Numerical solution of rainfall infiltration beneath flexible pavement

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Abstract: Water in pavement systems can lead to moisture damage and loss of strength. This study considered the simulation of water effect on the pavement and presented as perception, two rain intensities were selected (50, 80) mm/min at duration of 120 and 60 minutes, respectively. The methodology of the study consisted of three stages, first is to collect information and extracting cores second stage was testing the cores in the laboratory and the third stage was simulating the pavement using the 2-D finite element (SEEP/W 2007). The permeability of five sections was chosen at various ranges. The shape of the slopes (one way, two way) was considered, also the position of the water table at (0.5, 2, and 3) meter below the surface. Two types of cracks were taken: one sever crack that penetrates the wearing layer and the same crack penetrates the asphaltic layer. The results obtained indicted that the pavement is sensitive to the asphalt permeability, the infiltrated water inside the pavement increase by 27% when the permeability increased by 55% and water flux increased 70% when the permeability increased by 95%. Rain duration has more effect rather than its intensity.

1. Introduction

Sustained long period of water staying within a pavement system is undesirable because the free water can not only adversely affect the load carrying capacity of the pavement but also causes premature pavement failures. According to [1], accumulated water in the pavement structure can cause one or more of the following forms of deterioration: reduction in soil shear strength, pumping action in rigid pavements, migration of fines into drainable base layers, frost heave and thaw, differential swelling in expansive soils, stripping of asphalt in flexible pavement, and cracking in rigid pavement.

This water induced premature pavement failures can cause serious safety hazards to traffic as well as undermine the serviceability of the pavement [2], [3].

Unsaturated flow in pavement section is a complex problem since the moisture flow is driven in part by suction gradients, which can result in upward or lateral flow in some cases. Therefore, a finite element method like SEEP/W program can be used as a powerful analysis tool. SEEP/W is a 2-Dimensional, finite element modeling software package for simulating pore-water movement and pore pressure distribution within porous materials, such as soil and rock. SEEP/W simulations can incorporate both saturated and unsaturated seepage processes with material properties specific to the different layers comprising a pavement section [4].
2. Geometry of numerical modeling

For numerical modeling, SEEP/W software of Geostudio 2007 subset is used that has the ability to solve differential equations governing the problem for saturated and unsaturated materials. Studying and analyzing the vertical drainage and surface drainage behavior in the flexible pavement using a finite element module simulation is the aim of this study.

The case study model has a cross section of 10 m and 1m of soil on both sides of the pavement and the embankment soil extend to 3 m below the pavement to represent real conditions more accurately, these dimensions were based on the real data dimensions which were taken from the five pavements as it is mentioned in table (1). Five layers are assumed in the model: wearing 4 cm, binder 8 cm, base 10 cm, subbase 20 cm and compacted subgrade 20 cm. The mesh consists of 690 elements and 745 nodes. Two types of slopes generated in SEEP/W are: cambered slope and one-way slope. The geometry of the case study in shown in figure (1 to 4)

| Section number | Cross section width (m) | Asphalt layer thickness (cm) | Base layer thickness (cm) | Subbase thickness (cm) | Subgrade thickness (cm) | Slope 2% | Section description |
|----------------|-------------------------|----------------------------|--------------------------|-----------------------|------------------------|---------|---------------------|
| 1              | 15.5                    | Wearing=4                  | 18                       | 40                    | 40                     | One way slope | Express way         |
|                |                         | Binder=8                   |                          |                       |                        |         | Collector road way  |
| 2              | 8.25                    | Wearing=5                  | 10                       | 15                    | 20                     | One way slope |                      |
| 3              | 10                      | Wearing=4                  | 15                       | 20                    | 20                     | Two way slope | Local road way      |
|                |                         | Binder=8                   |                          |                       |                        |          |                    |
| 4              | 9                       | Wearing=4                  | 10                       | 20                    | 20                     | Two way slope | Collector road way  |
|                |                         | Binder=8                   |                          |                       |                        |          |                    |
| 5              | 7                       | Wearing=4                  | 10                       | 15                    | 20                     | Two way slope | Arterial road way   |

Table 1. The geometry description of the five sections
Figure 1. Case study model cambered

Figure 2. Case study model one way slope

Figure 3. Case study layer configuration
3. Material characteristics
SEEP/W material requirements to set a function are; the hydraulic conductivity and the volumetric water content for the asphalt layer. To get the required information, cores from different pavements were extracted and laboratory test was conducted; Permeability test (GeoSpec2 apparatus, the principle of analyzing the core is NMR (Nuclear Magnetic Resonance) NMR information gained for core reflects electrical signal distribution created by hydrogen protons found in the fluids that saturate the material in the core. Mobility of the hydrogen proton depends on nature of the pores, distribution of the pores and moving of the fluid inside the pores. The cores are first measured in the GeoSpec2 in their dry state and then soaked in water with vacuum sealer for three days so that it saturated 100% and then measured again in the GeoSpec2 device. The computer that is connected to the apparatus will give the result. The permeability and porosity values of the materials used in the case study analysis are summarized in table (2). The properties for the other layers (base, sub-base and subgrade) were collected from other sources, table (3) sums up these properties.

| Table 2. Material properties for the asphaltic layers from the permeability test (input parameters) |
|---|
| Section Number | Permeability (m/sec) | Porosity (%) |
| 1 | Wearing | 3.6E-009 | 0.0635 |
|  | Binder | 1.5E-008 | 0.0425 |
|  | Wearing | 9.453E-009 | 0.03589 |
| 2 | Binder | 1.7336E-008 | 0.054 |
|  | Wearing | 3.974E-010 | 0.0265 |
| 3 | Binder | 2.3856E-008 | 0.0698 |
|  | overlay | 1.536E-010 | 0.0228 |
| 4 | Wearing | 5.1456E-010 | 0.0284 |
|  | Binder | 7.152E-010 | 0.0356 |
| 5 | Wearing | 4.665E-010 | 0.0311 |
|  | Binder | 2.2666E-009 | 0.0337 |
Table 3. Input data for granular pavement layer.

| Layer      | Permeability (m/sec) | Source                                  |
|------------|----------------------|-----------------------------------------|
| Base       | 3.06e-006            | [5]                                     |
| Sub-base   | 1.98e-007            | [5]                                     |
| Subgrade   | 5.67e-011            | [5]                                     |
| Embankment | 6.78e-008            | Tested by the National Center for Construction Laboratories |

4. Boundary conditions

Boundary conditions have a significant influence in predicting the response of the model. Unite flux (q) boundary condition was used to simulate the rain effect on the pavement surface and head boundary (H) condition was used to simulate the water table effect. Two rain intensities were used 50 mm/min with rain duration of 120 minute and 80 mm/min with rain duration of 60 minute. In addition, water table was set at three positions 0.5, 2 and 3 meters under pavement. Boundary conditions used for this study are illustrated in figure (5).

![Figure 5. Boundary conditions rain and water table.](image)

5. Seepage analysis

Saturated/unsaturated analysis has been used in simulating the model. To generate a model in SEEP/W finite element program, the define view window appears; first step is to define model scale and geometry. The geometry step is very important in choosing right geometry and the scale can make a big difference in the result. The next step would be setting the material properties and choosing the appropriate function then the proper boundary condition is set at the model geometry. After finishing these essential steps, the model is read; clicking on the verify/optimize button to check for any warning for missing item then clicking on the analyze button and switching to the result view. The analysis is set at the beginning as a steady state and then, generating a transient state analysis the later would be the child of the parent analysis which is the steady state. The steady state analysis is used to study the effect of asphalt permeability with rain present on the pavement and the slope shape change.
(cambered and one way slope) and change on the pavement. The transient is study used to show the effect of rain intensity with duration and the effect of the distresses on the pavement surface and the change in the water table position under the pavement.

6. Steady state results
Steady state analysis is used to investigate the effect of the asphalt layer permeability and the slope shape change.

6.1 The Effect of the Surface Permeability
To inspect the effect of the material permeability on pavement drainage, a series of analyses were conducted for the pavement surfaces. Figure (6) shows that the effect of permeability is proportional to the water flux entering the pavement. When the permeability is increased, the amount of water flux increases and vice versa even though the pavement permeability is relatively small but still has an effect and small changes can make a difference as the water can enter the pavement even when the pavement in good condition. This means that the pavement is sensitive to the asphalt layer permeability. Figure (7) explains the distance from left.

![Figure 6. Effect of permeability on the flux of the pavement](image1)

![Figure 7. Explain the distance from the left of the pavement](image2)

6.2 The Effect of the Pavement Slope
Drainage of the road pavement is provided by shaping the road carriageway with a camber or cross slope
For this study, two slopes shaped 2% were generated to observe the effect of the slope shape on the total flux on the pavement surface. The analysis showed that when the slope shape differs, a slight change in the amount of water flux will happen and therefore the slope shape has a little impact on the drainage. The cambered slope gave better result since the amount of flux water was more than the side slope. The results of the analysis are presented in figure (8).

![Figure 8. Water flux with distance.](image)

7. Transient study
Two rain events have been applied to the pavement surface as a case study. Two scenarios were considered in this study: pavement with no distresses and pavement with cracks.

7.1 Rain Intensity and Duration
One of the features in the SEEP/W and transient flow is that it can provide the user with the amount of water that accumulated and water flux with time on the pavement surface. The rain intensity selection was on considering the recent five years change in climate; weather forecaster recorded a highest rain intensity which was 120 mm in some Iraqi regions. For the rain intensity and period analysis, the following were observed:

- The cumulative water flux on the pavement surface for the rain intensity of 50mm/min was more than that for 80mm/min rain intensity.
- When time was increased, the amount of the water that accumulated on the pavement also increased.
- The rain duration has more impact on the pavement than its quantity. This could be attributed to the fact that surface runoff is more likely to occur when the excess rain water accumulates on the surface of the pavement during a short period of time. It can be concluded that the longer the rain lasts, the longer it will affect the outflow pattern [7].
- The amount of the accumulated water increased by 50.1% in the rain intensity of 50mm/min rather than that for rain intensity of 80mm/min
- The rain intensity effect of 50mm/min and 80 mm/min on cumulative water flux is illustrated in figure (9).
Figure 9. The effect of rain intensity on the cumulative water flux.

7.2 Distress Effect
Distress takes so many forms, for this study, the crack was simulated by replacing one or more columns (depending on the size of the cracking) of elements with a material with much higher water permeability, a conductivity of 2,500 ft/day was used for the cracks [7]. Two types of cracks were simulated, the first was sever crack (10 mm) that extended to the wearing layer, second was the same crack at the full depth of the asphalt layer. The following results were observed:

- When the rain duration increased, the amount of cumulated water increased due to the presence of the crack.
  This indicates that the crack creates pathway for the water to enter the pavement, which causes more water to accumulate on the surface and more water flux inside the pavement.
- When the crack appears, peak flow will occur; while in the normal situation the water will mainly enter by seeping through the pavement layer and the soil.

The distress effect on water flow is illustrated in figures (10 to 12).

Figure 10a. Effect of distress on the water flux at rain intensity of 50mm/min.
Figure 10b. Effect of distress on the water flux at rain intensity of 80mm/min.

Figure 11a. Water flux vs. distance at section with no crack and with crack penetrating the wearing layer.

Figure 11b. Water flux vs. distance at section with no crack and with crack penetrating the asphalt layer.
From the previous figures, when the rain intensity was low, the water flux will be low and as a result, there is more water to accumulate on the pavement while in the high rain intensity, the water flux value was high and the accumulated water will be less than the low rain intensity. This could be attributed to the fact that surface runoff is more likely to occur when the excess rain water accumulates on the surface of the pavement during a short period of time. The distress effect was significant at the area of the crack and more water was accumulated on that specific area but as overall flow, the difference was not very significant.

### 7.3 Water Table Effect

Water table is set at three different locations to mark its impact on the water flowing. The water table set at 0.5 m beneath the subgrade, at 2m below the subgrade and finally at 3m. The aquifer that has the water table is highly variable across the area; it ranges between (0.4-5.1) meters below N.G.L [8].

The following results were observed:

- When water table becomes near the subgrade, the water flux decreases.
- The water flux changed with water table; the water table position has an effect on the water flux, the effect of water table is illustrated in figure (13).

![Figure 12. Water flux differences between the rain intensity of 50 mm/min.](image1)

![Figure 13. Water table effect on the water flux](image2)
From the previous figures, the water flux is increased when the water table becomes far from the surface due to the fact that when the soil is not saturated or partially saturated the pore water increases and that would attract more water to enter the soil. On the other hand, when the soil is saturated and that happens when the water table is near to the surface, the pore water pressure will decrease which means less water enters from perception and more water enters the pavement from the water table.

8. Conclusion
Based on the results obtained from this study, the following conclusions were made:

1. Pavement structure is very sensitive to the asphalt layer permeability as the amount of flux on the surface increased by 27% when the permeability was increased by 55% and water flux increased by 70% when the permeability was increased by 95%

2. Water flux on the surface increased by 28% when the slope shape was two ways (cambered) rather than that for the side slope (one way) which indicated that the two-way slope is more effective for water removal.

3. From the transient study, the amount of cumulative water flux increased with the increase in rain duration indicating that the rain duration is more important than its intensity; when the rain intensity is 50mm/min with a duration of 120 minute the cumulative water flux is 50% more than that for the rain intensity 80mm/min and rain duration of 60 minutes.

4. The water flux increased by 15% with the rain intensity of 80mm/min more than that for the rain intensity of 50mm/min. When the rain intensity is high with short duration the surface runoff will properly occur; therefore the amount of water accumulated on the surface when the rain intensity is 80mm with 60 minutes duration is lower than that for the rain intensity of 50mm/min with 120 minutes.

5. When the distress (cracks) occurred on the pavement surface, the amount of cumulative water increased by 1% when one crack penetrates the wearing layer only and by 18% when the crack penetrates the whole asphalt layer wearing and binder. This indicates that the amount of cumulative water increased when the crack penetrates deeper in the pavement layer.

6. This research revealed that with water table getting far from the pavement surface the water flux increased by 42% at water table of 2m below the surface and by 70% when water table is 3m below the surface. The water flux increases with water table increase in depth and vice versa. This is due to the fact that the pore water pressure increases with depth and the area above the water table is not saturated and therefore, it would attract more water to enter the pavement.

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