GROUNDWATER RUNOFF THROUGH PERVIOUS PAVEMENT

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1. INTRODUCTION

In the urbanized area, one of the flood control measures proposed recently is the use of pervious pavement through which the rainfall excess is infiltrated and recharged to the ground water zone. For a detailed quantitative analysis of the pervious pavement and to get an in - depth understanding of the seepage peculiar to unsaturated porous media, an extensive observation facility had been constructed at the baseball field of the University of Tokyo, with an intimate cooperation between the University of Tokyo and the Bureau of Sewerage Works, Tokyo Metropolitan Government.

Fig.1 shows the plan of the observation field in the baseball ground along with the position of measuring devices. 10 different combinations of substructures detailed as in Tab.1 had been installed to analize the flow through various sequences of substrata. More detail about the instrumentation is given elsewhere(3). As the first step in understanding the water movement through the materials utilized in the observation field, 3 small-size lysimeters had been prepared and the vertical sections are shown in Fig.2(horizontal section 21cm by 21cm). Lysimeter-F is prepared with undisturbed Kanto loam recovered on the campus of the University of Tokyo. In this paper a mathematical model to explain the water movement in the multi-layered substructure of a pervious pavement is presented and calibrated for the data measured in lysimeters for rainfall experiment and natural rainfall. The analysis is also extended to the relationship between rainfall and ground water runoff in the test plots of the baseball field.

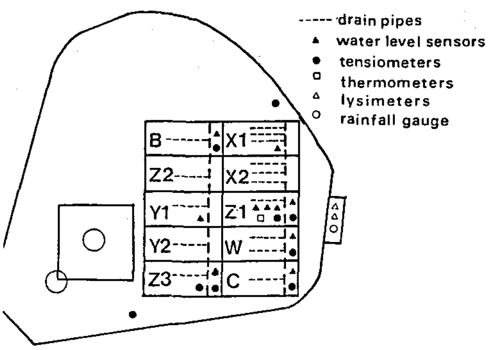

Fig.1 Plan of the observational field.

Tab.1 Detail description of substructures.

Plot name	Water tight sheet	Depth of crushed gravel	Number of drain pipe
Z1	without	30 cm	1
Z2	with	30 cm	1
Z3	without	30 cm	1
Y1	1/5 of area	30 cm	1
Y2	2/5 of area	30 cm	1
X1	with	30 cm	3
X2	with	30 cm	3
W	without	20 cm	2
B	with	10 cm	1
C	with	25 cm	1

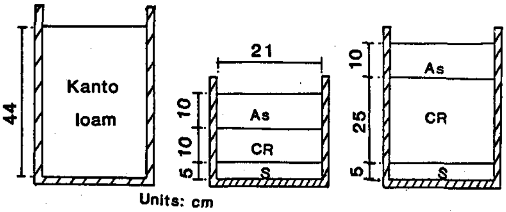

Fig.2 Vertical sections of the lysimeters.

2.MATHEMATICAL MODEL

Following assumptions are adopted in this study;

(1) The water flow in the unsaturated and saturated zones is considered to be continous. Thus both zones are treated together as an integrated system.

(2) Above the phreatic surface there exists a domain where the soil is still saturated but under negative pressure. In this domain, defined as the capillary fringe, the permeability is assumed to be equal to that of the saturated medium.

(3) In the unsaturated zone, the hysterisis is not taken into account and thus the pressure potential(ψ) and permeability are expressed by unique functions(1) of water content(θ) as in Eq.1.

$$k=k_s\left(\frac{\Psi_e}{\Psi}\right)^{2+\frac{2}{b}}, \qquad \Psi=\Psi_e\left(\frac{\theta_s}{\theta}\right)^b \tag{1}$$

where K_s is the coefficient of permeability when the zone is saturated. θ_s is the saturated water content. b is a parameter depending on the medium. ψ_e is the air entry water potential.

(4) Since the asphalt has a very high permeability, even the maximum rate of rainfall expected in Tokyo area can infiltrate into the subsurface without any ponding up.

The Richard's equation, expressed in terms of pressure potential(ψ), in its usual form(2) for an incompressible fluid had been utilized. The general form of the equation is expressed as,

$$C(\Psi)\frac{\partial\Psi}{\partial t}=\frac{\partial}{\partial x}\left[K_x(\Psi)\frac{\partial\Psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y(\Psi)\frac{\partial\Psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_z(\Psi)\frac{\partial\Psi}{\partial z}+1\right] \tag{2}$$

where $C(\Psi)=\dfrac{\partial\theta}{\partial\Psi}$

θ is the water content,
K_x, K_y, K_z , are coefficient of permeabilities,
ϕ is the total potential,(ϕ = ψ + z)
ψ is the pressure head.
z is the position head.

Since the material in the lysimeter is assumed to be homogeneous in the horizontal plane, a solution for the one dimensional mathematical expression of the Eq.2 may be representative of the whole situation. Also the dominancy of the vertical flow in the unsaturated zone has been verified by Owada(4) in his experiment with similar stratified media. That is, the assumption of no horizontal flow is reasonable for the lysimeters.

The boundary conditions utilized are as follows:

(i) At the ground surface, the rainfall or evaporation can be represented as:

$$\frac{\partial\Psi}{\partial z}=\frac{R}{K(\Psi)}-1 \tag{3}$$

where R is the flux accross the upper boundary, either positive or negative depending on either infiltration or evaporatioh.

(ii) At the surface of the draining pipe it is assumed to be of atmospheric pressure and thus the drainage occurs when the pressure head in the vicinity of the drain pipe exceeds the atmospheric pressure.

(iii) Initially there is no flow through the drain pipes and thus along a vertical $\phi = \psi + z$ = constant.

The implicit finite difference method is used to solve the governing equation. Although the differences in procedure arises due to the boundary conditions, the similar procedure had been described earlier by Freeze(2).

3.CALIBRATION BY LYSIMETER TESTS

The properties of the material used in the observational blocks are given in Tab-2. Since the compaction used in preparing the lysimeter is different from that during construction of the plots, the lysimeters are suspected to have slightly looser composition than those given in Tab-2.

For Kanto loam, the unsaturated media properties to represent the undisturbed sample in lysimeter-F is referred from the experimental results of Yamada(5) for similar soil and given in Tab.3. The simulations are performed on the lysimeter-F using the properties given in Tab.3. Through the experiments performed on lysimeter-F it had been noted that the drainage flow is highly dependent on the initail soil moisture condition of the Kanto loam. Since the weight of the lysimeter is continously recorded, an ad-hoc technique is adopted to guess the average soil moisture content from the weight, to be used to determine the initial total

Tab.2 Permeabilities of materials used in observational field

Material	Value
Asphalt	2.18×10^{-1} cm/s
Crusher run	1.20×10^{-2} cm/s
Sand	1.77×10^{-3} cm/s
Kanto loam	$1.66 - 2.97 \times 10^{-3}$ cm/s

Tab.3 Properties of Kanto loam

Parameters	Value
Permeability of saturated zone	2.0×10^{-3} cm/s
Saturation water content	0.52 cm^3/cm^3
Parameter "b"	7
Air entry water potential	- 20 cm

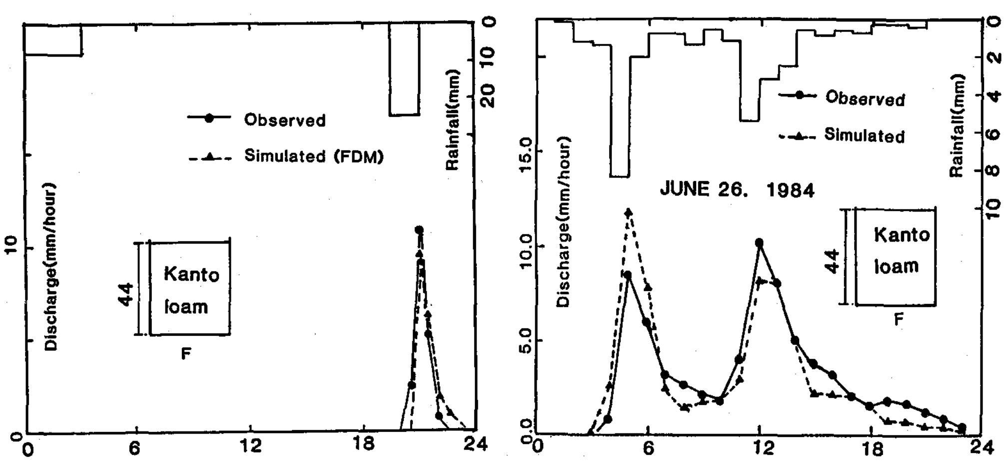

Fig.3 Drainage flow from the lysimeter-F
(a) rainfall experiment
(b) natural rainfall

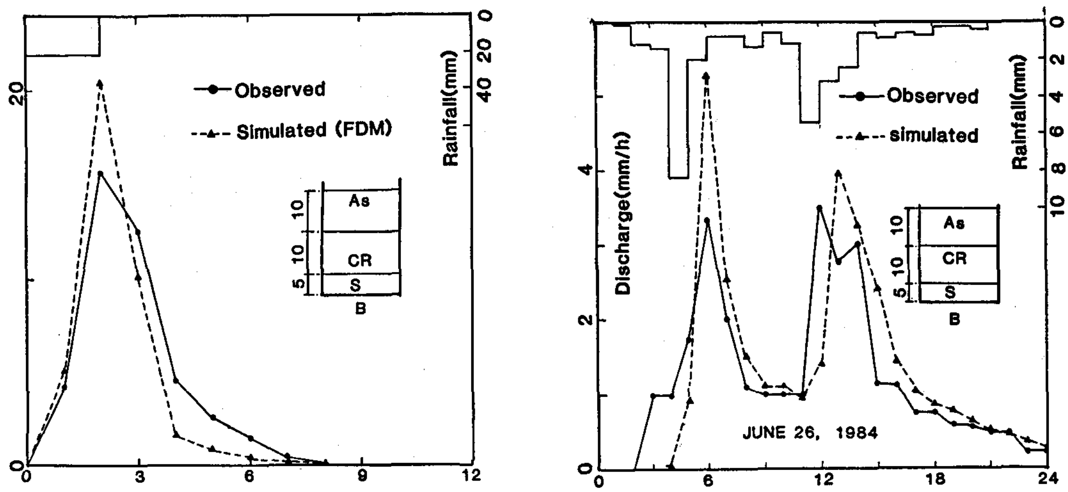

Fig.4 Drainage flow from the lysimeter-B
(a) rainfall experiment
(b) natural rainfall

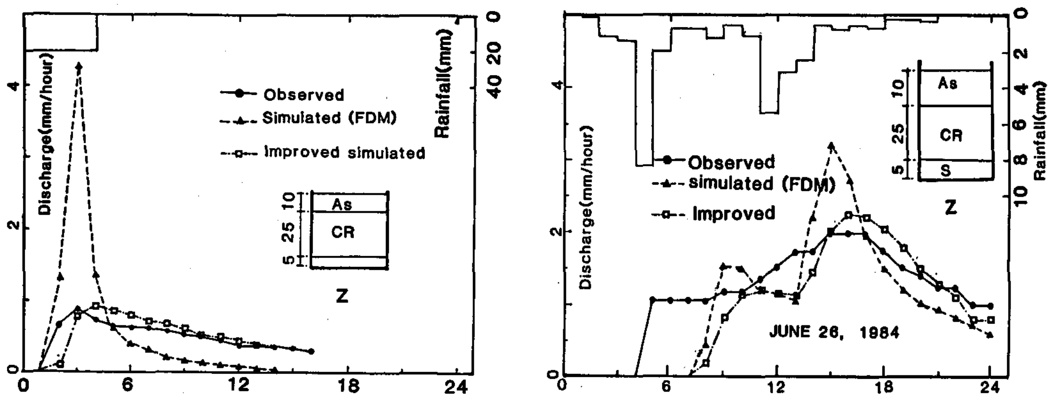

Fig.5 Drainage flow from the lysimeter-Z
(a) rainfall experiment
(b) natural rainfall

potential of the soil. When the soil at the vicinity of the drain pipe is in a unsaturated state the effect of capillary height of the soil on the outflow is also considered in simulation. For the purpose of ensuring the suitability of the mathematical model, a simulated results for the lysimeter-F is compared with the hydrograph of the artificial rainfall experiment carried out on this lysimeter. The Fig-3a shows fairly good matching for the artificial rainfall and the simulation for the natural rainfalls observed in the experimental station also compares reasonably well with the observed outflow from the lysimeter and one of these simulations is shown in Fig-3b.

The simulations carried out on the lysimeter-B with the properties given in Tab.1, which are the properties of the materials used to construct the observational blocks, give a reasonable matching with the observed drainage flow(see Fig.4a and Fig.4b). But the similar simulatioIns carried out on lysimeter-Z, do not give a good matching with observed drainage flow. Even with the properties slightly changed to accomadate the possibility of the difference in compaction does not show any improvement, instead shows a very different outflow. Therefore it was suspected that the cause is due to clogging either at the entrance of the drain pipe or the less permeable thin layer of washed out fine particles from the crusher run at the interface of the lysimeter-Z. Even though the cause is not understood clearly at this stage, it is found that the simulated outflow is improved by the introduction of a very thin layer of less permeable strata at the interface of crusher run and sand. The improved simulated curve with other curves are shown in Fig-5a and Fig-5b for the experimental and a natural rainfall respectively. At present, to find out the actual reason for this strange type of outflow through lysimeter-Z, another lysimeter being constructed.

4.TWO DIMENSIONAL ANALYSIS FOR THE BASEBALL GROUND

To apply the model to the observational field the block Z2 is chosen and the vertical cross section is shown in Fig.6. Here the interface between sand and the original soil is covered with the vinyl sheet so that no flow occurs across this interface. Since the sand has much higher capillary capacity, compared to the layer thickness, it is reasonable to assume that initially the pores are completely filled with capillary water. The water movement in the upper layers are considered to be one dimensional vertical flow, and described by Eq.2 and the rate of drainage from the crusher run layer is fed into the top of the sand layer and the water movement in this layer is traced using the following equation.

$$K_s \frac{\partial^2 \phi}{\partial x^2} + K_s \frac{\partial^2 \phi}{\partial z^2} = s \frac{\partial \phi}{\partial t} \qquad (4)$$

where K_s is permeability of saturated medium, ϕ is the total potential, s is the coefficient of storativity. Since there is no flow across PQ, QR, ST and TU, no flow boundary condition is used along these faces (ie, $\partial\phi/\partial x = 0$ along PQ and TU and $\partial\phi/\partial z = 0$ along QR and ST). At the drain pipe, pressure is assumed to be atmospheric. The vertical drainage from the one dimensional model is used as the flux across PU. Initially no flow through the drain pipe and thus $\phi = \psi + z =$ constant is used as the initial condition in the sand layer. With no flow conditions used at the impervious boundaries, the outflow from the drain pipe is simulated and one of the simulations is shown in Fig.7 along with the observed discharge.

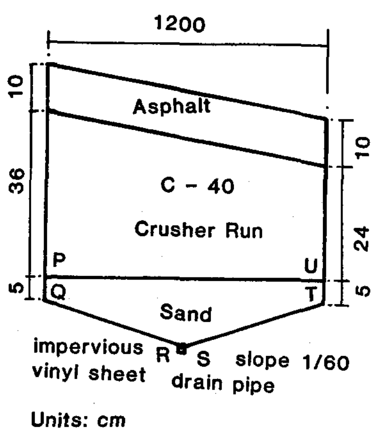

Fig.6 Vertical section of block Z2

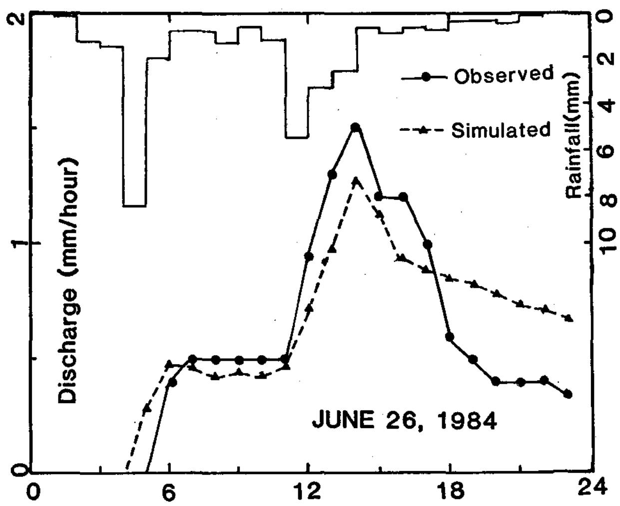

Fig.7 Dainage flow for block Z2

5. CONCLUSIONS

From the present study it can be concluded that;

1) The water movement in the substructures of the pervious pavement can be traced with the model presented here.

2) The charecteristic values in Tab.3 seems to be very good representative values for the Kanto loam in the vicinity of the University of Tokyo, Hongo campus.

3) If the peak flow or the time to peak is considered to be of interest, one dimensional model combined with the two dimensional analysis presented in this study provides an adequate mean for the analysis of water movement through substrata of pervious pavement.

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