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Water exclusion from tunnel cavities in the saturated capillary fringe

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Abstract

The problem of water flow around a tunnel cavity located in the saturated capillary fringe on top of a very permeable, freely draining substratum is considered for the critical non-leakage condition when there is uniform vertical downward flow through the upper surface of the saturated region. In this critical condition the soil–water pressure is equal to zero everywhere on the cavity wall that is also a streamline. The conditions at the upper fringe boundary are that the soil–water pressure is equal to the air-entry value of the soil and the flux through this surface is the uniform infiltration rate. The cavity surface and the fringe boundary which is elevated above the cavity position, are found through conformal mapping and the use of integral representations of non-standard mixed boundary-value problems. They are calculated for a range of infiltration rates and compared with those obtained by assuming the upper fringe boundary to be horizontal. The exact analysis given here gives larger tunnel cavities than those given by the approximate treatment of the problem. The results have application in the design of underground repositories against entry of seepage water, the construction of protective capillary barriers and in the design of interceptor drainage systems.

Keywords: Tunnel cavity; Water exclusion; Capillary fringe; Conformal mapping; Mixed boundary value problems

1. Introduction

The analysis of water flow around cavities in unsaturated soils shows the effect on soil–water behaviour resulting from man-made excavations. It also facilitates the understanding of the role of macropores in unsaturated flow. Philip et al. [14] initiated analytical studies of the perturbation of vertical unsaturated soil–water flow due to the presence of cavities, using the so-called quasi-linear model that assumes an exponential dependence of hydraulic conductivity on soil–water pressure, in an investigation of the flow around circular cylindrical cavities. These were developed further in a series of papers [8,11–13,15] concerned with the soil–water behaviour in the presence of two- and three-dimensional cavities of various shapes.

Water will flow into a cavity when the soil–water pressure at any point on its wall becomes greater than atmospheric. Philip's analysis elucidated conditions under which an air-filled cavity (that has the same effect when not leaking water as an impermeable stone) excludes descending seepage water (the subcritical regime) or admits water (the supercritical regime). In the critical regime some part of the cavity boundary is just less than atmospheric pressure so that any further increase leads to water seeping into the cavity. There is a critical cavity shape where the soil–water pressure everywhere on the cavity wall is atmospheric and the cavity wall is also a streamline. For an infinite flow field and a soil having an exponential hydraulic conductivity function as assumed in Philip's analysis, the cavity shape is parabolic-cylindrical for two dimensional tunnel cavities and paraboloidal for three-dimensional cavities [15]. The analysis has been further developed by Kacimov and coworkers [1,5].

A different physical situation occurs when cavities are located in a saturated capillary fringe above a water table when there is infiltration from the unsaturated soil above, seeping downwards to a water table. Youngs [21] calculated the critical shape of tunnel cavities for water exclusion in this situation. His analysis notes that the hydraulic conductivity in this tension-saturated region is the same as that of the saturated soil under positive

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