A REALISTIC MODEL FOR DRAINAGE OF WATER THROUGH A JOINTED CONCRETE PAVEMENT

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INTRODUCTION

In history engineers recognized that pavement performance could be improved by providing subdrainage for pavement sections. Every text book on pavement design could be counted to contain a statement related to Cedergren's Statement "there are just three things necessary for good roads, and they are drainage, drainage and more drainage". The basic concept of designing a subdrainage system is to limit the extent and duration of excess moisture in the pavement subgrade and structural section.

The design of a subdrainage section has two stages. In the first stage the rainfall occurs, subsequent flow through the pavement is usually assumed to be in a steady state condition (i.e. inflow=outflow). In the second stage, the rainfall is assumed to have ceased and an unsteady state of flow exists until the pavement is fully drained. In designing a subdrainage system, the first step is to estimate the net inflow into the subdrainage layer, then the drainage layer thickness and permeability are "sized" to accommodate the flow through. The second step is to evaluate the time to drain and therefore the efficiency of the drainage system.

There are two approaches widely used in estimating the net inflow to pavements. Cedergren (*1*) utilizes a design precipitation rate based on a 1 hour/1 year frequency multiplied by factors of 0.3 to 0.5 for bituminous pavements and 0.5 to 0.67 for concrete pavements. This approach is largely empirical and results in overestimation of the inflow rate. Moreover, it places emphasis on rainfall intensity rather than the duration. Moulton (*2*) addressed rainfall as well as other sources of moisture in determining the net flow for which to design pavement subdrainage systems. Rainfall components of infiltration includes crack as well as general surface infiltration. Moulton also suggested that rainfall duration instead of intensity is more critical. He recommends a crack infiltration rate of 0.015 $cm^3/sec/cm$ (2.4 $ft^3/day/ft$). Moulton admitted that the infiltration rate was empirical and at the time there were no realistic estimates of the surface infiltration rate.

This paper presents subdrainage analysis of a jointed concrete pavement using a finite element method (FEM) of analysis. The analysis is performed on an instrumented section of US 36 in Hendricks County, Indiana. The section was instrumented as part of a study performed by Ahmed et al. (*3*). Data collected included rainfall and outflow as well as other data.

TEST SECTION

The instrumented section was on the West bound driving lane of US-36 in Hendricks County, Indiana. A rain gauge was located on the right-of-way adjacent to the instrumented section. Flow from the outlet pipe was measured with a tipping bucket device. Data was collected from the test section using a battery powered data collection system. Details of the instrumentation and data collection system are given by Ahmed et al. (*3*). The instruments were retrofitted in the in service pavement.

The pavement section consisted of a 21.6 cm jointed plain concrete pavement with bituminous shoulders and with a bituminous stabilized subbase. The joints were unsealed. Figure 1 shows a cross section of the pavement. Pavement transverse and longitudinal slopes were 1.3 and 0.6 percent, respectively. Distance to the next upstream outlet pipe was 242 m.

GOVERNING EQUATIONS FOR MATHEMATICAL MODELING

Two flow conditions could exist in this kind of analysis, steady or unsteady (transient) flow. Transient flow is the general case in which the water head at every point in the analysis area (domain) is changing with time. Darcy's law and the equation of continuity are the two governing equations for the flow. Darcy's law is as follows:

$$Q = -K A \frac{dh}{dl} \qquad (1)$$

In general (three dimensions), the equation becomes:

$$q_i = K_{ij} \frac{\partial h}{\partial x_i} \qquad (2)$$

Where,

Q = flow rate, cm^3/sec,
K = hydraulic conductivity, cm/sec,
A = cross section perpendicular to the flow, cm^2,
dh/dl = water head gradient,
i = free index that takes a number of 1, 2, or 3 (x, y, or z),
j = dummy index that takes a number of 1, 2 or 3 (x, y or z),
q_i = flow rate in the i direction,
K_{ij} = hydraulic conductivity tensor,
$\partial h/\partial x_j$ = gradient vector.

The continuity equation states that for a saturated condition, the sum of the flow rate change in all directions must equal to zero:

$$\frac{\partial q_i}{\partial x_i} = 0 \qquad (3)$$

Where,

i = dummy index,
q_i = flow rate,
x_i = direction.

Hassan and White (*4*) explain in more detail the mathematical equations and the finite element formulation for a pavement subdrainage analysis.

MATERIAL PROPERTIES

Two essential material properties are required for the subdrainage analysis. These are the moisture-suction relation and the permeability-moisture content relation. Laboratory tests were performed on the #53 bituminous base, #5 bituminous base, and the # 7 trench material to establish their moisture suction relations. Table 3 shows the gradation of these materials. Saturated hydraulic conductivity was also obtained from laboratory testing (*3*). Table 1 lists the hydraulic properties for the materials in the test section.

ANALYSIS APPROACH

Hassan and White (*4*) conducted a similar study for flexible pavement subdrainage systems. Those pavement sections were newly constructed and instrumented for the study. Also, the longitudinal grades of the test sections were approximately zero. These test sections were analyzed as a two dimensional problem which simplified and reduced the time of analysis.

The concrete section in the current analysis has a 0.6 percent longitudinal grade. The first approach was to use a three dimensional analysis to account for infiltration into both transverse and longitudinal joints. Although the analysis would be realistic, analysis time would be significant. Another approach was to conduct a two dimensional analysis of a transverse pavement section which would only include the longitudinal centerline and edge-shoulder joints. This approach would ignore the transverse joint contribution to infiltration. For a zero longitudinal grade, infiltration through the transverse joint would not be significant. However, with a longitudinal grade significant transverse joint infiltration is possible. To address the problem, a decision was made to conduct a two-dimensional analysis making a coordinate transformation. In making the coordinate transformation, the analysis cross section would be taken in the direction of the major resultant flow path direction, shown as x' - z' plane in Figure 2. As a result, there are two zones of analysis, sections 1 and 2 in Figure 2. Section 1 has a uniform length of 197 cm. In section 2, the position of the transverse joint would vary and depend on the longitudinal position of the section. For simplification, one section was analyzed with the transverse joint equidistant from the longitudinal and edge-shoulder joints. A unit length was assumed in the y direction in both sections. The predicted outflow curve from the FEM analysis was multiplied by the section width (y direction). A total flow curve is obtained by simply adding the outflow curves of the two sections. The difference or time shift of flow between different points along the edge drain is neglected. This time is usually small (less than ½ an hour) when compared to the duration of drainage.

FINITE ELEMENT MODELING

The area of the pavement modeled is shown in Figure 1. This model consists of the 3.65 m driving lane and 76.2 cm of the shoulder which extends to the outside edge of the collector trench. Finite element meshes for the two sections are shown in Figures 3 and 4. These figures show the section with two and three joints, respectively. The subgrade was classified as CL by the Unified Soil Classification System (USCS). Its permeability was determined to be 1.1 E-05 cm/sec (*3*). From previous research conducted by Hassan and White (*4*), the water content in the subgrade when close to a high permeability layer does not change significantly for short periods of analysis such as the period of a rainfall event. Therefore, the subgrade was eliminated from the analysis and an impervious boundary was imposed at the bottom of the base layer.

The ABAQUS General Finite Element (*5*) software was used for the analysis. Element size is an important factor in the solution convergence process. ABAQUS guidelines for the initial time increment versus the element size is as follows:

$$\Delta t > \frac{\gamma\, n}{6k\, K_s} \frac{ds}{du} (\Delta l)^2 \qquad (4)$$

Where,

Δt =initial time step,
γ = unit weight of water,
n = porosity,
k = saturated permeability,
k_s = permeability -saturation function (0 to 1),
ds/du = rate of change of saturation with respect to pore pressure,
Δl = typical element dimension.

When the solution does not converge, the element size has to be reduced. Experience from the previous analysis of flexible pavement drainage sections was used to adopt the element sizes and numbers shown in Figures 3 and 4.

ANALYSIS

Rainfall Modeling

Factors contributing to the performance of pavement subdrainage systems include intensity and duration of rainfall, pavement surface moisture condition and moisture condition of all the underlying layers. The number of factors and their interaction makes simulation of a rainfall and pavement drainage difficult. Two techniques were considered to represent rainfall events. The first was to apply a constant flow boundary on the surface of the pavement for the period of the rainfall. The second was to assume a constant head at the pavement surface for the period of the rainfall. The first approach is less realistic as it controls the amount of water infiltrating the pavement. In fact, the actual amount of rainfall that infiltrates the pavement is constantly changing with the rainfall as well as moisture conditions of the pavement layers. In the latter, more realistic approach, moisture infiltration depends directly on the changing moisture conditions in the pavement system.

Two rainfall events are analyzed in this paper. Constant head was assumed by assigning the pore pressure at the surface a value of zero for certain periods during the rainfall event. Previous analysis experience by Hassan and White (*4*) has shown that controlling the rainfall by the "on and off" method appears to be reasonable. Depending on the pavement surface permeability, which is generally low (1E-04 to 1E-05 cm/sec), surface water from a high intensity rainfall will overrun the pavement surface to the side of the road. On the other hand, an extended rainfall (usually with low intensity) will supply the pavement continuously with water. This approach also agrees with the results reported by Moulton (*2*) who showed that duration is more important than intensity. Table 2 shows the actual rainfall intensity and the corresponding simulation for both rainfall events.

Analysis

Rainfall event one is a relatively simple event, as shown in Figure 5, and was used to calibrate the model. After calibration, the model was utilized to analyze the second rainfall event, shown in Figure 6. The calibration starts with an assumption as to the infiltration capacity of the joint, as well as the outlet pipe capacity. For the joint infiltration, an initial infiltration rate of 0.026 cm^3/sec/cm (2.4 ft^3/day/ft length of the crack) was used, as suggested by Moulton (*2*). Joint width was assumed to be 0.635 cm (1/4"), resulting in an assigned joint element permeability of 0.04 cm/sec (unit dimension was assumed in the y direction). It is to be noted that the joint width is one recommended for pavement design purposes.

The outlet pipe was simulated by adding a small element at the bottom of the trench with a cross section of 0.5 cm^2/cm length of the pipe. Permeability of the element was taken as 0.4 E-03 cm/sec (*4*).

Rainfall Event One Rainfall event one and the associated subdrainage outflow are shown in Figure 5. In comparing the measured and predicted outflow, three parameters were considered for goodness of fit; peak flow, drainage duration, and total volume drained. The duration of outflow is considered to be from the beginning of the flow curve until the flow becomes asymptotic. The cutoff rainfall intensity was taken to be 0.2 cm/hr (*4*). As noted, the single event nature of this rainfall was useful in calibrating the model. Several trial analyses were made with different values of joint permeability (K_j) and outlet permeability (K_o) (pipe inlet capacity). Figure 7 shows the outflow curve with K_j= 0.011 cm/sec and K_o=0.38 E-03 cm/sec. The measured and predicted drainage durations were 19 and 21 hours, respectively. The ratio of the predicted to the measured outflow volume was 1.05. The measured and predicted peak flow were 1231.2 and 1311.4 lit/hr, respectively.

Rainfall Event Two Rainfall event two was more complex than event one in the sense that it included varying rain over a period of time. Figure 6 shows the measured rainfall and outflow volumes. The K_j and K_o values obtained from model calibration for rainfall event one were used in the analysis of rainfall event two. Figure 8 shows the outflow curve obtained from the analysis. The measured and predicted drainage duration were 30 and 32 hours, respectively. The ratio of the predicted to measured outflow volumes was 1.1. The measured and predicted peak flow were 723.9 and 1010.6 lit/hr, respectively.

For this complex rainfall event, the calibrated parameters did not give as good a fit as for event one. Another attempt to obtain a better fit of the curve was made by slightly changing the slope of the moisture suction curve for the trench backfill material. The slope was changed by reducing the upper most value of the suction curve from -75 to -50, as illustrated in Figure 9. The effect of changing the slope is shown in Figure 10. The drainage time is reduced to 30 hours, predicted peak flow was 695.4 lit/hr and the total volume remained unchanged. The curve provides a better fit for the field results. Changing the slope of the moisture-suction curve was considered reasonable. There is variability in the laboratory moisture-suction test. Also, there is variability of pavement materials.

CONCLUSIONS AND RECOMMENDATIONS

Experience with this type of analysis has shown that the infiltration capacity is directly related to outflow volume of water. The joint infiltration capacity appears to agree with measured field results at a value of 0.0066 cm^3/sec/cm (0.61 ft^3/day/ft) length of the crack. The infiltration rate is 3.9 times less than the assumed infiltration capacity suggested by Moulton. This is even though the joint was not sealed or may have been sealed but was in poor condition. Both the outlet pipe capacity and infiltration control both occurrence of the peak and duration of the outflow.

The two dimensional analysis utilized appears to be reasonable. Time of analysis is greatly reduced from that of a three dimensional analysis. More analysis is strongly recommended with available field data to further verify the model and collect more data on a reasonable infiltration capacity with different joint seal conditions.

The moisture suction laboratory test is not a sensitive test, a small change in the suction value will dramatically affect the numerical analysis. The reason is that most of the drainage layers are open graded materials and therefore do not attain very high suction values. It is recommended that when conducting such a test more emphasis should be directed to the low suction zone of the suction curve (less than 1 bar).

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Table 1 Hydraulic Properties of the Materials

Material	Suction, bars[a]								Permeability, cm/sec
	0	0.05	0.33	0.6	1	3	5	15	
#53 Bit. Base	1.0	--	0.93	--	0.88	0.87	0.83	0.82	0.02
#5 Bit. Base	1.0	--	.97	0.94	.91	.84	.82	.80	1.1E-05
#7 Trench Backfill	1.0	0.3	--	--	--	--	--	--	0.07

[a] degree of saturation corresponding to suction values.

Table 2 Rainfall Simulation

Time	Rainfall Event 1		Rainfall Event 2	
	Actual (cm)	Simulation	Actual (cm)	Simulation
1	0.0254	I	0.03	I
2	0.0254	I	0.45	0
3	0.1524	I	0	I
4	0.1524	0[a]	0.01	I
5	0.0508	I	0	I
6	0.2286	0	0	I
7	0	I	0	I
8	0.025	I	0	I

I = Impervious.
0 = zero pore pressure on the surface of the pavement
[a] = was considered because of the preceding hour intensity

Table 3 Gradation of Materials

Sieve Size (mm)	#53 Bit. Base	#5 Bit. Base[a]	# 7 Trench Backfill[a]
37.5	100	100	
25	90	85-100	100
19	80	60-90	45-95
12.5	68	30-65	40-70
9.5		15-50	20-50
No.4	48	0-20	0-15
No.8	38	0-15	0-10
No.16	--	--	--
No.30	21	--	--
No.50	--	--	--

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Figure 9 Moisture-Suction Relation for # 7 Trench Backfill Material

Figure 10 Analysis of Rainfall Event 2

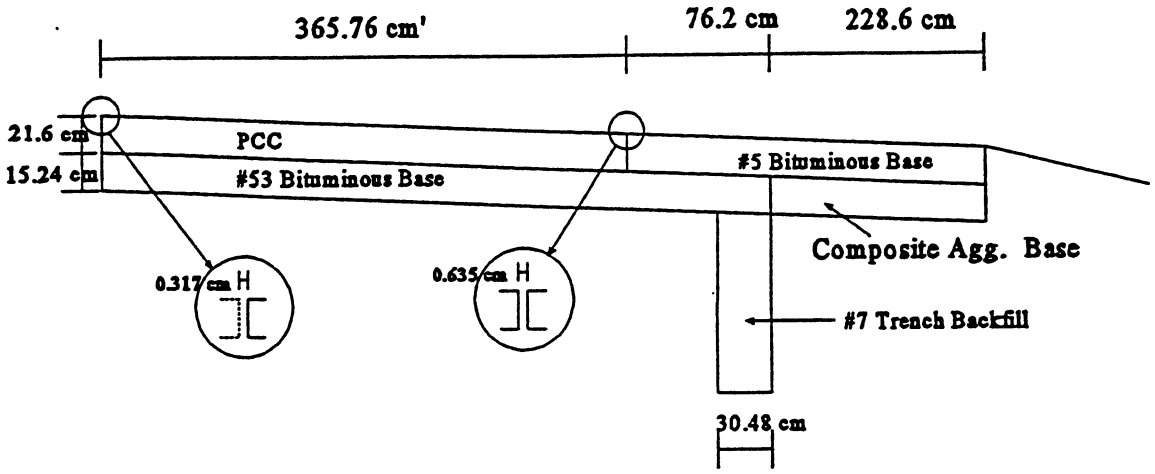


Figure 1 Cross Section of the Pavement

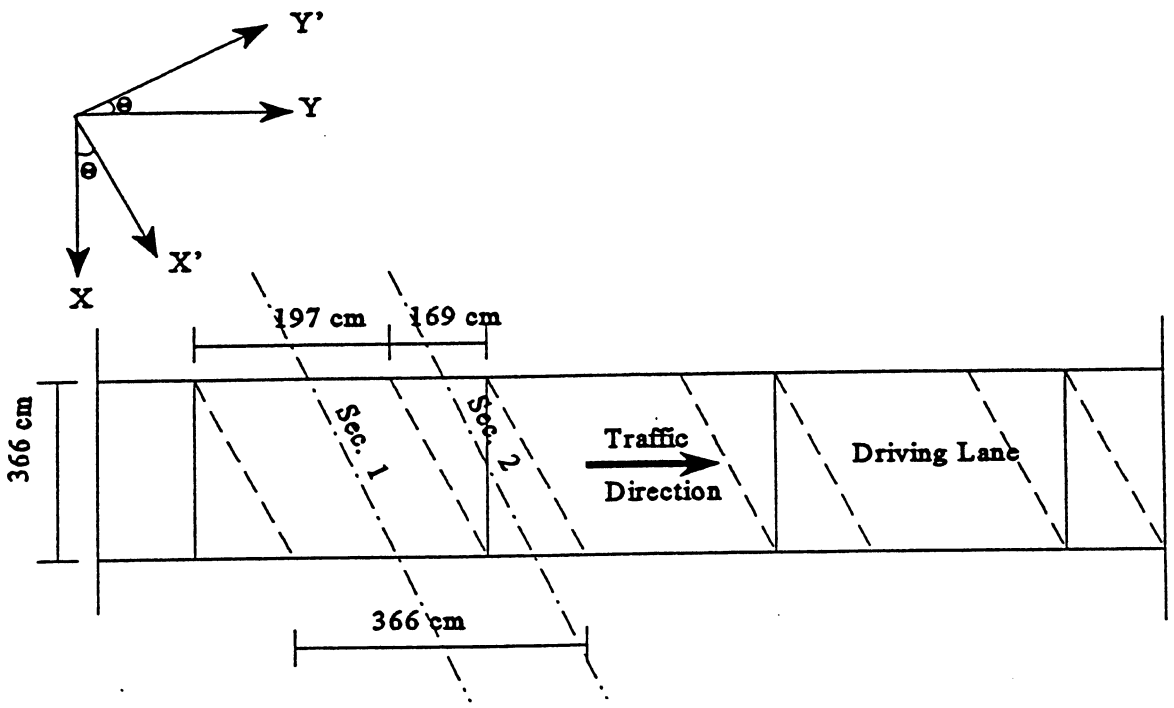
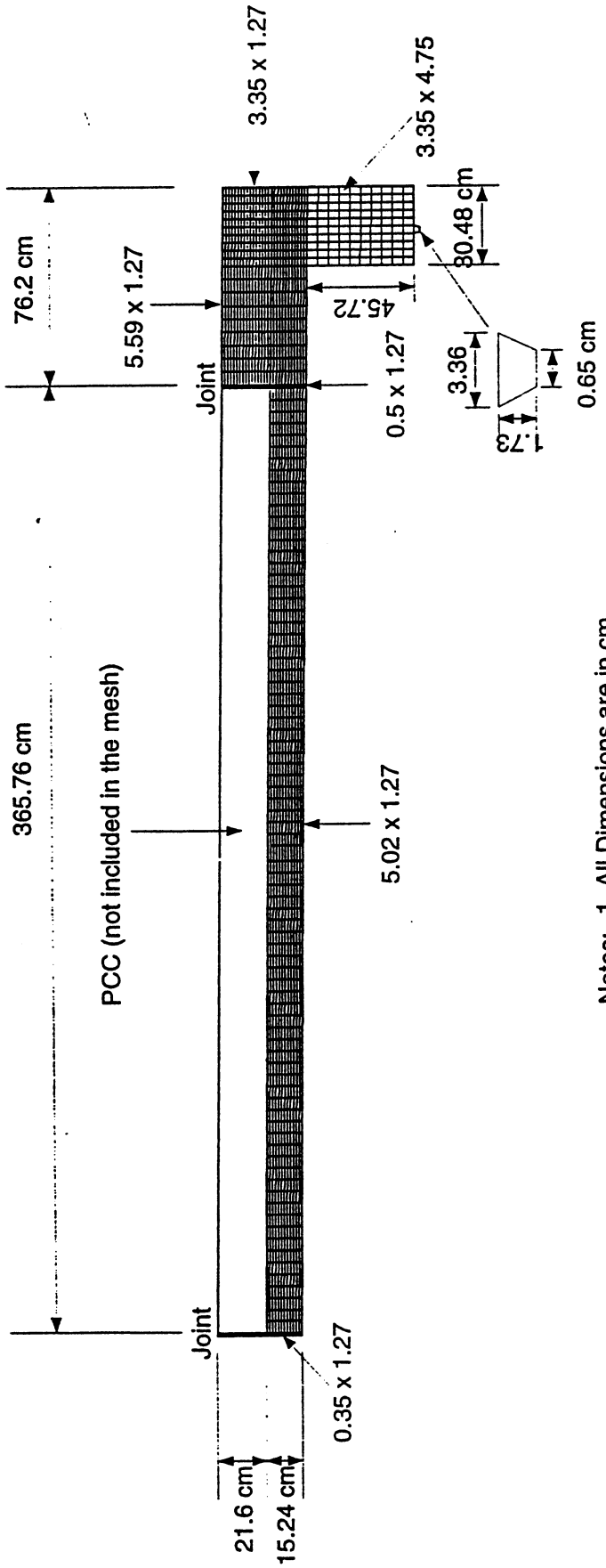
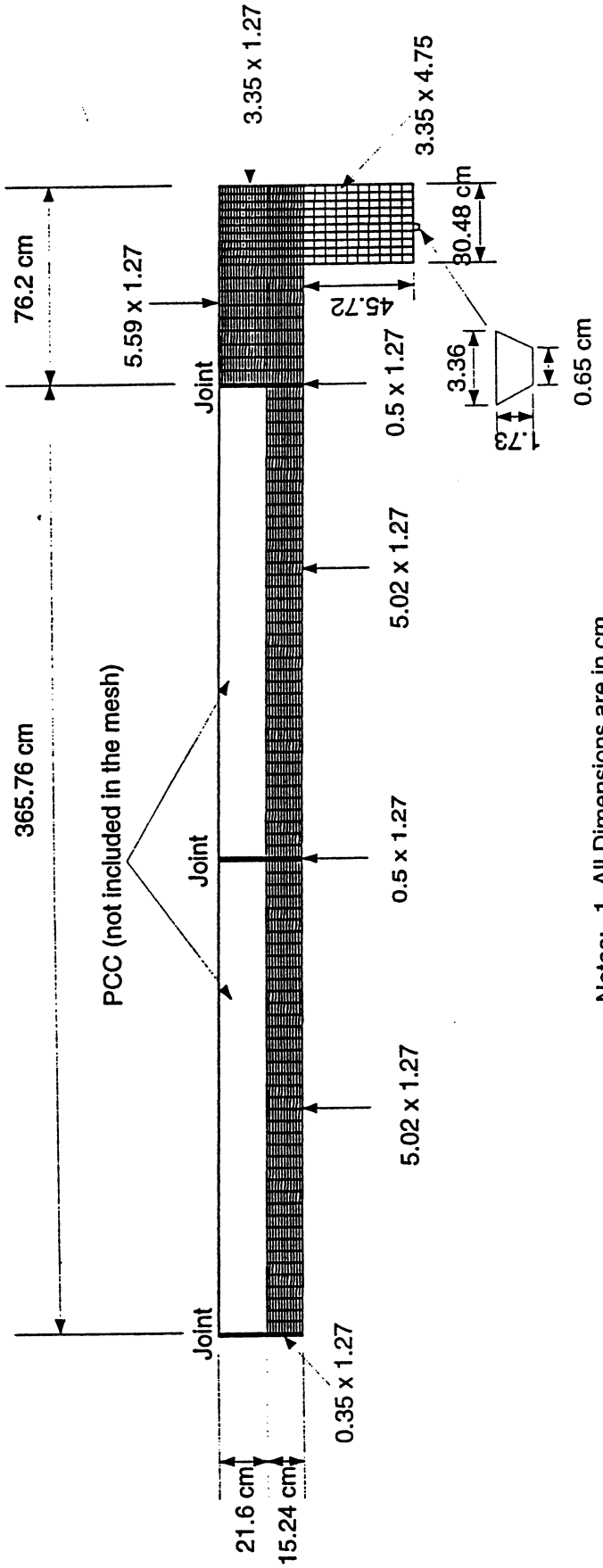


Figure 2 Analysis Zones



Notes: 1. All Dimensions are in cm.
2. All Elements are Quadrilateral.

Figure 3 Finite Element Dimensions for Section 1



Notes: 1. All Dimensions are in cm.
2. All Elements are Quadrilateral.

Figure 4 Finite Element Dimensions for Section 2

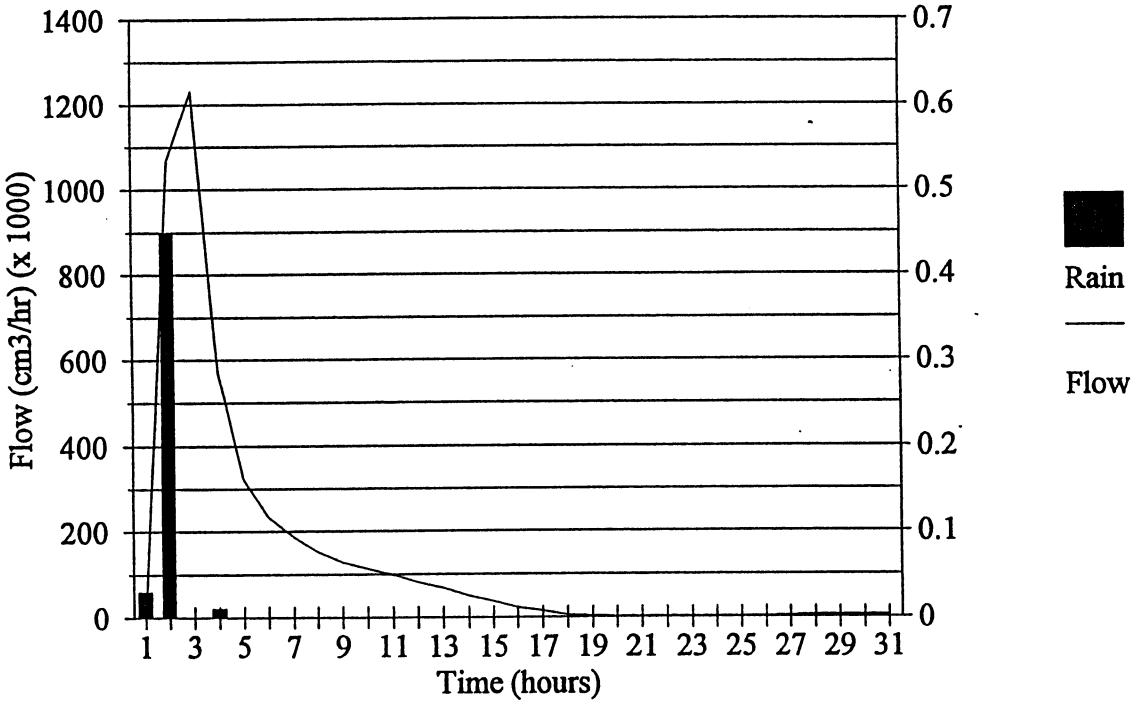


Figure 5 Rainfall Event 1

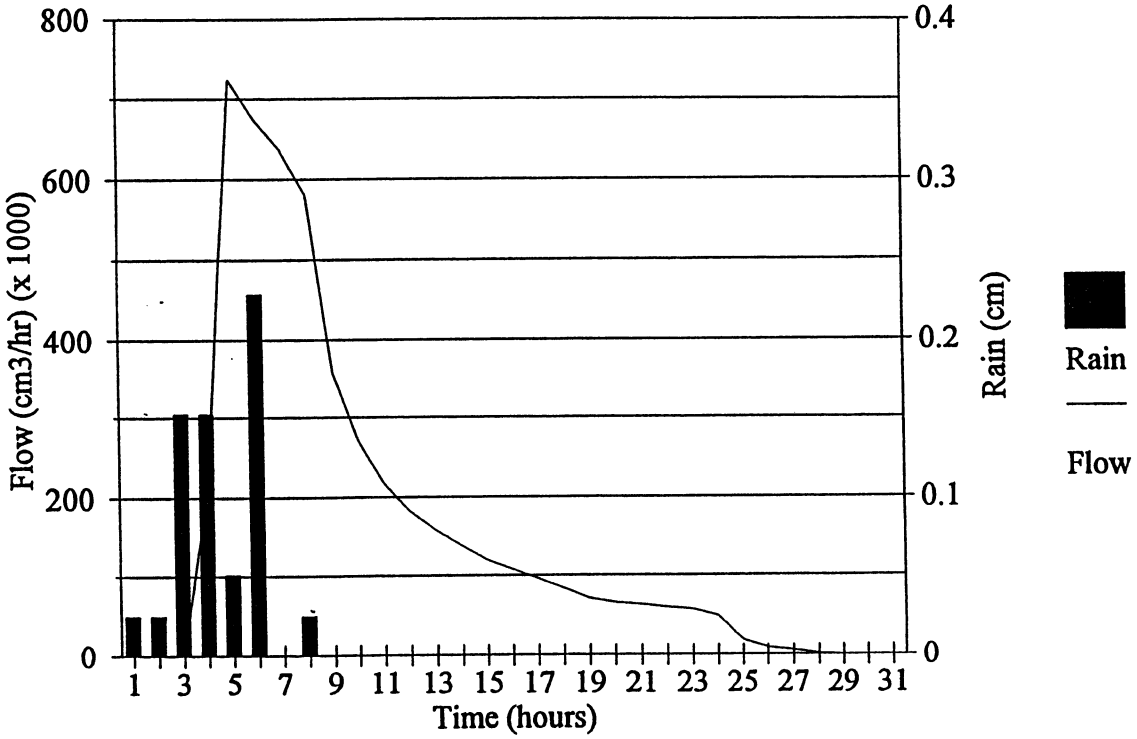


Figure 6 Rainfall Event 2

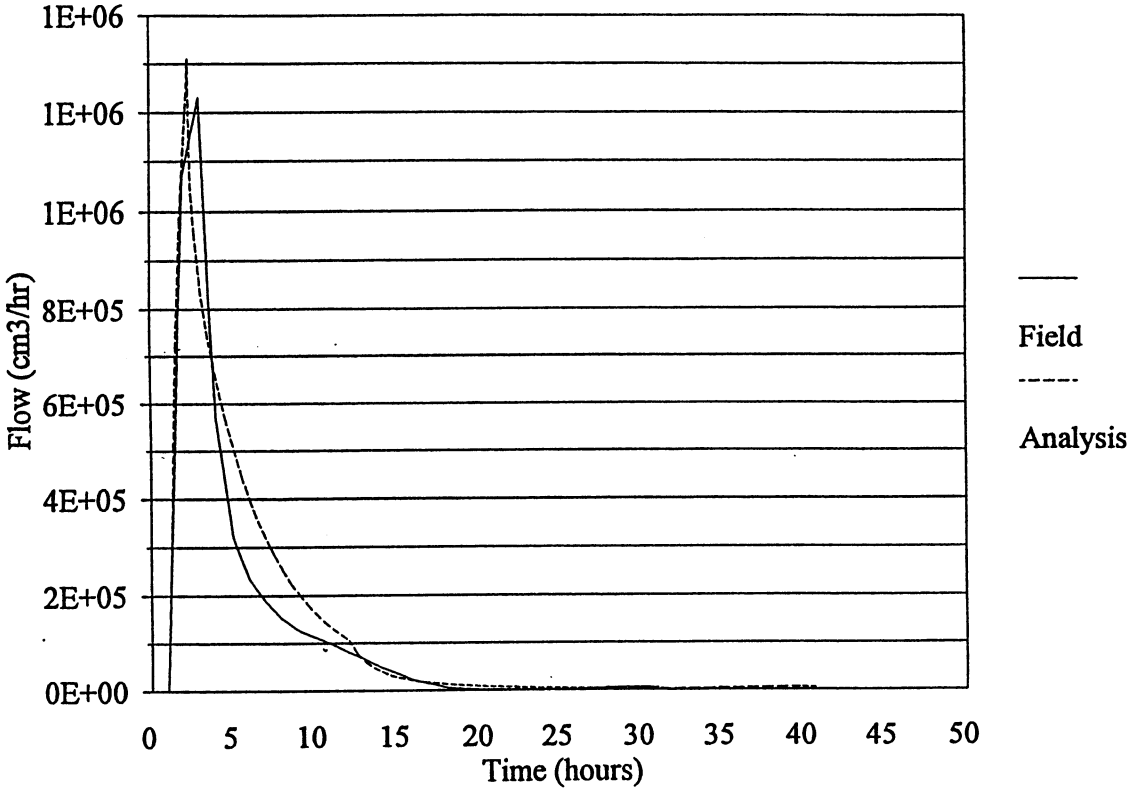


Figure 7 Rainfall Event 1

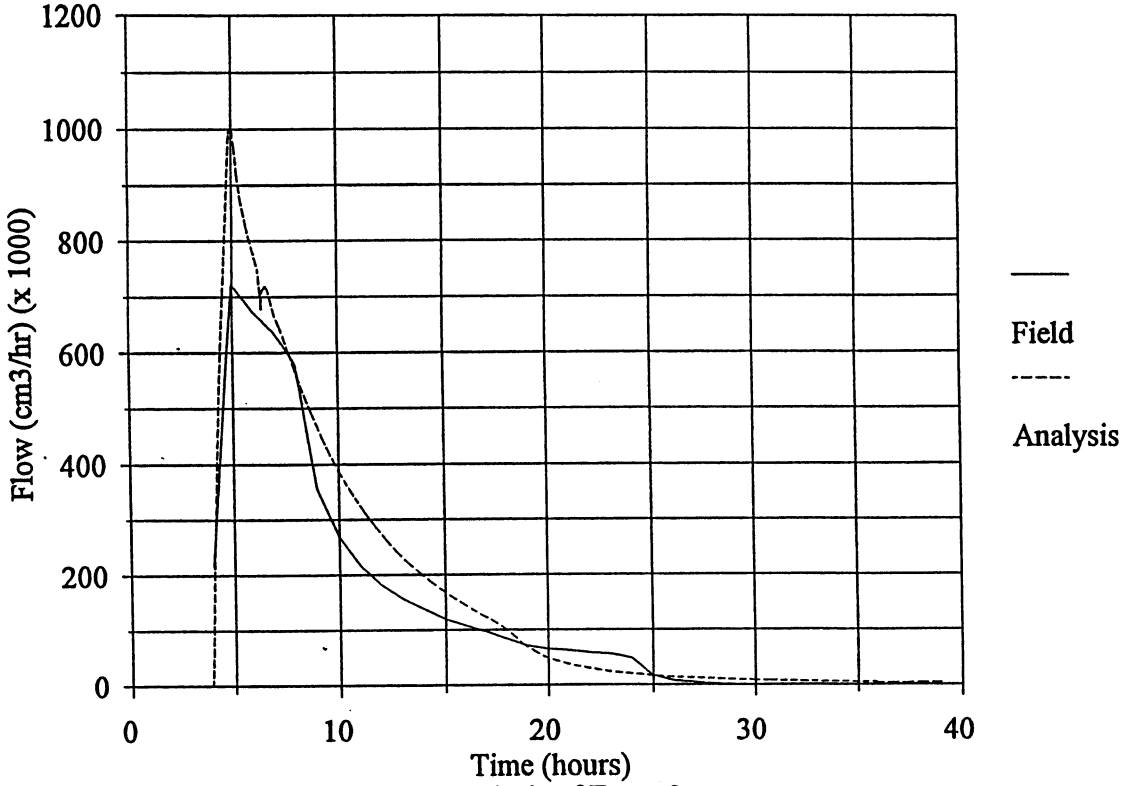


Figure 8 Analysis of Event 2.

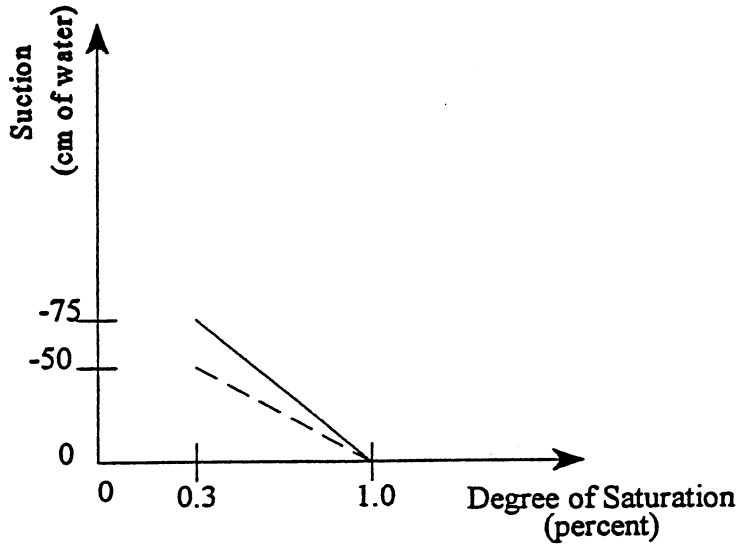


Figure 9 Moisture-Suction Relation for # 7 Trench Backfill Material

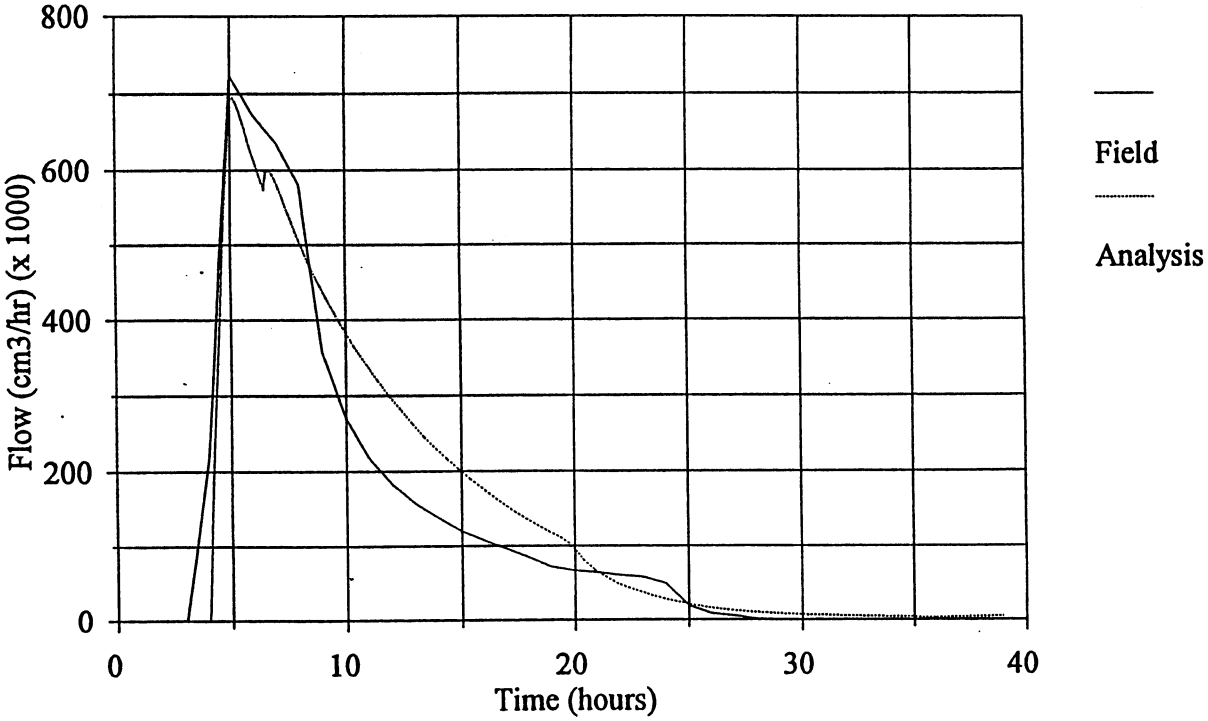


Figure 10 Analysis of Rainfall Event 2

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