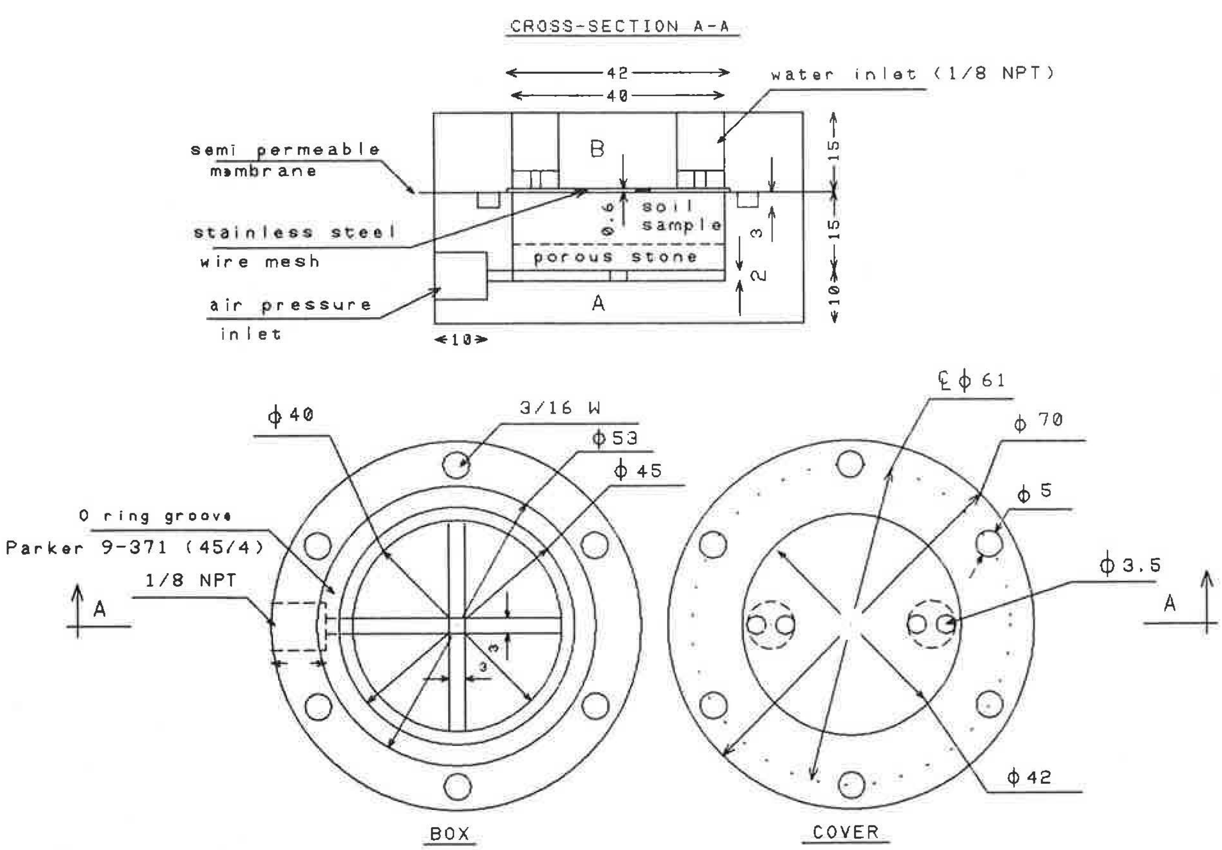

FIGURE 1 Equipment for measuring retention curve in constant void ratio (dimensions in mm).

TEST PROCEDURE

The soil specimen can be compacted or undisturbed (in this research only compacted samples were tested). The samples are statically compacted directly in the specimen box to a desired initial void ratio and water content. The initial conditions should be such as to ensure a wetting of the specimen during the test. The specimen dimensions are 4 cm diameter and 0.5 cm height. The specimen height is relatively small in order to reduce the time required to reach equilibrium.

When suction is controlled using air pressure, the test procedure is as follows:

1. Specimen is compacted to the desired initial void ratio and water content directly in the specimen box. The suitable semipermeable membrane is placed on the sample and the box is closed tightly.
2. The desired air pressure is applied to the specimen. This air pressure is kept constant. Since the specimen is relatively dry, equilibrium between the air pressure and the sample water pressure is reached almost instantaneously.
3. The water supply is connected to the box cover. The water fills the mesh holes, and flows to the soil specimen through the semipermeable membrane. The specimen water content is increased until equilibrium is established.
4. The test is stopped and the water content of the soil specimen is measured.

Using this procedure the following problems were encountered:

- There is small but constant diffusion of air through the membrane from the specimen chamber to the box cover. This diffusion slows the rate of water flow into the soil specimen. Consequently, the time required for equilibrium was of the order of 2 to 3 weeks.
- Although the membrane is supported by the box cover, there were many cases where it was punctured by the applied air pressure.

Where suction is controlled by an osmotic solution, the test procedure is similar to the one described above. The differences between the two procedures are as follows:

- The air pressure in the soil specimen is atmospheric (the opening at the bottom of the cell is opened to the atmosphere).
- The membrane used is pervious to water but impervious to the salt molecules.
- Osmotic solution in a certain concentration is circulated through the box cover and the stainless steel meshes. The salt used is Carbowax-Polyethylenglycol 6000, which has also been used by Zur (*6*), Kassiff and Ben Shalom (*7*), and Samocha (*8*). In order to keep the concentration of the solution at a constant value, a large volume of solution is used and the solution is circulated constantly through the box cover.

Using osmotic solution in order to control suction has several advantages:

- The time needed to reach equilibrium is just 3 or 4 days.
- There were almost no cases of membrane failures.
- Test can be conducted up to 3000 kPa of suction (*6*).

A potential disadvantage of using osmotic solution is the possibility of membrane corrosion. It was found by Samocha (*8*) and Ben Shalom (*9*) that after about a week the membrane is torn by corrosion. Because the proposed equipment reaches equilibrium after 3 to 4 days, however, it appears that this problem is not relevant in the present case.

TEST RESULTS

All tests were made on "Mizra clay," a typical Israeli expansive clay. The basic properties of this clay are

- Liquid limit (LL) 78 percent;
- Plastic limit (PL) 29 percent;
- Percent fines (passing No. 200) 98 percent; and
- Specific gravity (*Gs*) 2.78.

The initial water content in all the tests was 10 percent.

Test results, conducted with air pressure up to 700 kPa and osmotic solution up to 1962 kPa are given in Table 1 and Figure 2. Some tests were conducted with pure water, keeping the air pressure in the sample at atmospheric value. Equilibrium was reached after 3 days. Water contents in equilibrium were equal to the expected water content at full saturation, which is equal to e/Gs. An additional series of tests was performed using osmotic solution and varying the testing time. It was found that maintaining the sample in the cell longer than 3 to 4 days did not affect the results in any systematic way.

Table 1 shows that there is a good agreement between results of tests made with air pressure and tests made with osmotic solution (in the range of 0 to 700 kPa where air pressure tests could be conducted). Figure 2 shows that the retention curves depend on the void ratio. The separation between curves of different void ratios is more pronounced at high water contents (low suction values). A possible explanation of this trend is that, in relatively wet soils, small voids are filled with water and suction is controlled by the bigger voids. The size of the large voids is changed with void ratio, and hence in this range the suction shows strong dependence on the void ratio. In relatively dry soils, the bigger voids are empty of water, and suction is determined by the size of the smaller voids. Changes in void ratio have only a small effect on the size of the small voids; hence in this water content range the suction is almost independent of the void ratio.

A comparison was made between the retention curves obtained in this research and the results obtained by Livneh et al. (*10*) using the pressure plate apparatus, and the same Mizra clay. It should be emphasized that the results of Livneh et al. (*10*) correspond to a drying process starting from saturation. From Figure 2 it appears that, in general, the void ratio of the tests conducted by Livneh et al. (*10*) were very high. The initial void ratio (at saturation) is greater than 1.5.

It may be of interest to point out that the retention curves in Figure 2 are by definition loci of constant effective stresses. Adding a facility for measuring the swelling pressure developed in this test will make this type of equipment extremely useful for studying the principle of effective stress in unsaturated swelling soils.

TABLE 1 SUCTION MEASUREMENT RESULTS

e_0	suction (Kg/cm^2)	w(%) (air press.)	w(%) (Carbowax)
1.1	0	41.8 40.1	
	2	26.8 26.4	27.2
	4	26.3 26.2	25.6
	6	25.2	23.9
	8		24.9
	15		21.8
	20		20.6
1.0	0	35.3 38.1	
	2	28.4	25.6 28.4
	4	28.1 27.6	27.0
	6	26.0	23.0
	8		24.2
	15		20.8
	20		19.8
0.9	0	33.7 33.3	
	2	25.7 26.1	25.4
	4	24.8 24.6	24.2
	6	25.4 24.1	23.4
	8		24.0
	15		20.8
	20		20.1
0.8	0	29.4	
	2	28.0	
	4	24.1	
	6	23.5	
	8		23.6
	15		20.2
	20		19.7

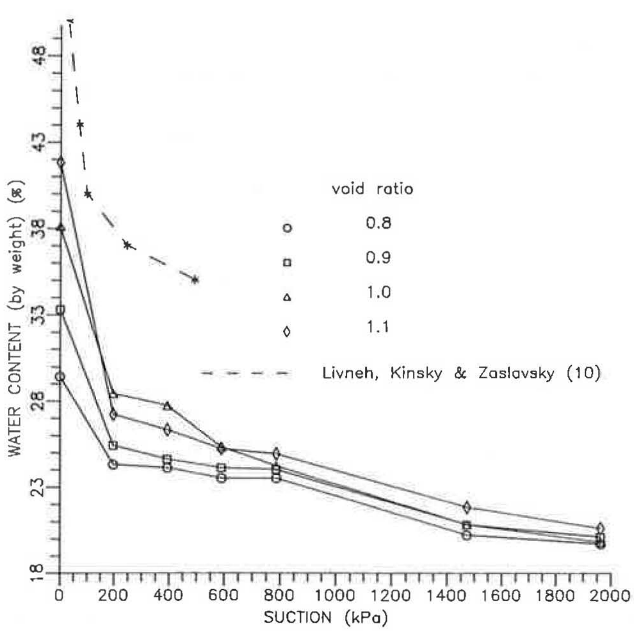

FIGURE 2 Suction versus water content and void ratio (Mizra clay).

SIGNIFICANCE OF THE PRESENT SUCTION CHARACTERIZATION

In order to study the implications and significance of the dependence of suction on both void ratio and water content, a one dimensional free swell flow problem in expansive soil was analyzed. The method of analysis is an extension of the approach presented by Uzan, Baker, and Frydman (*11*). Complete details of this procedure can be found in the work of Keissar (*12*).

The numerical implementation of this procedure requires an iteration solution of flow and stress-deformation problems in each time step. Both of these problems are solved using finite element technique. The geometry of the finite element mesh used for the analysis of the one dimensional free swell problem is given in Figure 3. The boundary conditions of this problem are as follows:

- Zero water potential at the bottom of the sample (boundary AB);
- Zero flux through the boundaries AD, DC, and CB; and
- No external stresses on the specimen top (boundary DC).

The problem defined by these boundary conditions is one dimensional for both flow and deformation, and it corre-

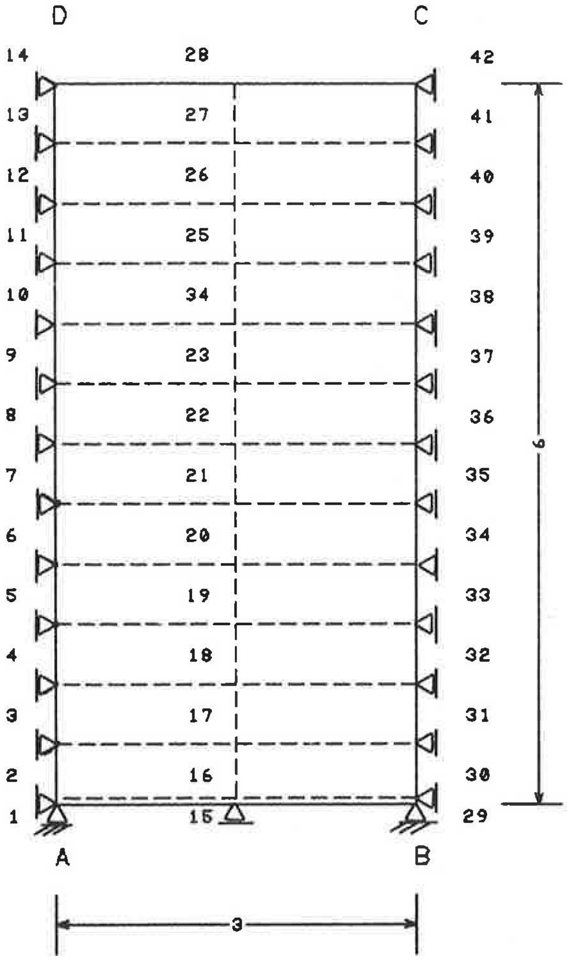

FIGURE 3 One-dimensional problem—geometry and elemental mesh (dimensions in cm).

sponds to a "free swell" test in an odometer. The problem was solved for the following initial conditions:

- Initial void ratio is 1.0;
- Initial water content is 0.21; and
- Distribution of initial water potential as implied by the initial conditions and the nature of the suction function.

Three different models of the suction function were analyzed:

Case 1. Suction is assumed to depend on both water content and void ratio, according to the approach presented in this paper. The experimental values given in Figure 2 were used for the purpose of the analysis. These curves were measured at w_0 = 10 percent, compared with the initial water content of 21 percent assumed in the analysis. Further tests conducted with the same equipment, using the same soil at w_0 = 21 percent, showed no significant effect on the retention curves (*13*).

Case 2. Suction is assumed to depend on water content only. This case is included in order to establish the significance of the relation between suction and void ratio to the results of the analysis. The suction function for e = 1.0 in Figure 2 was used for the purpose of the analysis. This suction function is consistent with the assumed initial void ratio of 1.0.

Case 3. Conventional suction curve as a function of water content. This case is included in order to illustrate some of the difficulties that result from the use of conventional retention curves for the analysis of flow in swelling soils. The experimental function found by Livneh et al. (*10*) and given in Figure 2 was used for the purpose of the analysis.

A number of additional parameters and constitutive relations are required in order to completely specify the problem. These parameters are related to the stress-deformation behavior of the material, interaction between the flow and deformation regimes, and dependence of permeability on the state of the system (w,e). Since the purpose of the present section is to investigate the significance of the new characterization of suction on a swelling problem, these variables are the same for all three suction curves presented above. Actual values for these parameters were established for Mizra clay and are presented in the work of Keissar (*12*).

For the initial conditions given above and from the suction functions found in this research, the initial suction is 1670 kPa. For the same initial water content, the initial suction based on Livneh et al. (*10*) is approximately 34,000 kPa. This last value is obtained at an unknown void ratio, and it is probably not consistent with an initial void ratio of 1.0. The use of classical retention curves always results in this type of inconsistency when flow in swelling soils is considered.

The results of the analysis for the three models of suction function described above are presented in Figure 4. On the basis of this figure, it may be concluded that

- The dependence of suction on void ratio has a considerable influence on the flow regime. This influence is seen both in Case 2 (suction independent of void ratio) and Case 3 (classical retention curve) as compared with Case 1 (present characterization).
- Using the retention curve found with the pressure plate apparatus (Case 3), the flow rate is much greater than the flow rate resulting using the suction functions based on the proposed measurement technique (Cases 1 and 2). The reason for this difference is the much higher initial value of suction inferred in Case 3, which implies a large gradient on wetting and therefore very high flow rates.
- The water contents obtained in Case 3 are very high, exceeding the water content at saturation at the calculated void ratios. The reason for this erroneous result is that the retention curve of Livneh et al. (*10*) corresponds to an unrealistically high void ratio, as discussed above.

It is seen that the dependence of suction on void ratio has a significant effect on the analysis of flow and deformation in swelling soils. If one does not use suction values that are consistent with the actual void ratio of the sample (as is the case when classical retention curves are used) then the results may contain large errors and inconsistencies.

SUMMARY AND CONCLUSIONS

It is natural to assume that the potential of water in unsaturated soils is a function of the geometry of the water field pore

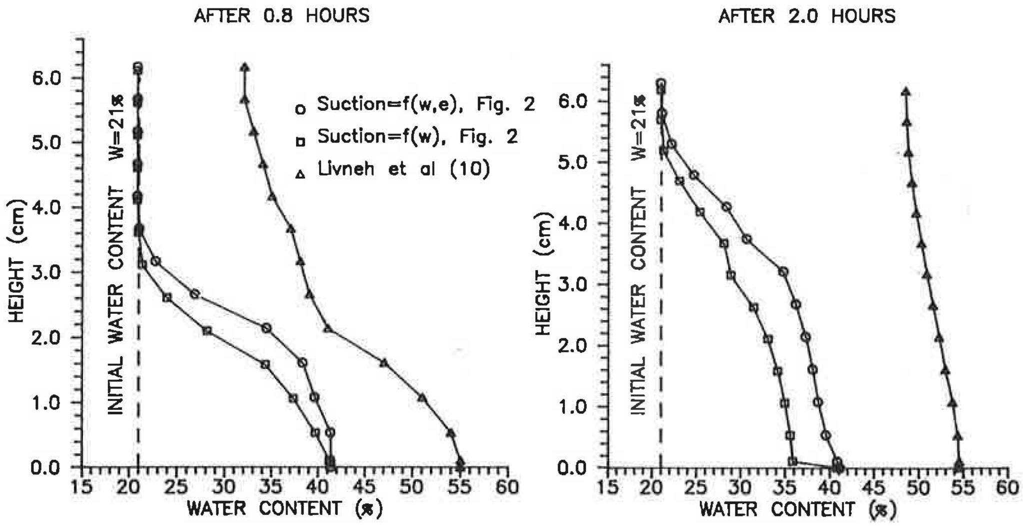

FIGURE 4 One-dimensional free swell flow and expansion problem—results.

space, and hence depends on both water content and void ratio. A new experimental procedure was developed in order to characterize the dependence of water potential on the void ratio. In this procedure, suction is measured under constant volume conditions, essentially in a type of "swelling pressure" test. It is argued that the mechanical swelling pressures that developed during such a procedure have no effect on the measured values of suction, due to the "drained" nature of the test.

Preliminary test results show that, as expected, suction depends on the void ratio. This dependence is particularly significant in the range of small suctions. The implications of this new characterization of water potential on the analysis of flow and deformation in swelling soils are demonstrated in a number of case studies. It is shown that the dependence of suction on void ratio may have a significant effect on the results of such an analysis. Moreover, the use of conventional retention curves, which are obtained without control of the void ratio, may result, with inconsistencies in the calculated results.

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