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MOVEMENT OF AIR THROUGH WATER IN PARTLY
SATURATED SOILS

BY

P. J. WILLIAMS

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Movement of Air through Water in Partly Saturated Soils

WHEN the water content of a soil is reduced below saturation, the interfaces between air and water lie within pores, and are curved because of surface tension, σ . The pressure of the water P_w is lower than that of the surrounding air P_a by

$$P_a - P_w = \frac{2\sigma}{r_s} \quad (1)$$

where r_s is the radius of the interfaces. As the water content is reduced, drainage occurs from progressively smaller openings, and the interface radius decreases. The pressure of the water also falls, in accordance with equation 1, producing the well known "suction-moisture content" relationship.

In many situations of geotechnical and agricultural interest the soil is partly saturated. In a sample of the soil the interfaces between the external air and the pore water are curved but localized near the surface. In addition, there are usually bubbles of air within the soil, totally entrapped by water-filled pores. They may be spherical, or sufficiently large to occupy a number of interconnected pores. If the water pressure is uniform, then such a bubble can only have the same pressure as the external air if its interface (or interfaces) with the water also has the radius r_s . These interfaces usually have some other radius, and accordingly the air pressure within the bubbles is not usually the same as that of the atmosphere. Because the solubility of air in water depends on the air pressure (Henry's law), it follows that there will often be a gradient in the concentration of dissolved air in the water.

When the interface (or interfaces) of a bubble is of greater radius than that at the surface of the soil sample, the gradient will occur from the vicinity of the sample surface towards the vicinity of the bubble. The existence of a concentration gradient results in a diffusion of air in solution towards the region of lower concentration. When the saturation concentration is exceeded, however, air will come out of solution. An entrapped bubble can thus be enlarged. The process will be a continuing one. As the radius of the bubble increases, the air pressure within it falls further so that the saturation concentration in its vicinity is further reduced. Its growth may eventually be stopped by its extension into small pores, where the interfaces will again have a small radius.

This process of air movement by diffusion through water can, of course, also occur in the opposite direction and cause entrapped air to decrease in extent or to disappear. This will be the case when the interfaces of the entrapped air have the smaller radius.

The process is relevant to studies of infiltration and of drying of soil horizons near the soil surface, to the interpretation of laboratory suction-moisture content tests, and to geotechnical considerations of the mechanics of partly saturated soils. Few articles in the wide literature in these fields, however, give even scant attention to the significance of air movement in this way.

A simple experiment has been devised to observe the process. A soil ranging from fine silt to medium silt was prepared by crushing chiolite ($\text{NaF} \cdot \text{AlF}_3$). This naturally occurring mineral has a refractive index close to that of water (in which it is practically insoluble), and when the pores of the soil are filled with water small samples are quite transparent. Air within the pores is fully visible. Such a sample was placed in a specially constructed pressure membrane apparatus, consisting basically of a small 'Perspex' cell, part of which could be placed under a microscope. The sample was placed in the cell, above a drainage opening covered by a membrane filter. The air pressure in the cell could be raised, and drainage of water from the sample to the outside could occur through the membrane. Air leakage does not occur because of the smallness of the pores of the membrane which remain totally filled with water at the air pressures in question.

After the air pressure is raised, drainage occurs from the sample but soon appears to stop. The pressure of the water in the pores is then uniformly atmospheric, because the water phase is in continuous connexion with water in the drainage tube under the external (room) pressure. The interfaces between the air and the water are then curved with a radius which depends on the pressure applied to the air. These interfaces, depending on the pore size, will to some extent lie within the "soil". The air pressure can be selected with regard to the pore size, such that the air only extends into a few larger pores near the sample surface. In one such test, an air pressure of 0.22 kg/cm^2 was applied.

Fig. 1a shows entrapped air bubbles, situated 3-4 mm within an otherwise saturated part of the sample. The photograph was taken about 20 min after the air pressure in the cell was raised. As the water pressure had by this time again become uniformly atmospheric, volume changes of the bubbles due to temporary changes of water pressure were completed. Subsequently the bubbles enlarged slowly and 26 h later had the forms shown in Fig. 1b. By this time enlargement had slowed down, and it is apparent that the interfaces (now lying within pores

Fig. 1. Three bubbles entrapped in a partly saturated soil sample. *a*, Shortly after the establishment of an external air-water pressure difference, $P_a - P_w = 0.22 \text{ kg/cm}^2$; *b*, the same bubbles 26 h later.

surrounding the cavities in which the bubbles originally occurred) again are of a size (given by equation 1) comparable with that of the interfaces to the external air.

In the present example the geometry is complicated and allows only a rough estimate of the rate at which the bubbles should grow. The observed rates are compatible with this estimate. The experimental observations reported here are also sufficient to leave little doubt as to the cause of the well known and problematical entry of air into devices for measuring pore water pressure which are used in field measurements in partly saturated soils. Even though such devices are isolated from soil air by filters with fine pores totally filled with water, air occurs within the device after a period of time and prevents its correct operation. It moves by diffusion from the small and restricted bubbles in the soil pores, to the larger bubble which can grow in the chamber of the pressure measuring device.

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