Simulation of Climatic and Vegetation Effects on Pavements on Expansive Clays

M. PICORNELL AND MOHD ASRI B. ABD RAHIM

The flow of moisture through a continuum cannot explain the very wet conditions present under pavements in semiarid and arid climates. A possible major cause is the presence of shrinkage cracks. In this manner, the water infiltrates through the cracks where it is slowly absorbed on the crack walls. This water is, then, effectively trapped within the soil mass because the prevailing suction gradients are not large enough or do not act for sufficiently long times to remove significant amounts of moisture. A simplified model to simulate the infiltration of rainfall through the crack fabric and the removal of soil moisture by soil evaporation and plant transpiration along the sides of a pavement is described. The moisture movement through the crack fabric is simulated as an open channel flow. The moisture transfer from the cracks to the soil on the crack walls is assumed to be one-dimensional absorption. The results of simulations for several climatic regions of Texas are presented. For all these regions, the model predicts steady closing of the crack fabric under the pavement. The time to closing ranges from less than 1 year for the climatic conditions of Houston to more than 8 years for the climatic conditions of El Paso. In contrast, the shrinkage cracks under the edge of the pavement and within the soil adjacent to the pavement close during wet periods and then reopen again during extended dry periods. For the wetter climates, the cracks are generally closed and only open during periods of consistent dry weather. For the drier climates, the cracks remain open at all times.

Pavements build on expansive soils are known to develop roughness not associated with traffic. This type of pavement roughness has been attributed to the presence of shrinkage cracks in the subgrade soils (*1*). Rainfall can penetrate very fast through the crack fabric. The water, impelled by gravity and under positive pressures, goes where the crack directs it. The water in the cracks has little exposure to the atmosphere, which allows ponding time for the water to seep into the soil matrix on the crack walls. This seepage causes concentrated surface heaving along the trace of the crack and consequently the development of roughness.

Pavement roughness reduces the serviceability index significantly and thus requires periodic maintenance, such as releveling and overlays, to restore riding quality. The Texas State Department of Highways and Public Transportation has been trying for some time to reduce the expenses associated with this periodic maintenance by installing vertical moisture barriers. Field test sections have been implemented in San Antonio, Texas, on IH-37 (*2*) and along IH-30 in Greenville, Texas (*3*). Additional test sections have been recently established and are being monitored.

M. Picornell, Civil Engineering Department, University of Texas at El Paso, El Paso, Tex. 79968. M. A. B. Abd Rahim, Univeristi Sains Malaysia, Minden, 11800 Panang, Malaysia.

The purpose of the moisture barrier is to isolate the subgrade soils from seasonal climate changes. In the first trials (*2*), the moisture barrier was placed to a depth of 8 ft, on the basis of moisture content monitoring data for the region. Later on, it was recognized (*4*) that one of the main functions to be performed by a vertical moisture barrier is to prevent rainwater from accessing the crack fabric within the subgrade soils. This need led to choosing the depth of the barrier on the basis of the expected maximum possible depth of shrinkage cracks at the site.

Field monitoring data obtained on several test sections indicated that the role of the vertical moisture barrier can be different at different sites. In the test sections of IH-37 in San Antonio, Texas, suction measurements on both sides of the barrier indicated (*5*) that the soils enclosed by the barrier remained at a nearly constant suction during more than 2 years. Meanwhile, the soils outside the barrier were experiencing significant suction changes. Field measurements also indicated lack of roughness development in the test sections, whereas in the adjacent control section roughness was developing at a steady rate. In this case, the moisture barrier had protected the soils under the pavement of the moisture changes observed in the soils on the side of the pavement. In contrast, pavement roughness measurements at the trial sections on IH-30 have indicated (*3*) that the test sections experienced higher rates of roughness development than adjacent control sections. At this site, the barrier actually retained moisture inside rather than keeping it outside.

These results suggest that the barrier can play different roles depending on site-related conditions. Among the most influential factors are the climate, pavement surface conditions, initial moisture conditions of the subgrade soils, and moisture barrier depth. Furthermore, the site location, such as on a hill, on a slope, or in a cut, will also affect the role played by a moisture barrier.

These considerations illustrate the need of a physically based model that would account for the movement of moisture through the shrinkage cracks, and the seepage of this moisture into the soil matrix, together with realistic models for the replenishment and removal of moisture from the subgrade soils.

REVIEW OF EXISTING LITERATURE

Infiltration into expansive soil deposits has long been considered to be affected by the presence of shrinkage cracks. There is ample evidence (*6,7*) in the literature that rainfall percolates through cracks and then slowly seeps into soil peds. As the soil matrix gains moisture, it swells and progressively closes the cracks.

The presence of shrinkage cracks in expansive soil deposits is apparent. In very dry soils, profuse surface cracks form on the ground surface. Cracks with openings on the ground surface up to about 1 in. and several feet deep (*8*) have been reported. Furthermore, the crack patterns and frequency have been observed (*8,9*) to depend on the vegetative cover. The crack opening decreases from a maximum at the soil surface to zero at the crack tip. The variation of the crack opening with depth has been described with curves of linear shrinkage versus depth (*9*). Morphological studies (*10*) have revealed the presence of approximately rectangular blocks of soil formed by aggregation of soil peds. These studies also revealed that infiltration of rainwater into the crack fabric is determined by the soil surface microrelief. The water is directed towards the cracks through surface depressions. Then the water runs down the crack faces, wetting only a small fraction of the exposed crack surface. This effect causes the bulk of rainwater that is penetrating the cracks to move directly to the tip of the cracks.

The presence of cracks in aquifer-bearing formations results in two distinctive flows taking place: one through the cracks and the other through the porous medium between cracks. The water inside the cracks is more mobile than the water within the matrix of the porous medium. Traditionally, the modeling of this type of flow has been approached with Barenblatt's (*11*) double porosity concept. However, this approach is not appropriate in the present application under unsaturated conditions. An additional complication is the fact that cracks in expansive soil deposits close as the soil matrix gains moisture; thus the porosities do not remain constant.

The first known attempt to include the effect of shrinkage cracks on infiltration was by Richards (*12*). In this work, the subsoil was divided into blocks and two permeability coefficients were used, one along the cracks and the other through the soil matrix. This model did not account for changes caused by the swelling and shrinkage of the soil.

The moisture accumulated inside the crack fabric and in the soil blocks can be depleted as a result of evaporation at the soil surface and plant transpiration. Soil evaporation has been proved to be an ineffective mechanism of moisture removal from the soil by a number of investigators (*13–15*). The consensus is that even a small amount of soil evaporation forms a dry soil crust at the soil surface that prevents further evaporation from taking place. Existing field monitoring data (*15*) suggest that soil evaporation might affect only the soil within the upper foot of the soil deposit.

Plant transpiration, by way of contrast, is a much more effective mechanism of moisture removal from the soil. The native vegetation, such as roadside grasses, removes water from the soil through the root system. Nevertheless, when the soil suction reaches the wilting point of the vegetation, all transpiration ceases. Because of the extremely small permeabilities of expansive soils, the removal of water by the root system is confined to the rooting depth of the vegetation (*16*).

These considerations suggest that a model that could approximate field behavior would have to consider the following:

1. The infiltration of rainfall into an expansive soil deposit takes place primarily through the crack fabric,
2. The soil mass is divided into approximately parallelepipedic blocks by the crack fabric,
3. The moisture transfers from the cracks to the soil blocks,
4. The gain in moisture causes swelling of the soil blocks and thus modifies the crack fabric, and
5. The removal of water from the soil mass is primarily determined by the transpiration of the native vegetative cover.

MAIN FEATURES OF THE MODEL

The model considers a fixed length of highway. The subgrade soils are considered divided into parallelepipedic blocks. The model formulates several water balances within this section, when subjected to a sequence of climatic conditions.

The rainfall on the pavement is subdivided into infiltration through the pavement and runoff to the side drainage ditch. The model adds the rainfall infiltration to the volumes of water stored in the cracks. For this purpose, the model keeps track of two total volumes of water stored in the crack fabric of the subgrade soils: one for the soils under the pavement and inside the barrier, and the other for the soils outside the vertical moisture barrier.

The water stored in the crack fabric is lost to seepage into the soil blocks, to transfers of water under the barrier, or to transpiration through the root systems of roadside vegetation. The water balances for the soils on both sides of the barrier are formulated on a daily basis, except during rainfall events when the water balances are formulated every minute.

Every time that the water balance is formulated, the volume of water transferred to the soil blocks is used to reconsider the block sizes and, thus, the geometry of the crack fabric.

Climatic Conditions

The regional climatic conditions are summarized in two daily parameters: rainfall depth and potential evapotranspiration. On days with rainfall larger than trace, a third parameter is needed: rainfall duration. The daily time series with these parameters can be actual weather data or based on stochastic simulation for the regional climatic conditions. A more thorough description of the weather data and analysis needed has been provided by Abd Rahim and Picornell (*17*).

Rainfall Depth Assignment

The rainfall depth on the pavement surface is subdivided into two parts. The first part corresponds to the infiltration through cracks and fissures of the pavement. The second part is the remaining rainfall depth that is assigned to runoff to the side drainage ditch.

The infiltration through the pavement is added to the water stored in the crack fabric beneath the pavement. If the crack fabric within the subgrade fills with water, the remaining rainfall depth is assigned to runoff to the side drainage ditch.

The infiltration into the soil outside the barrier is the result of direct rainfall in the area plus the runoff coming from the pavement surface. The runoff from the pavement surface is multiplied by a factor selected by the user, to account for runoff coming from higher areas of the pavement and drainage ditch.

The infiltration into soils adjacent to the pavement is assumed to replenish the water within the crack fabric. The maximum depth of water that the model allows to pond within the drainage ditch can be arbitrarily selected. If the water level within the crack fabric accumulates to this limit, the rest of the potential infiltration is lost.

The combined possibilities offered by the depth of water ponding within the drainage ditch and the multiplying factor of the runoff from the pavement cover all possible cases of drainage conditions.

Cross Section Definition

Input for the model includes the characteristics of the pavement surface, the moisture barrier, and the crack fabric within the subgrade soils. The model only contemplates one-half of the pavement surface split along the centerline of the highway. A typical cross section is shown in Figure 1.

The surface of the paved subgrade is considered to be horizontal. The program starts by fitting a series of soil blocks of specified dimensions from the subgrade surface down to the actual crack depth for the three soil regions labeled *Uncovered*, *Pavement*, and *Edge* in Figure 1. All the distances and slopes labeled in this figure can be arbitrarily specified. The thickness of the base and subbase, the depth and width of the vertical moisture barrier, and the rooting depth of the roadside vegetation can also be specified. On the basis of the relative depth of the barrier and the rooting depth of the roadside vegetation, the cross section is subdivided into the three zones: *Pavement*, *Edge*, and *Uncovered* indicated in Figure 1. The zone *Edge* consists of the soils enclosed within the barrier near the edge of the pavement. The width of the *Edge* zone is selected to be equal to the distance from the bottom of the barrier to the bottom of the root zone of the roadside vegetation. The model then considers that the roadside vegetation can develop roots within this zone, and thus, evapotranspiration can remove soil water from the cracks and from the soil blocks within this soil region.

SHRINKAGE CRACK FABRIC

The geometry of the crack fabric is specified by a list of block sizes with depth. Morphological observations (*10*) in dry clayey soils indicate that the soil mass is divided into parallelepipedic blocks of increasing sizes with depth. Figure 2 shows some of the block sizes typical for several soil conditions.

The model can accept a user supplied sequence of blocks from the subgrade surface to the crack depth. The model uses this sequence to divide the subgrade soils into blocks. Then the model shrinks these blocks on the basis of the initial moisture conditions specified. During the simulation, the model keeps track of the position of the centroid and the sizes of each block. On the basis of the positions of all blocks and their sizes, the crack volume available for storage of rainfall can be calculated.

Initial Subsurface Conditions

The properties of each soil block in the size list can be specified. Thus, it is possible to define as many soil layers as block sizes are included in the set of soil blocks. The input needed

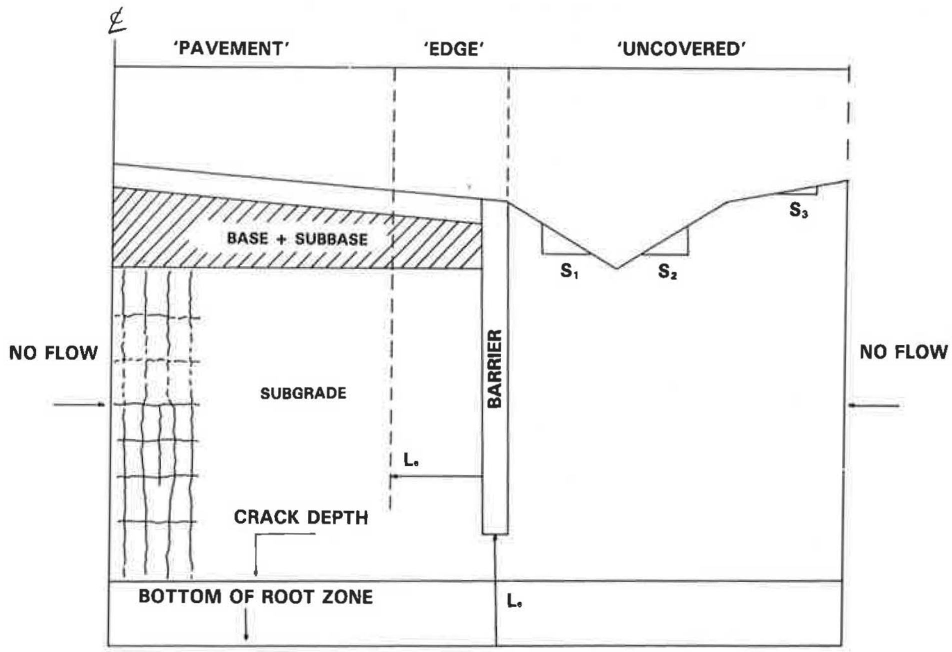


FIGURE 1 Main features of highway cross section.

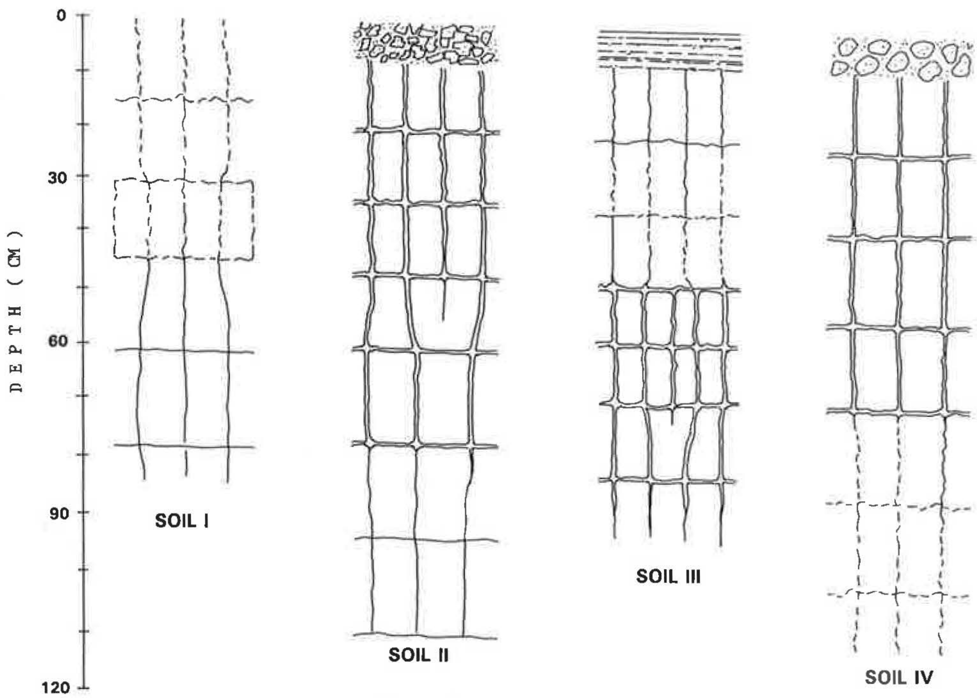


FIGURE 2 Soil block sizes for several different soils.

includes the initial state of the subsurface soils and the flow properties of each soil type specified. The initial state of the subsoil can be described by the shrinkage and suction profiles with depth.

Holmes (*18*) has shown that clayey soils remained essentially saturated to very high suctions, such as 100 bars. For the subgrade soils, the soil suctions of interest range from a field capacity of 0.3 bar to the wilting point of the vegetation around 15 bars. Thus it is reasonable to assume that the volume change of a soil block is identical to the volume of moisture gained or lost by the soil block. This volume of water is controlled by the specific moisture capacity, that is, the slope of the moisture characteristic curve of the soil.

The flow properties of the soil matrix can be specified independently for each block. In this sense, the specific moisture capacity and the permeability for each soil type have to be specified for a range of suction from 0 to over 15 bars.

Development of Block Curves

The rate of moisture transfer from the cracks to the soil blocks is approximated with a master block curve developed for each block size and soil type. This curve is derived by modeling a one-dimensional unsaturated water flow within the soil block. The soil inside the block is assumed to be at a constant suction initially. The water flow is assumed to take place along the smallest side of the block. The full master curve is developed in two steps: a wetting and a drying phase.

In the wetting phase, the soil block is subjected to a zero suction at the two exposed faces. For every time step, the volume of water flowing into the block is calculated for both exposed faces. The volume of water absorbed by the block is assumed to be equal to the volume heaved by the block; thus allowing to calculate the variation of the block's volume with time.

In the drying phase, the block at the same initial suction is exposed to a soil suction of 15 bars at both exposed faces. The volume of moisture extracted from the block at each time step is calculated using the same one-dimensional water flow. Again, the volume change of the block is assumed to be equal to the volume of water lost through both exposed faces. The simulation proceeds until the flow (intake or release) at the two exposed surfaces is smaller than 0.01 cm^3/day.

The results of the two phases are incorporated into a single master curve for each block. Examples of master curves for several block sizes are shown in Figure 3. These curves are used during the simulation to determine the rate of moisture transfer from the crack fabric to the blocks and the change in sizes of the soil blocks on gaining or releasing soil water.

Pavement Surface Conditions

Rainfall infiltration through the pavement surface is estimated with the same procedure outlined by Liu and Lytton (*19*). This procedure allows two alternative ways to estimate the infiltration rate through the pavement surface depending on the information available. When there is no information about the type of pavement or the length of cracks and joints on the pavement surface, the infiltration is estimated on the basis of the worst of several published cases (*20*). If the pavement surface conditions are known, then the infiltration through the pavement surface is determined on the basis of the pavement type and length of cracks and joints as proposed by Ridgeway (*21*).

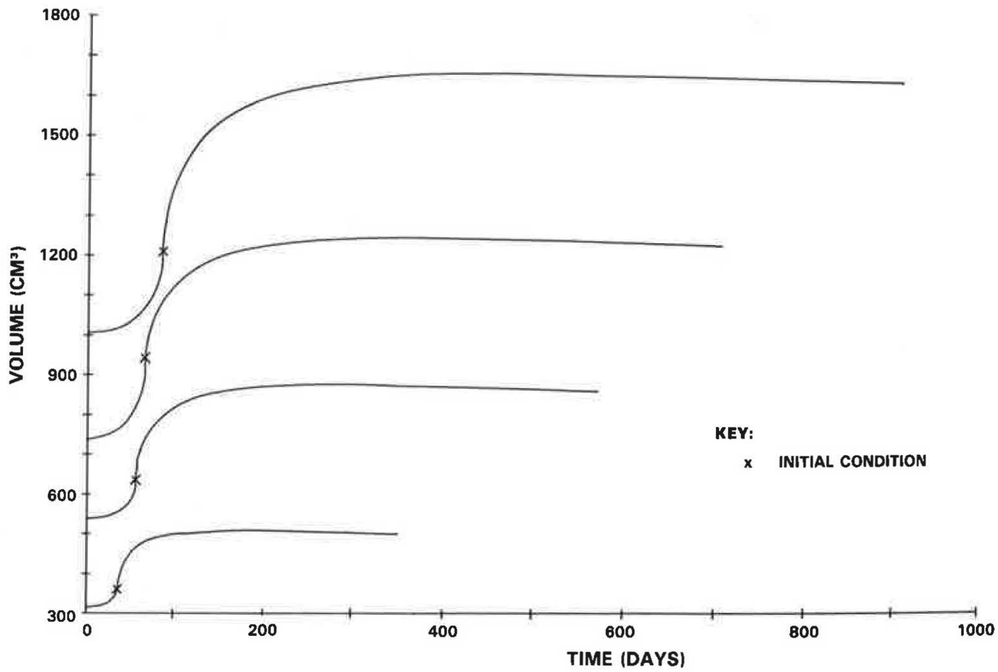


FIGURE 3 Examples of master block curves for several block sizes.

Roadside Vegetation

The native vegetation growing along the roadside provides the most effective mechanism for removing moisture from the subsurface soil within the rooting depth of the vegetation. The amount of water removed by the plants is determined by the environmental demand imposed on the plants, the potential evapotranspiration, and to some degree the exposure of the plants to the environment. This exposure is measured by the leaf area index (LAI). This index measures the leaf surface area exposed per unit of ground surface area.

The taller the vegetation, the larger is the LAI. Mowing roadside grasses is a common practice. The result of mowing is a large sudden decrease of the LAI, which reduces exposure of the vegetation to the environment and, thus, reduces the water removal from the soil mass. Any desired sequence of LAI for a 365-day year can be used by the model to assess the actual evapotranspiration.

Moisture Removal Assignment

The actual removal of water from the subgrade soils is determined by the potential evapotranspiration and the storage of moisture in the soil profile. The actual evapotranspiration is estimated using a simplified procedure (*22*) verified for the climatic conditions of central Texas. The difference between the water depth stored in each block from field capacity to the wilting point is taken as the total storage possible in the block. The sum of the storage for all the blocks in the block sequence is the maximum storage for the soil profile.

The potential evapotranspiration is subdivided into potential soil evaporation and plant transpiration on the basis of the LAI. The effect of the stage of drying is then evaluated independently for the two components. Soil evaporation is evaluated from the matrix properties of the soil as summarized in a diffusion parameter. Plant transpiration passes through several stages, but in all cases the actual plant transpiration is estimated on the basis of the LAI and monthly averages of actual evapotranspiration. After the two components have been evaluated, they are added together to determine the actual evapotranspiration.

After the actual evapotranspiration is known, it has to be determined from where the water has to be removed. The first choice is whether the water has to be removed from the cracks or from inside the soil blocks. A second choice has to be considered: whether the water should come from the soil mass adjacent to the pavement or from the soil mass under the pavement. The evaporation from the soil surface can take place only at the *Uncovered* soil surface outside the pavement area. However, plant transpiration removes water from the soil inside the rooting depth of the vegetation. Thus, if the vegetation can spread roots under the pavement, plant transpiration can be supplied by soil water stored in the soils under the pavement.

For this purpose, the soil mass has been subdivided into the three regions shown in Figure 1. The soil region *Pavement* is not accessible to the roots of the roadside vegetation, implying that the moisture in these soil blocks cannot be removed. In this sense, the soil blocks in this region can only swell, but there is no mechanism to permit shrinkage or removal of moisture from these blocks. In contrast, the moisture in the crack fabric can flow from the *Pavement* to the *Edge* and to the *Uncovered* soil region in response to differences in water levels. The soil region *Edge* is assumed to be accessible to the root system of the roadside side vegetation, and thus, soil water can be removed from this region. The *Uncovered* soil region is the most exposed, and soil water can be removed from this region by the two mechanisms soil evaporation and plant transpiration.

In summary, the actual evapotranspiration is removed from the soil in the *Edge* and *Uncovered* regions. Therefore, the soil blocks in these two regions can experience swelling and shrinking, implying that the cracks could close during wet periods and open again during consistently dry periods. This process contrasts with that of the cracks in the *Pavement* region that are only allowed to close.

The rooting depth of the roadside vegetation has a large influence because the shrinking under the edge will open cracks allowing rainfall water to bypass the barrier, if the barrier did not extend to the rooting depth of the roadside vegetation. Most commonly, the roadside vegetation is grass. There is a wealth of information (*16*) indicating that grasses have maximum rooting depths of 8 to 9 ft. However, when shrubs or trees grow in the vicinity of the pavement, much larger rooting depths should be expected.

The actual evapotranspiration depth is taken from the water stored in the cracks. When the cracks do not hold enough water to satisfy all the actual evapotranspiration, the remaining is taken from the soil blocks in the *Edge* and *Uncovered* regions. The water stored in the crack fabric of the *Uncovered* region is the first source of water, followed by the *Edge* region. When the water in the crack fabric has been depleted, the actual evapotranspiration is taken from the soil blocks. The moisture from the blocks is removed from the soil block that is under the wettest conditions. The decision of which block is the wettest is based on the relative positions of the blocks along the master block curves.

Block Absorption and Desorption

The model keeps track of three sets of blocks; one on each of the three soil regions: *Pavement*, *Edge*, and *Uncovered*. For each block, and at every time step, the coordinates of the center of the block, the width, length, and height of the block, and the total volume of each block are recorded.

The total volume of the soil block at any time indicates the position of the soil block along the master block curve. This position also determines the rate of volume increase for any period of time that the soil block is submerged. This increase is obtained from the master block curve, increasing the time step desired and finding the corresponding new volume of the block.

The rate of desorption of the soil blocks subject to water removal by the root system of the vegetation is determined by the actual evapotranspiration. The water removal will cause the blocks to slide down along the master block curve. On rewetting, the block will start from a lower position along the master block curve.

Crack Fabric Reconsideration

The crack fabric depth is evaluated and tracked for each of the three soil regions: *Pavement*, *Edge*, and *Uncovered*. The program keeps track of one set of soil blocks for each region. Each set consists of the number of soil blocks of different sizes at increasing depths specified by the user. The changes occurring in this set of blocks times the number of soil blocks fitted within the corresponding region are used to calculate crack opening changes within the region.

The soil within the second and third soil regions are subject to drying by the root system of the vegetation. Thus the crack depth in these zones is subjected to closing during wet spells and crack opening during dry spells. The program keeps track of one set of blocks for each region and assumes that the rest of the blocks within each region behave identically to the set of blocks tracked. Thus the changes recorded for the set of blocks times the number of blocks fitted inside the region are used to calculate crack openings within the regions.

Water Transfer Underneath the Barrier

The program considers one water level on each side of the barrier. The transfer of water from one side to the other is assumed to take place through the shrinkage cracks in the soil underneath the vertical moisture barrier. If these cracks close, all transfer of water between the two sides is stopped.

The water transfer when the cracks are opened is impelled by the difference in elevation between water levels. The flow of water through the cracks is estimated using Manning's formula. The hydraulic radius is calculated at every time step taking into account the wetted perimeter of all shrinkage cracks included in the highway section being analyzed.

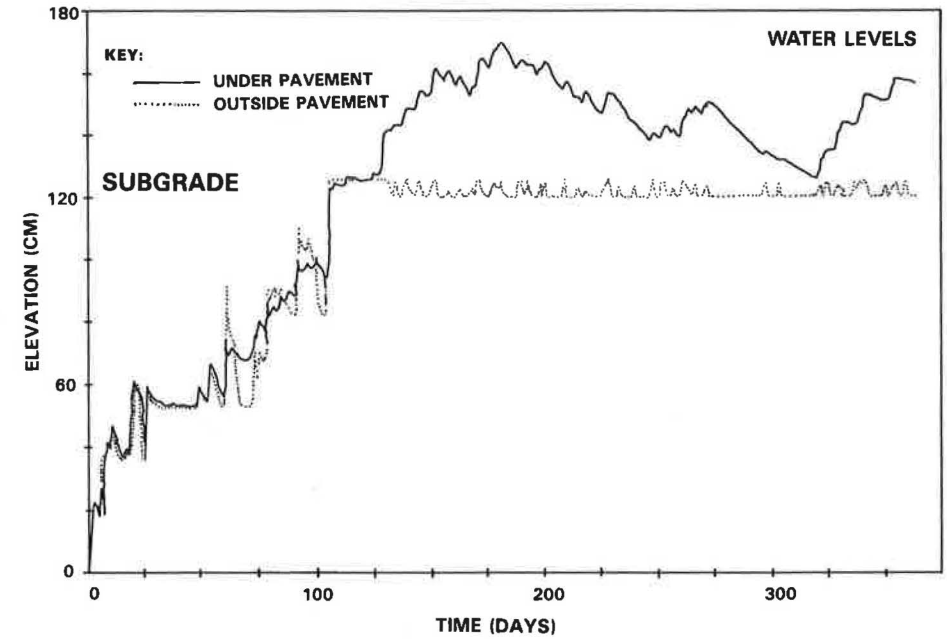
RESULTS OF TRIAL RUNS AND DISCUSSION

The model has been used in several trial runs to illustrate the effects of the more relevant parameters on the infiltration of rainfall into the subgrade soils. The first few runs were intended to illustrate the effect of the climatic conditions. Stochastically generated weather data for Houston, San Antonio, Dallas-Fort Worth, and El Paso, Texas, were used for these runs. Several extra runs were performed for the climatic conditions of San Antonio for different moisture barriers to illustrate the effect that the barrier has on the wetting process of the subgrade soils. Thorough documentation of all the results of these runs has been provided by Abd Rahim and Picornell (*17*).

Effects of Climate

The first set of runs was performed for the same subsurface soil and pavement conditions. Specifically, the crack fabric was assumed opened to 1.20 m below the subgrade surface and the moisture barrier extended 0.70 m below the subgrade surface. The initial subgrade moisture conditions, the block sequence, and the flow properties of the soil used have been provided by Abd Rahim and Picornell (*17*). The period of simulation was 5 years for the climatic conditions of Houston, Dallas-Fort Worth, and San Antonio; for El Paso the simulation extended over 10 years. The results of the simulation at each site are summarized in annual plots of water levels within the crack fabric and elevations of the crack tips in the *Pavement*, *Edge*, and *Uncovered* soil regions.

The plots obtained from the first year of the simulation for Houston, Texas, are shown in Figure 4. The crack tip at the beginning of the simulation has been used as the reference point for the elevations shown in all figures. Figure 4 shows



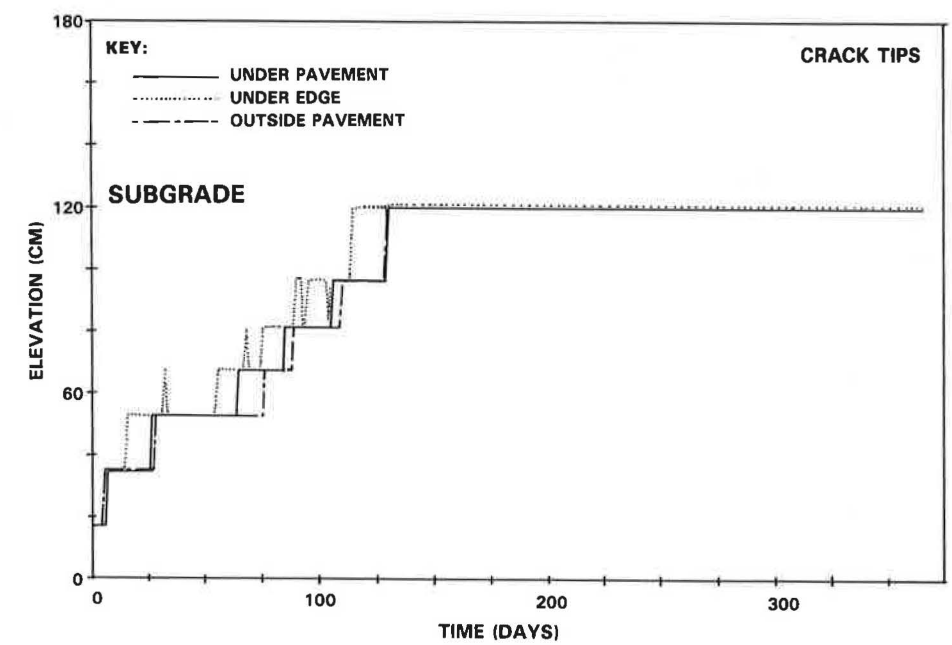


FIGURE 4 Results of simulation for first year in Houston, Texas.

that the water levels in the crack fabric fill the cracks on both sides of the barrier in about 4 months. Thereafter, the cracks remain full during the rest of the simulation, with the exception of a few short summer periods. The cracks under the moisture barrier close in a month and never open again. In the three soil zones, all the cracks close to the subgrade surface in about 4 months. Thereafter, the cracks open annually for periods of 1 to 2 months, and then close again for the rest of the year.

The results of the simulation for San Antonio, Texas, exhibit similar patterns. The plots for the first and second years of the simulation are presented in Figures 5 and 6. The water levels in the crack fabric exhibit a general increasing trend with occasional fluctuations during the first 2 years. In general, the water level in the *Uncovered* region lags behind the water level within the *Pavement* region. The crack tip elevations indicate that about 2 months after the beginning of the simulation the cracks under the barrier close, and about 18 months from the beginning, the cracks in the *Pavement* region have closed to the subgrade surface. During the first 2 years, all crack tips exhibit a general increasing elevation trend with the cracks in the region *Uncovered* lagging somewhat. After the first 2 years, the cracks in the *Edge* and *Uncovered* regions have closed and only open occasionally during the summer months.

The results of the simulations for Dallas-Fort Worth are similar to the results for San Antonio. The water level in the *Pavement* soil region reach the top of the subgrade in less the period of the simulation. The results of these simulations indicate that when the pavement is cra ked or fissured, a large fraction of the rainfall infiltrates through the pavement and into the subgrade. The result is that the subgrade soils in the *Pavement* region can swell faster than the soils in the *Uncovered* region. These results could explain the observed behavior (*3*) in IH-30 that exhibited faster roughness development in the sections with moisture barrier than in control sections.

SUMMARY AND CONCLUSIONS

A computer program has been assembled to simulate the movement of water under a pavement on a cracked swelling soil subgrade. Specifically, it was desired that the program could account for the infiltration of rainfall through cracks and joints on the pavement surface and the horizontal water flow through the shrinkage crack fabric.

The basic assumption has been that the crack fabric displays a simple geometric configuration of superimposed parallelepipeds. The water is assumed to flow through the cracks under positive pressure, and then is slowly absorbed by the soil blocks. As the water is absorbed, the blocks swell and the geometry of the crack fabric changes. The water absorbed by the blocks is assumed to be immobilized unless the road side vegetation has established roots within the blocks.

Trial runs for some climatic conditions of Texas exhibit a wide range of possible behavior; under the wetter conditions of Houston the cracks close in a matter of a few months, while for the drier conditions of El Paso the cracks remain open during the 10 years of simulation.

These results have shown that the shrinkage crack fabric under the pavement steadily closes even under the dry conditions of the El Paso climate. The wetter the climate, the faster the cracks close; from a minimum of 4 months in Houston to a maximum of 7 years in El Paso.

Trial runs performed with several moisture barrier depths have indicated hat if the pavement surface has cracks and joints that allow water infiltration, the moisture barrier can cause faster swelling under the pavement than the surrounding soils.

REFERENCES

1. M. O. Velasco and R. L. Lytton. Pavement Roughness on Expansive Clays. *Research Report 284-2*. Texas Transportation Institute, Texas A&M University, College Station, 1981.
2. M. L. Steinberg. Deep Vertical Fabric Moisture Seals. *Proc., 4th International Conference on Expansive Soils* (D. Snethen, ed.), ASCE, New York, 1980.
3. D. A. Gay and R. L. Lytton. Moisture Barrier Effects on Pavement Roughness. In *Measured Performance of Shallow Foundations*, Geotechnical Special Publication 15, ASCE, New York, 1988.
4. M. Picornell. The Development of Design Criteria to Select the Depth of a Vertical Moisture Barrier. Dissertation. Texas A&M University, College Station, 1985.
5. M. Picornell, R. L. Lytton, and M. L. Steinberg. Matrix Suction Instrumentation of a Vertical Moisture Barrier. In *Transportation Research Record 945*, TRB, National Research Council, Washington, D.C., 1983.
6. D. E. Kissel, J. T. Ritchie, and E. Burnett. Chloride Movement in Undisturbed Swelling Clay Soil. *Proc., Soil Science Society of America*, Vol. 37, 1973, pp. 21–24.
7. G. Blake, E. Schlichting, and U. Zimmermann. Water Recharge in a Soil with Shrinkage Cracks. *Proc., Soil Science Society of America*, Vol. 37, 1973, pp. 669–672.
8. J. R. Johnston and H. O. Hill. A Study of the Shrinking and Swelling Properties of Rendzina Soils. *Proc., Soil Science Society of America*, Vol. 9, pp. 24–29.
9. A. Z. El Abedine and G. H. Robinson. A Study on Cracking in Some Vertisols of the Sudan. *Geoderma*, Vol. 5, 1971, pp. 229–241.
10. J. Bouma and L. W. Dekker. A Case Study on Infiltration Into Dry Clay Soil. I. Morphological Observations. *Geoderma*, Vol. 20, 1978, pp. 27–40.
11. G. I. Barenblatt, Y. P. Zheltov, and I. N. Kochina. Basic Concepts in the Theory of Seepage of Homogeneous Liquids in Fissured Rocks. *Prikladnaya Matematika i Mekhanika*, Vol. 24, 1960, pp. 1286–1303.
12. B. G. Richards. A Mathematical Model for Moisture Flow in Horsham Clay. *Civil Engineering Transactions, Institution of Engineers*, Australia, Vol. CE10, No. 2, 1968, pp. 220–224.
13. J. T. Ritchie and J. E. Adams. 1974. Field Measurements of Evaporation from Soil Shrinkage Cracks. *Proc., Soil Science Society of America*, Vol. 38, pp. 131–134.
14. A. A. B. Williams and J. T. Pidgeon. Evapo-Transpiration and Heaving Clays in South Africa. *Geotechnique*, Vol. 23, No. 2, 1983, pp. 141–150.
15. B. J. Richards. Moisture Flow and Equilibria in Unsaturated Soils for Shallow Foundations. ASTM STP 417. *Permeability and Capillarity of Soils*, 1967, pp. 4–34.
16. M. Picornell and R. L. Lytton. Behavior and Design of Vertical Moisture Barriers. In *Transportation Research Record 1137*, TRB, National Research Council, Washington, D.C., 1987, pp. 71–82.
17. M. A. B. Abd Rahim and M. Picornell. Moisture Movement Under the Pavement Structure. Research Report 1165-1. Center for Geotechnical and Highway Materials Research, University of Texas at El Paso, 1989.
18. J. W. Holmes. Water Sorption and Swelling of Clay Blocks. *Journal of Soil Science*, Vol 6, No. 2, 1955, pp. 200–208.
19. S. J. Liu and R. L. Lytton. Environmental Effects on Pavements—Drainage Manual. Report FHWA/RD-84/116. Texas Transportation Institute, Texas A&M University, College Station, 1985.
20. B. J. Dempsey and Q. L. Robnett. Influence of Precipitation, Joints, and Sealing on Pavements Drainage. In *Transportation Research Record, 705*, TRB, National Research Council, Washington, D.C., 1979, pp. 13–23.
21. H. H. Ridgeway. Infiltration of Water Through the Pavement Surface. Transportation Research Record 616, TRB, National Research Council, Washington, D.C., 1976, pp. 98–100.
22. C. W. Richardson and J. T. Ritchie. Soil Water Balance for Small Watersheds. *Transactions of the American Society of Agricultural Engineers*, 1973, pp. 72–77.

Publication of this paper sponsored by Committee on Environmental Factors Except Frost.