Drainage Design of Porous Pavement System for Urban Runoff Control

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ABSTRACT: Increased urbanization causes more and more natural ground surface to be covered by impervious man-made surfaces. This has the direct effect of increasing the volume of surface runoff to be discharged through man-made drainage systems. Peak runoff volume of the design rainfall governs the capacity of the drainage systems. Porous pavement systems can be employed to serve as temporary storage of rainfall to reduce the volume of peak runoff. This paper examines the feasibility of implementing such a scheme for roads and car-parks in Singapore based on pavement drainage considerations. Due to the abundance of rainfall in Singapore, pavement thickness design of the porous pavement system is governed by the drainage storage capacity requirement. A rational procedure for the design is proposed in this study. Key considerations in the drainage design and selection of porous pavement materials are addressed. A finite element model is adopted to determine the drainage properties and thickness requirements of the various layers of the pavement system. The issues relating to short-term and long-term runoff control are studied. Factors affecting the design include the choice of design rainfall, the length of storage period needed, drainage properties of pavement materials available, the level of water table and the drainage properties of the natural subgrade.

DRAINAGE DESIGN OF POROUS PAVEMENT SYSTEM FOR URBAN RUNOFF CONTROL

INTRODUCTION

Surface runoff in built-up areas has to be collected by drains and discharged at suitable points into natural water bodies. As increased urbanization causes more and more natural ground surface to be covered by impervious man-made surfaces, the investment in the drainage network also increased rapidly. Since the downstream drainage structure must carry all the runoff collected upstream plus the additional runoff downstream, the incremental investment cost of expanding the drainage structure is much higher than the increase in built-up area. Any effective measure of reducing the design peak surface runoff will therefore have a multiplying effect on the cost saving of drainage structure investment. It was with this aim that the urban drainage authority of Singapore had initiated a project to study the feasibility of using porous asphalt pavements as a temporary storage of rainfall to reduce the volume of peak surface runoff in built-up areas.

Reducing the volume of peak surface runoff would lower the capacity requirement of the drainage structure, thereby cutting down the investment and maintenance costs needed on the entire drainage system. Other possible benefits of the proposed scheme have also been identified. For example, it could be applied to reduce the flooding potential of flood-prone areas. The water stored could be used for watering of roadside gardens and plants, and washing of facilities and structures nearby.

As opposed to the conventional water-tight dense-graded asphalt pavement construction, a porous pavement system allows water to flow downward into the pavement structure. The use of porous pavement systems for urban runoff control is not new. Research and development of such systems was initiated by the Franklin Institute Research Laboratories in the early 1970s to combine porous friction surface course with porous base course [1, 2]. Since then, trial projects have been conducted in Delaware [3], New England [4], Arizona [5] and Philadelphia [4]. The complexity involved in the selection of construction materials and considerations related to their drainage design appears to be the main reason that has prevented wider applications of this type of construction [6, 7].

This paper explores the feasibility of adopting porous asphalt pavement construction in Singapore with a wet tropical climate and an annual precipitation of more than 2,400 mm. Due to the abundance of rainfall in Singapore, pavement thickness design of a porous pavement system is governed by the drainage storage capacity requirement. A rational procedure for drainage capacity design is proposed in this study. A finite element model is adopted to determine the drainage properties and thickness requirements of the various layers of the pavement system. Factors affecting the design include the choice of design rainfall, the length of storage period needed, drainage properties of pavement materials available, the level of water table and the drainage properties of the natural subgrade.

APPROACH OF DESIGN

The complete drainage design of a porous pavement structure consists of material selection, clogging resistance evaluation and drainage analysis. The procedures adopted in the present research for material selection and clogging resistance evaluation of surface and base courses are presented elsewhere [8-10]. Presented in this paper are considerations for drainage analysis.

Based on the current practice of porous asphalt surface course construction, a thickness of 75 mm was adopted as the surface layer thickness for the porous pavement system. The thickness of the base course, known as the reservoir course of the porous pavement system, was to be determined through the finite element drainage analysis based the storage capacity requirement. A structural analysis on a trial thickness design consisting of 75 mm porous asphalt surface layer and 300 mm base course, had shown that the design was structurally adequate for typical urban traffic in Singapore. A laboratory wheel tracking test was also conducted to confirm the structural soundness of the design against rutting. As will be shown in the results of finite element analysis, the thickness of the base course (i.e. reservoir course) based on storage capacity consideration far exceeds the required structural thickness.

Short-Term and Long-Term Drainage Control

The local authority required two different designs to be considered, namely a short-term and a long-term drainage control design. The short-term drainage control design refers to the case where the aim was to relieve the peak runoff flow or for flood control. This was to be achieved by temporarily holding rainwater within the pavement structure and discharging the water through the normal drainage system at an appropriate time after the rainfall has stopped. Under this requirement, the porous pavement structure is to provide a storage capacity to hold the precipitation of a single design storm. The associated roadside drainage system is no different from those for normal road design, except that it could now be designed for a lower peak runoff volume.

The long-term drainage control becomes necessary when there is a need to store rainwater within the porous pavement structure for a prolonged period of time. This means that multiple rainfalls over the period of storage must be considered. The period of storage, and hence the storage capacity required, is dependent on the time interval of water being discharged for use and the quantity of water used each time. It was assumed in the design that a pump would be used to extract water from the storage. The required storage capacity of the pavement system was based on a design monthly precipitation and prescribed water extraction rate and frequency.

Determination of Design Precipitation

The design rainfall for the case of either the short-term or long-term drainage control was not the same as that selected for normal roadside drainage facilities. In the design of normal drainage facilities, the peak runoff volume governs the capacity requirement. In the present case, however, both the rainfall intensity and the total amount of precipitation were of the main concerns. It turned out that the permeability of the porous asphalt surface course as well as those of the underlying porous pavement layers, with values higher than 1 mm/s, were higher than the normal design rainfall intensity of about 150 mm/h in Singapore by more than 20 times. Therefore, it was clear that the governing design consideration was the total amount of precipitation of a single rainfall.

To determine the design rainfall that would provide the most critical total precipitation, the intensity-duration-frequency (IDF) curves for different return periods were examined and the intensity-duration combination that produced the largest total precipitation for a given return period was selected as the design rainfall for the return period. Table 1 shows the results of this analysis for different return periods.

The long-term drainage control analysis presented in this study was for a design storage period of one month. In other words, it was assumed that at the end of design period, the water within the pavement system would be emptied to start the next design period. Similar to the case of short-term drainage control, it was the total precipitation that governed the storage capacity design. For long-term drainage control over the period of one month, it was necessary to determine the most critical design monthly precipitation.

A statistical method was employed to determine the design monthly precipitation. The monthly precipitation data for the last 20 years (1981 to 2000) were used for the analysis. The maximum monthly total precipitation from the 12 monthly data of each year was identified. The 20 annual maximum monthly precipitations were ranked and percentile values were assigned accordingly. It was found that the data fitted the Pearson Type III distribution best. Figure 1 shows the plot of the data on a Pearson Type III probability paper. The design monthly precipitation for a given return period could thus be computed based on the Pearson Type III distribution model. Table 2 shows the results of the data analysis for the most recent 20 years, indicating the total rainfall depth and the assumed rainfall intensity of each return period.

Since the main objective of the drainage control was to provide a porous pavement structure with adequate storage capacity to store the design precipitation without causing overflow or flooding, it was decided to consider the case where all the rainy days in the selected design month fell consecutively from the beginning of the month. This represented the worst scenario for the storage capacity requirement for the case of long-term drainage control.

Selection of Pavement Materials

The pavement structure consisted of two main components, namely a porous asphalt mixture surface course, and a coarse granular reservoir course. The porous asphalt mixture was an existing design in use in Singapore for porous surface construction that drained surface runoff laterally into roadside drains. It was selected from several available designs due to its superior clogging resistance characteristics [11]. Table 3 shows the characteristics of this porous mixture. It was an open-graded mixture containing 5% of modified asphalt binder, and had an air void content of 23.6%.

The two governing selection criteria for the surface porous asphalt layer were: (i) the permeability of the porous asphalt mixture must be sufficiently high to drain the design rainfall intensity effectively by not permitting rainwater to accumulate above the top pavement surface; and (ii) the mixture must have good clogging resistance so as to maintain an adequate level of drainage capacity during its intended design life. The earlier phase of this study recommended that a suitable porous asphalt mixture should have an air void content of not less than 20%, and an initial permeability of more than 5 mm/s [10]. The procedure of clogging resistance evaluation developed for the present study has been presented elsewhere [9].

The porous base layer was the main layer that provided the needed storage capacity. As such, it must contain sufficiently high porosity in order to offer the space for water storage. It must also be resistant to clogging against residual soils. To provide the needed storage capacity, a porosity of 30% or more was necessary. The authors had examined 5 different gradations of open-graded granular base materials on the basis of their clogging resistance, and had recommended a gradation for adoption in this study [12]. The properties of the selected reservoir base material are given in Table 3.

Material Properties

The properties of porous asphalt mixture surface course, and the coarse granular reservoir course, as well as those of the subgrade soil had to be determined as they were inputs to the finite element analysis. The typical subgrade soil in Singapore was the Bukit Timah residue soil of a granite formation. Depending on the degree of weathering, the sol ranges from silty sand to silty clay.

Table 3 summarizes the properties for the three materials. In addition, the following two properties were required for unsaturated flow and transient flow analysis: hydraulic conductivity function, and water content characteristic function. These two functions were necessary for the finite element program to determine the permeability and water content of an unsaturated porous medium from the associated pore pressure. Figure 2 shows the input functions for the three materials of interest in this study.

Other Design Considerations

To proceed with the design of the porous pavement system, other system parameters and considerations need to be specified as follows:

1. The overall geometric design of the roadway is such that only the portion of rainfall falling within the width of the pavement will flow vertically into and stored in the pavement system.
2. Rainfall falling outside the pavement width will be drained away from the pavement into the normal surface drainage system provided for a typical roadway.
3. The proposed porous pavement system for water storage is applicable only when the ground water-table is lower than the base of the lowest layer of the pavement structure. It was assumed in the design analysis that the water-table coincided with the base of the lowest pavement layer. This represents the most critical case for calculating storage capacity need during the design rainfall without causing flooding.

FINITE ELEMENT MODELING

Choice of Finite Element Program

The finite element code used for the study was SEEP/W [14]. This special purpose finite element program for seepage analysis was selected because it had the capability to simulate unsaturated flow and transient flow analysis. The ability to analyze unsaturated flow condition was a key requirement for realistic simulation of the vertical downward flow of rainwater through the unsaturated porous pavement layers. The transient analysis capability was required to study and monitor the state of drainage within the porous pavement during the design storm.

Boundary Conditions

Three types of boundary conditions were applied to the finite element model. A flux boundary was used at the top pavement surface to simulate rainfall falling onto the pavement. Along the vertical line of symmetry that cut through the center of the pavement system, a no-flow boundary was applied. It did not allow any seepage of water across it. A third type of boundary, known as the infinite boundary, was specified for the vertical boundary of residual soil away from the pavement system and the bottom horizontal boundary of the subgrade residual soil. The infinite boundary was specified because the seepage problem is unbounded.

Mesh Design and Convergence Analysis

Finite element mesh design and the time steps for the transient analysis were the main considerations for the convergence analysis of the finite element model. Time steps were considered in conjunction with mesh design to create a model that was suitable for the analysis of the porous pavement so that accuracy is not sacrificed for the speed of simulations.

A series of element sizes and time steps was explored. An example of mesh design is shown in Figure 3 which consists of two sizes of element: a uniform fine size elements for all layers of the porous pavement, and a coarse size elements for the subgrade and surrounding soils. The phreatic surface of the water in the porous pavement rose as more and more rainwater flowed into it, and reached the highest level shortly after the rain had stopped. The final level of the phreatic surface, which was of major interest for the evaluation of storage capacity need, was chosen as the basis for convergence analysis.

It was found that when the element sizes were decreased to 0.0625 m for the fine size elements and 0.125m for the coarse size elements, the results of the simulations stabilized and further reductions of element sizes produced negligible improvements. The analysis also concluded that the largest incremental time step that would still generate sufficiently accurate results was 200 seconds. The same mesh design and time step were also worked well for the long-term drainage control analyses. Hence they were adopted for the finite element models for both the short- and long-term drainage control analyses.

RESULTS OF FINITE ELEMENT ANALYSIS

Major Design Implications

It is noted that the porous pavement system will only storage rainwater falling within the pavement width (see Figure 3). This was an important consideration as finite element analysis that included rainfall beyond the pavement width and allowed the rainwater to infiltrate into the subgrade, clearly indicated that rainwater from the surrounding areas would flow into the high porosity high permeability pavement system. The porous pavement system would serve as a sump collecting water from the surrounding sources if measures were not made to intercept such flows. This would severely jeopardize the intended runoff-control function of the porous pavement system. Therefore, it is imperative that surface runoff from outside the pavement width be collected by surface drains, and subsurface water be intercepted and directed away from the porous pavement system.

The depth of existing water-table is also a controlling factor that critically affects the feasibility of the proposed porous pavement system. The full storage capacity of the porous pavement system could be utilized only if the depth of ground water-table is greater than the thickness of the porous pavement. In other words, the proposed porous pavement system would be applicable in areas where the ground water-table is sufficiently deep. In Singapore, except for some low-lying coastal areas, the depth of ground water-table varies from 1.5 m below ground surface to as much as 10 m in hilly areas. This presents a favourable condition for the implementation of the porous pavement system.

The finite element drainage analysis also revealed that the relatively low permeability of the subgrade Bukit Timah residual soil would practically function as a impervious boundary to the porous pavement system. It would take months for the water stored in the porous pavement system to drain away from the surrounding residual soil. This means that the pavement thickness and storage capacity computed from the analysis was conservative. It would still serve its intended function of runoff control if subgrade soils of higher permeability were encountered.

Short-Term Runoff Control

The objective of the short-term runoff control analysis was to determine the required thickness of the porous pavement to temporarily store rainwater to reduce the peak runoff volume of roadside drains. Finite element analyses were performed for return periods of 2 to 50 years. Figure 4 shows that after the rain had started, the phreatic surface within the porous pavement slowly rose from the initial ground water-table level. The rising of the phreatic surface continued until shortly after the rain had stopped. The phreatic surface continued to rise briefly after the rain had stopped due to the time taken by rain water to reach the phreatic surface from the top pavement surface.

Table 4 presents the pavement thickness requirements computed by the finite element analysis for different return periods. The thickness requirement of the porous pavement system increased with the length of the return period selected. For a return period of 10 years, which was the common return period adopted for drainage design locally, the pavement thickness required was 1.375 m.

Long-Term Runoff Control

The objective of the long-term runoff control was store rainwater within the porous pavement system over a prescribed period of time. A storage period of one month was selected for the analysis. However, since the pavement thickness required was too large if storage were to be provided for the full design monthly precipitation, a scheme that included intermediate discharging of stored water was considered. The analysis was to determine the frequency, pumping rate and duration that were required so that the pavement thickness design for the short-term runoff control would be sufficient for the long-term runoff control.

Based on the design monthly precipitations for return periods ranging from 2 years to 15 years, and assuming the worst case of having all the rainfalls in the month to fall successively in the beginning of the month, the finite element analysis suggested that the same pavement thickness as determined by the short-term runoff control could be adopted if pumping was to be performed 4 times a week for 30 minutes each time. The pumping rate required was 2.5 liters per minutes for square meter for return periods of 5 years or less, and 3 liters per minutes for square meter for return periods of 10 and 15 years. Figure 5 shows the movement of phreatic surface caused by the rainfall and pumping, as obtained from the finite element simulations.

SUMMARY AND CONCLUSION

This paper has described the considerations and procedure for the design of a porous asphalt pavement system for urban runoff control. The main aim of the paper was to demonstrate the application of the procedure using finite element modeling. The proposed drainage design procedure of the porous pavement system consists of the procedure steps:

(1) Determination of runoff control needs. The needs include type of control in terms of the time duration over which the runoff must be held back (e.g. short-term versus long-term control), the design return period and hence the design precipitation.
(2) Determination of subgrade soil properties and the depth of ground water-table to assess the applicability of a porous pavement system.
(3) Selection of mix design for porous asphalt surface course and the gradation of the reservoir base course. Besides possessing adequate structural stability, the materials

must have good drainage and clogging resistance properties. The recommended minimum porosity and permeability of the surface course porous asphalt mixture were 20% and 5 mm/s respectively. The corresponding desirable minimum values for the reservoir course were 30% and 20 mm/s.

(4) Analysis using finite element simulation to determine the pavement thickness requirement.

It has been demonstrated that finite element simulation could be employed effectively to study the storage capacity need of a porous asphalt system. The important design considerations and the type of material properties required were illustrated by means of a case study in Singapore. The scheme proposed was one in which the pavement thickness was first determined for the most critical rainfall based on the so-called short-term runoff control criteria. This design would be able to reduce the peak runoff volume for the urban drainage facilities. For longer term runoff control, a pumping scheme was proposed so that the same pavement thickness design could be retained. A porous pavement structure of a total thickness of the order of 1.2 m to 1.6 m was found adequate for the Singapore conditions.

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List of Tables and Figures

TABLE 1 Design rainfalls for short-term drainage control

Return Period (Years)	Intensity (mm/hr)	Duration (Minutes)	Total Precipitation (mm)
2	93.33	700	93.33
3	110.00	600	110.00
5	128.33	700	128.33
10	151.67	700	151.67
15	163.33	700	163.33
25	180.83	700	180.83
50	192.50	700	192.50
100	210.00	700	210.00

TABLE 2 Design rainfalls for long-term runoff control

Return Period (Years)	Total Precipitation (mm)	Intensity (mm/h)
2	547.58	1.69
3	596.97	1.84
5	647.25	2.00
10	704.27	2.17
15	734.10	2.27

Table 3 Materials properties of porous asphalt, reservoir course and subgrade soil

Porous asphalt												
Grading (mm)	19	13.2	9.5	6.3	4.75	3.35	2.36	1.18	0.6	0.3	0.15	0.075
Percent Passing	100	98.1	45.6	18.8	18.4	17.2	15.6	12.4	10.1	8.2	6.3	3.6
Reservoir course												
Grading (mm)	50	37.5	19	10	4.75	2.36						
Percent Passing	100	97.5	70	50	15	0						
Subgrade soil												
Grading (mm)	2	1.18	0.6	0.425	0.3	0.212	0.15	0.063	0.0494	0.035	0.0249	0.0177
Percent Passing	92.32	81.2	67.16	61.74	57.8	55.02	53.36	49.2	48.18	47.38	46.58	44.97
Grading (mm)	0.0131	0.0093	0.0066	0.0047	0.0034	0.0014	0.0013					
Percent Passing	41.76	40.15	38.55	36.94	34.69	23.45	21.52					
	Porous asphalt				**Reservoir course**				**Subgrade soil**			
% Asphalt	5				-				-			
% air void	23.6				37.4				-			
Liquid limit (%)	-				-				46.2			
Plastic limit (%)	-				-				21.6			
Density (kg/m^3)	1883.6				1659.1				1521 (Bulk)			
Permeability (m/s)	6.404E-03				3.224E-02				9.565E-09			

TABLE 4 Pavement thickness for short-term runoff control

Return Period (Years)	**Depth of Pavement (m)**
2	1.125
3	1.250
5	1.250
10	1.375
15	1.500
25	1.500
50	1.625

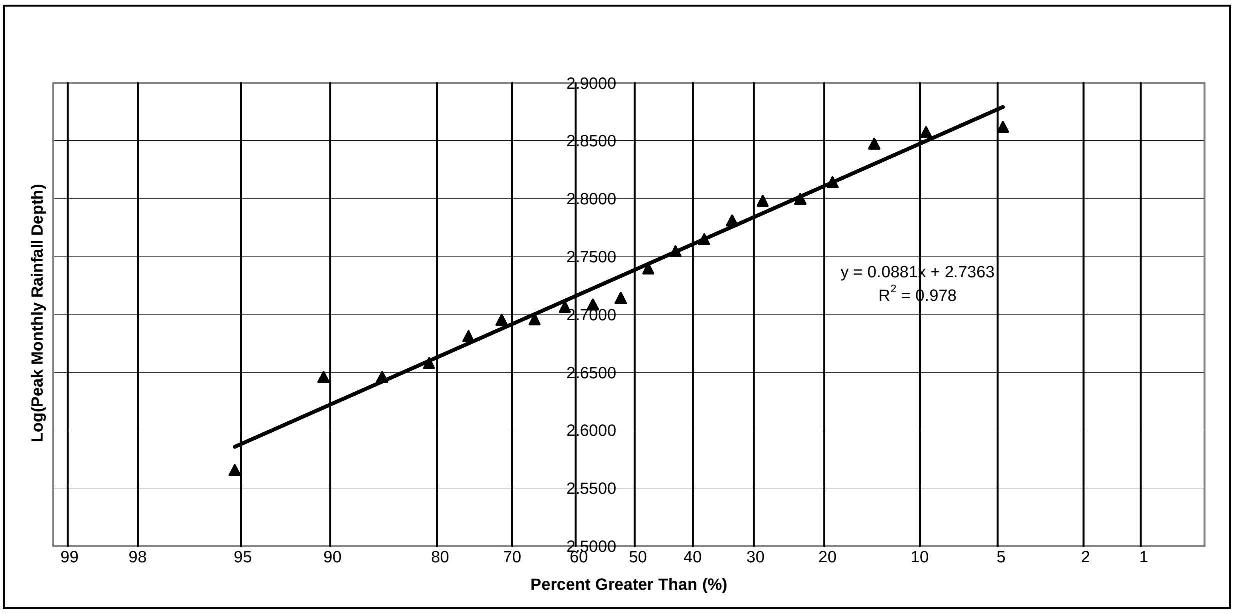
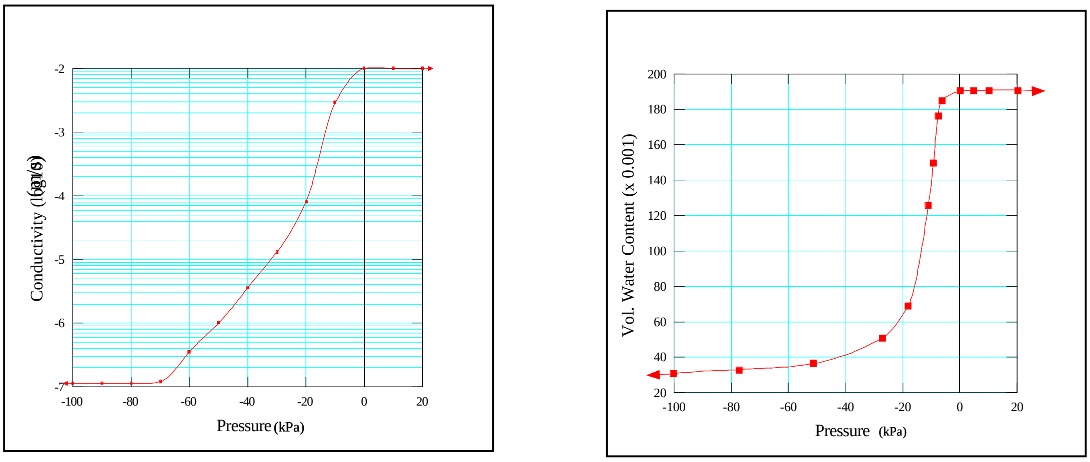
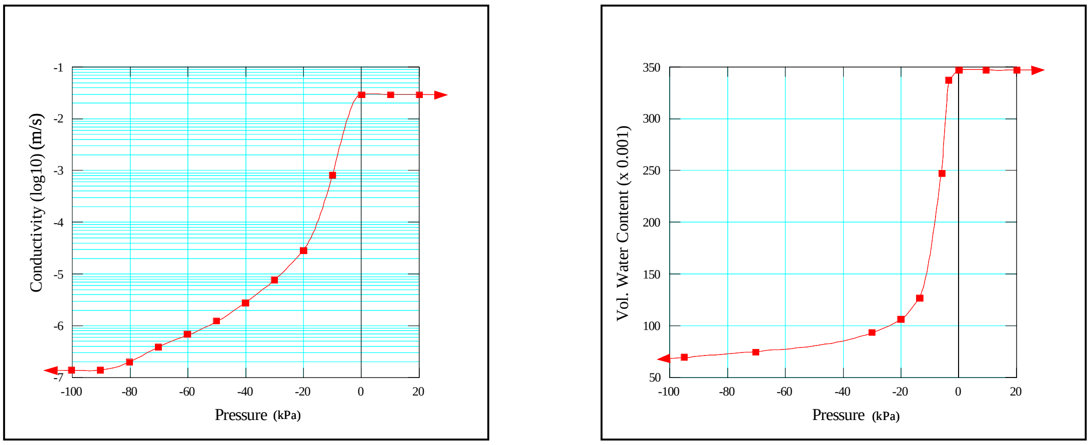


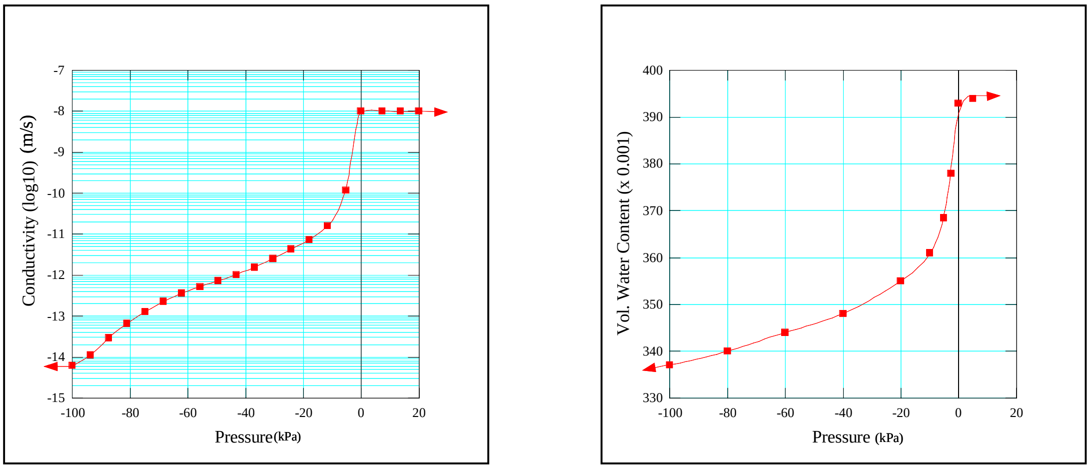
Figure 1 Plot of annual maximum monthly precipitation on Pearson Type III probability paper



(a) Hydraulic conductivity function of porous asphalt (b) Water content function of porous asphalt



(c) Hydraulic conductivity function of reservoir course (d) Water content function of reservoir course



(e) Hydraulic conductivity function of subgrade soil (f) Moisture content function of subgrade soil

Figure 2 Hydraulic conductivity and moisture content functions of pavement materials and soil

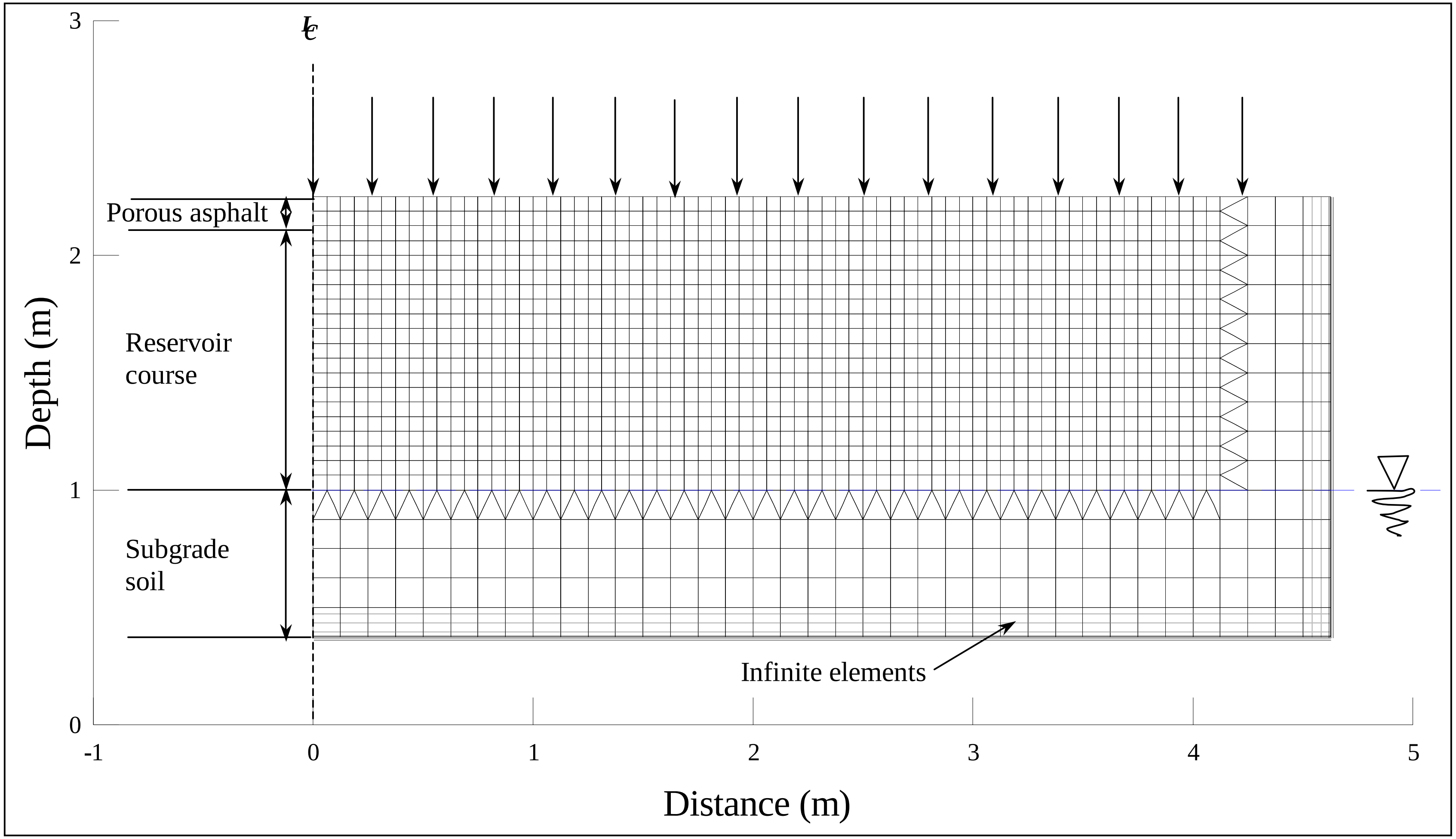


Figure 3 Finite element model

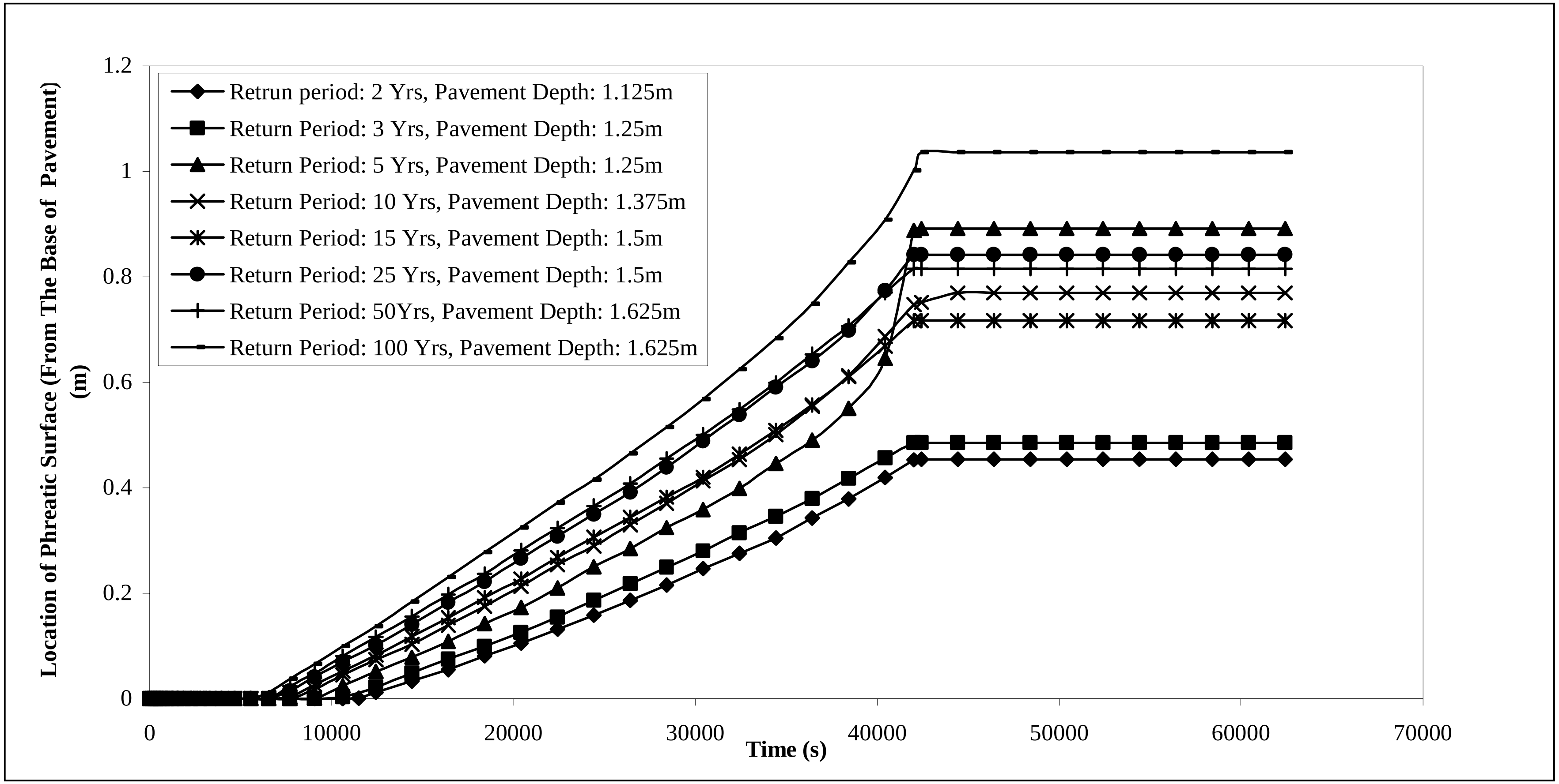


Figure 4 Movement of phreatic surface during design storm for short-term runoff control

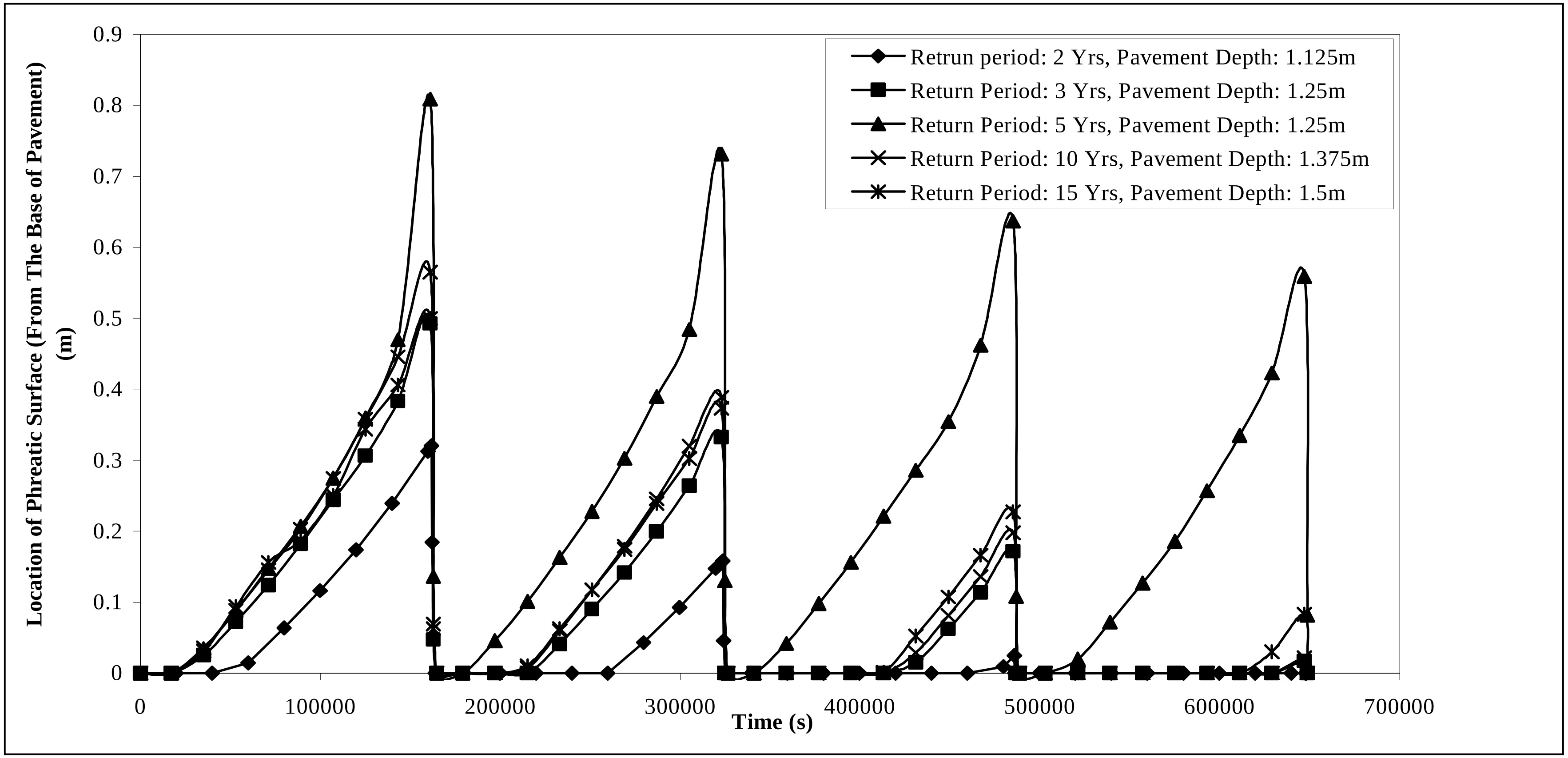


Figure 5 Figure 5 Movement of phreatic surface during multiple storms for long-term runoff control