

## DISCUSSIONS

## Matrix suction and diffusive transport in centrifuge models: Discussion<sup>1</sup>

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The discussers would like to commend the author's venture into the use of centrifuge modeling technology in the study of unsaturated soils, particularly as it relates to contaminant-transport problems. Centrifuge modeling, as an independent approach to predicting field behavior, provides a potentially fruitful area of research.

There are several questions, related primarily to the details of the experiment and the interpretation of the data, that, if answered, would assist the readers in understanding the research results presented. In addition, the discussers have a concern regarding one of the key technical terms used in the paper. The concern is with respect to the spelling of a soil suction term. Two spellings can be found in the research literature for the suction component associated with the capillary forces in the pore water. The two spellings are (i) matric suction and (ii) matrix suction. It appears that many geotechnical engineers are not aware of the history of the spelling (or misspelling) of this term and probably a short review of the usage of this term would be appropriate.

One of the stress state variables for an unsaturated soil is matric suction, which is defined as the difference between the pore-air and pore-water pressures. There appears to have been some confusion in the literature over the spelling of the term, matric suction. The 1963 report of the International Society of Soil Science to establish soil physics terminology defines the term and spells it as matric suction. In 1964, the Symposium-in-Print entitled "Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas" (Aitchison 1964) was presented to the First International Conference on Expansive Soils in 1965. The first article in this publication is a statement of the Review Panel that sets forth the notation and definition of terms for expansive soils. The proposed notations are referenced to the International Society of Soil Science. Unfortunately, the capillary suction component of the soil is spelled as matrix suction while the definition is the same as that given in 1963 by the International Society of Soil Science.

This has subsequently led to confusion in the literature regarding the spelling of the capillary component of suction.

In 1970, the International Society of Soil Science published a glossary of soil science terms using the spelling matric suction. In 1976, the Canada Department of Agriculture, Ottawa, published a glossary of terms in soil science using the spelling matric potential. In 1979, the International Society of Soil Science Society again reviewed their terminology, maintaining their previous spelling as matric. The International Society for Soil Mechanics and Foundation Engineering has never adopted terminology for the suction components of an unsaturated soil.

The research literature appears to have consistently used the spelling matric suction, with the exception of a small portion of the geotechnical literature which has used the spelling matrix suction. It is suggested that a spelling consistent with the soil physics and soil science literature be used throughout the geotechnical community.

The discussers wish to raise several questions related to the details of the centrifuge model. It would be appreciated if the author could provide a detailed description with respect to three aspects of the test procedures. First, the procedure and the type of analytical method used for the determination of the salt concentration of the pore water. Second, the methodology used in simulating the spill in the model and the precautions taken to prevent any leakage in the lateral direction. Third, the time scale involved in spilling the 128 ml of salt solution into the soil column for the 25g model. According to the author, chloride tracer was used for the study of the contaminant transport in the drained soil; however, the results presented in the paper were given as sodium chloride concentration. A clarification of this difference would be helpful.

Results of the water-content profiles (author's Fig. 4) seem to indicate that the spill that contains 10% NaCl solution has moved vertically downward towards the water table. At the end of 2 months, the results show that the wetting front has moved down to a depth of 4.5 m, and at the end of 6 months, the spill has drained from the top 2 m and has advanced into the water table. Results of the concentration profile (author's Fig. 5), on the other hand, show that the salt has moved predominantly in the lateral direction and has only penetrated 2 m in the vertical direction. At the end of 1 year, the spill has completely drained from the soil but the salt has remained stationary at a depth of 3 m. If the movement of the spill is a result of a potential gradient

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**Table 1.** Effect of the degree of saturation on  $D^*/D^0$ .

Volumetric water content	Olsen and Kemper (1968) using $K = 0.005$	van Rees (1989)
0.4 (assuming $S = 100\%$ )	0.273	0.54
0.268 (i.e., $S = 67\%$ )	0.073	0.25

(total head =  $\pm$  pressure head plus elevation head), then advection transport would be dominant and the dissolved salt would have moved along with the water with some spreading at the wetting front due to mechanical dispersion and molecular diffusion. The discussers have difficulty correlating the concentration profile with the water-content profile and would appreciate it if the author could explain the key mechanisms operative in the centrifuge model. The results seem to show that the pathways for water flow and the pathways for contaminant transport are different.

The results of the effect of water content on the effective diffusion coefficient,  $D^*$ , are available in a number of soil science studies (Klute and Letey 1958; Porter et al. 1960; Rowell et al. 1967; Warncke and Barber 1972; Barraclough and Tinker 1981). The discussers feel that the assumption that the value of  $D^*$  at 67% saturation is the same as the value of 100% saturation may not be realistic. Calculation of  $D^*/D^0$  at various volumetric water contents are given in Table 1, assuming a soil porosity of 0.4. The volumetric water content corresponding to 67% saturation would be 0.268. The values of  $D^*/D^0$  were estimated using the following empirical relationships proposed by Olsen and Kemper (1968):

$$[1] D^* = K e^{b\theta_w} D^0$$

where

$D^*$  is the effective diffusion coefficient of the chemical species in the soil,

$K$  is the empirical constant ranging from 0.005 to 0.001 for sandy loam to clay soils,

$b$  is the empirical constant, a value of 10 has been suggested by the authors,

$\theta_w$  is the volumetric water content,

$D^0$  is the diffusion coefficient of the chemical species in free solution; and the empirical relationship given by van Rees (1989) as

$$[2] D^* = 3.13\theta_w^{1.92} D^0$$

The discussers also felt that it would be more reasonable to simulate the centrifuge model using the partial differential equation for contaminant transport of conservative chemical species as shown below

$$[3] \frac{\partial(\theta_w C)}{\partial t} = \frac{\partial\left\{\theta_w D^*(\theta_w) \frac{\partial C}{\partial r}\right\}}{\partial r} + \frac{1}{r^2} \frac{\partial\left\{\theta_w D^*(\theta_w) \frac{\partial C}{\partial \theta}\right\}}{\partial \theta} + \frac{\partial\left\{\theta_w D^*(\theta_w) \frac{\partial C}{\partial z}\right\}}{\partial z} - \frac{\partial(q C)}{\partial r} - \frac{1}{r^2} \frac{\partial(q C)}{\partial \theta} - \frac{\partial(q C)}{\partial z}$$

Expanding the above equation gives

$$[4] \frac{\theta_w \partial C}{\partial t} + \frac{C \partial \theta_w}{\partial t} = \frac{\partial\left\{\theta_w D^*(\theta_w) \frac{\partial C}{\partial r}\right\}}{\partial r} + \frac{1}{r^2} \frac{\partial\left\{\theta_w D^*(\theta_w) \frac{\partial C}{\partial \theta}\right\}}{\partial \theta} + \frac{\partial\left\{\theta_w D^*(\theta_w) \frac{\partial C}{\partial z}\right\}}{\partial z} - \frac{\partial\left\{K(\theta_w) \frac{\partial h}{\partial r} C\right\}}{\partial r} - \frac{1}{r^2} \frac{\partial\left\{K(\theta_w) \frac{\partial h}{\partial \theta} C\right\}}{\partial \theta} - \frac{\partial\left\{K(\theta_w) \frac{\partial h}{\partial z} C\right\}}{\partial z}$$

where

$\theta$  and  $r$  are polar coordinates,

$z$  is the distance along the  $z$  axis,

$\theta_w$  is the volumetric water content,

$C$  is the concentration of the chemical species,

$D^*(\theta_w)$  is the diffusion coefficient of the chemical species for unsaturated soil,

$K(\theta_w)$  is the hydraulic conductivity of unsaturated soil,

$q$  is the water flux,

$h$  is the hydraulic head.

The boundary conditions of which can be described mathematically as

$$C(r, z, t) = C_0 \quad \text{for } 0 < t < t_1 \quad \text{and} \quad 0 < r < r_1$$

$$C(r, z, 0) = 0 \quad \text{for } r > 0 \quad \text{and} \quad z > 0$$

where

$t_1$  is the spill period,

$r_1$  is the radius of spill area,

$C_0$  is the concentration of the spill.

The discussers realize that the solution to the above equation is complex and the difficulties in numerical modeling associated with the nonlinearity of the parameters. However, the functional relationship between hydraulic conductivity and saturation of the soil, is well defined. Could parametric studies be carried out to determine the diffusion coefficient or the coefficient of hydrodynamic dispersion, if there is adsorption?

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## Matrix suction and diffusive transport in centrifuge models: Reply<sup>1</sup>

R.J. Mitchell

The writer thanks the discussers for this opportunity to respond to questions on centrifuge modelling.

The writer first became aware of the other spelling (matric) after the paper was published when a reviewer of a subsequent paper, submitted to an American Society of Civil Engineers sponsored conference, questioned the use of matrix. The Scientific Authority for that conference indicated that either spelling was acceptable. After being properly introduced to it, I must confess that I like "matric" and shall endeavour to use this spelling in the future.

Salt concentrations in the pore water were determined by comparing the conductivity of samples (which were oven dried and then mixed with 500 cm<sup>3</sup> of deionized water) with a calibration relation produced from conductivity measurements on a similar mass of sand, with known quantities of salt, dispersed in 500 cm<sup>3</sup> of deionized water. The detailed procedure and calibration curves are presented by Cooke (1991). This method, as indicated in the paper, is thought to be accurate to about 0.5 ppt when used with inactive (clean) sand. It is presumed that conductivity mea-

surement defines the chloride tracer. Sodium chloride was, indeed, used as described in the paper.

The 10% NaCl solution (128 ml for the 25g models) was released over a period of about 2 min into a receiving reservoir, which can be seen in the top section of the container column shown in Fig. 3 of the paper (called a containment ring in the paper). The reservoir used in the 200 mm diameter column was 60 mm in diameter, such that the instantaneous introduction of 128 ml of fluid would create a fluid depth of close to 45 mm. The receiving reservoir was 80 mm high and penetrated (sharpened cutting edge) about 20 mm into the sand to help prevent lateral escape of the fluid being contained. The 100 mm diameter column had a reservoir whose relative dimensions were similar (i.e., an instantaneous fluid depth of about 22 mm in a 40 mm high reservoir that penetrated about 10 mm into the sand) and fluid was injected over a time period of about 0.5 min (a 20 min prototype interval in both cases). There was an unknown transient pressure gradient created by the rise and fall of the salt solution in the containment ring. This would, of course, contribute to lateral flow of the fluids but it is believed that this effect was similar at the two model scales. The writer apologizes for not including this experimental detail in the paper.

In comparing Figs. 4 and 5 of the paper the discussers have realized a difficulty that also perplexed this author briefly; namely, why did the salt stay in the sand? The

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