Transmission and Redistribution of the Negative Pressure in Soil : Experimental studies on the New Subsurface Drainage Method by the Use of Negative Pressure II

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Experimental studies on the New Subsurface Drainage Method by the Use of Negative Pressure II

Sanji TEJIMA, Yoshihiko OGINO, Katsuhiko YABE, and Kazuo MURASHIMA

Laboratory of Utilization of Water in Agriculture, College of Agriculture

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Abstract

The previous paper[1] presented the negative pressure drainage method. This method is to such and drain the soil water forcibily through porous materials by using the negative pressure of the water. In the present paper, experiments of a one dimensional vertical soil column and of a small scale model at the experimental field were carried out and the transmission and redistribution of the pressure in the coil were discussed.

The following were made clear.

(1) In vertical system, the negative pressure drainage given the pressure head H_p, negative, at the height x has the same effects as the water table is lowered and kept at the height $x + H_p$ in the gravity drainage.

(2) The lower the permeability of the porous material is, compared to that of the soil, the less the efficiency of the pressure transmission and drainage discharged are. From two dimensional steady-state drainage analyses, the maximum discharge is obtained employing the relation between hydraulic conductivity and anti-air permeability of the porous material.

(3) For a full scale project of this drainage method on farms, technical problems of the construction and maintenance still remain to be solved.

1. Introduction

The driving force to suck and drain the soil water in the negative drainage method is given as the negative pressure of the water. Even in the natural equiliblium stage of the soil water, the water starts flowing according to the hydraulic gradient when the new pressure adds to the water. In the present paper three problems are discussed. The first problem is on the process of the water flow and the redistribution of the pressure in the soil after adding the negative pressure to the water itself. For the water flow Eq. (*1*) is derived from the equation of continuity and the unsaturated form of Darcy's law.[2]

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K(\Psi)\ \nabla h) \qquad (1)$$

where θ is the volumetric moisture content, t is the time, ∇ is the vector differential operator, $K(\Psi)$ is the unsaturated hydraulic conductivity, Ψ is the pressure head, and h is the hydraulic head. Inserting the specific moisture capacity $C = d\theta/d\Psi$ and the relation $h = \Psi + z$, the Ψ – based equation is obtained.

$$C\frac{\partial\Psi}{\partial t} = \nabla\cdot(K(\Psi)\nabla\Psi) + \frac{\partial K(\Psi)}{\partial z} \tag{2}$$

where z is the vertical co-ordinate. To one dimensional vertical flow Eq (3) applies.

$$C\frac{\partial\Psi}{\partial t} = \frac{\partial}{\partial z}(K(\Psi)\frac{\partial\Psi}{\partial z}) + \frac{\partial K(\Psi)}{\partial z} \tag{3}$$

The solution, the hydraulic and the pressure head at any point and at any time, is obtained approximately by the numerical methods. Here, experiments and simulation for the one dimensional vertical system are carried out.

The second is the problem with respect to the properties of the porous materials. The transmission of the negative pressure to the soil through the porous materials and drainage discharge are controlled by the given negative pressure and hydraulic conductivity of the porous materials. For two dimensional steady-state water flow through homogenous soil, Eq. (4) applies.

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \tag{4}$$

Then the distributions of the hydraulic head and the pressure head are solved using

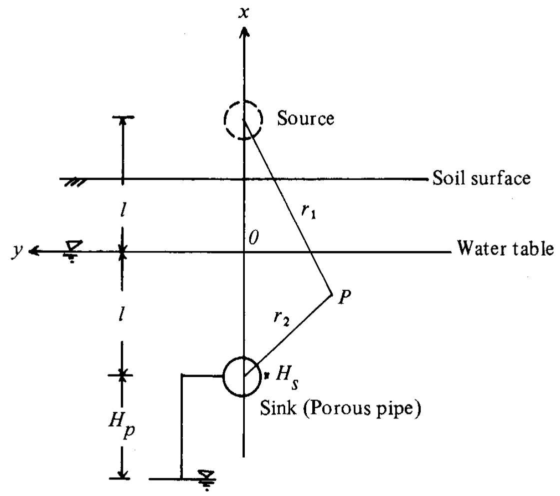

Fig. 1 Schematic diagram of two dimensional steady state negative pressure drainage.

the comformal mapping method. Fig. 1 shows a schematic diagram of two dimensional negative pressure drainage. The pressure head H_p is given in the porous pipe. The hydraulic head at point P can be written as

$$h = \frac{2(Hs-l)}{ln(\frac{16l^2+d_2^2}{d_2^2})} \cdot ln(\frac{r_1}{r_2}) \tag{5}$$

The inflow rate Q_{in} and outflow rate Q_{out}, per unit length of the porous pipe, can be written respectively as

$$Q_{in} = 2\pi Ks \frac{2(Hs-l)}{ln(\frac{16l^2+d_2^2}{d_2^2})} \tag{6}$$

$$Q_{out} = 2\pi K_p \frac{(Hp-Hs)}{ln(\frac{d_2}{d_1})} \tag{7}$$

where Hs is the pressure head of the soil contacts with the porous pipe, Ks and Kp are the hydraulic conductivity of the soil and pipe respectively, d_1 and d_2 are the inside and outside diameters of the pipe respectively. At the steady state, $Q_{in} = Q_{out}$, thus the pressure head Hs is given as

$$H_s = \frac{(\frac{Kp}{K_s}) \cdot Hp \cdot ln(\frac{16l^2+d_2^2}{d_2^2}) + 2l \cdot ln\,(\frac{d_2}{d_1})}{(\frac{K_p}{K_s}) \cdot ln\,(\frac{16l^2+d_2^2}{d^2}) + 2 \cdot ln\,(\frac{d_2}{d_1})} \tag{8}$$

In the cases where the water table is below the porous pipe and over the soil surface, Q_{in}, Q_{out}, H_s and the distribution of the pressure head are obtained by the same procedures described above.

The last is the problem of applying the negative pressure drainage method to the field. The previous paper presented the experiments in the laboratory using a porous pipe 22.5 cm length. Here, extending the connected porous pipe line system to an 8-m-length, observation on the drainage effects is done at the experimental field. Then technical problems of the construction and maintenence of this system are indicated.

2. One dimensional vertical drainage

(1) Experimental procedure

The sample soils are *Toyoura sand* and *Kuroboku loam* classified as sand and fine sandy loam respectively. Their physical properties are given in Table 1, and the relations between the pressure head and water content are shown in Fig. 2.

A schematic diagram of the experimental apparatus is shown in Fig. 3. The acrylic pipe is 120 cm in length and 5.0 cm in inside diameter. The glass filter, 0.5 cm in thickness, was set at the bottom of the pipe, and the negative pressure of the water was given. Each sensor of the tensiometer was inserted at a height of 1 cm and 5 cm above the filter, and the other sensers were inserted at intervals of 10 cm. The sample soil was carefully packed to a height of 115 cm so as to be given a uniform bulk density throughout the column.

Each run for the sand and loam consists of following three steps; the saturation of the soil with the water, the gravity drainage and the negative pressure drainage. The gravity drainage continued until the discharge from the outlet stopped and measured pressure heads in the soil reached steady values. The last step was conducted by giving a 100-cm-negative pressure head to the filer.

(2) *Numerical simulation*

For the case of the negative pressure drainage in the homogeneous vertical soil column having the initial distribution of the pressure head after gravity drainage, the boundary conditions with reference to Eq. (*3*) take the forms

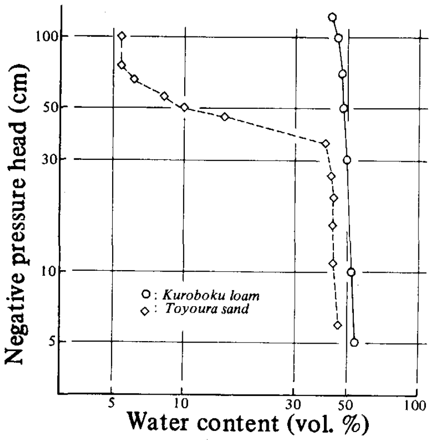

Fig. 2 Relation between pressure head and water contents of *Kuroboku loam* and *Toyoura sand.*

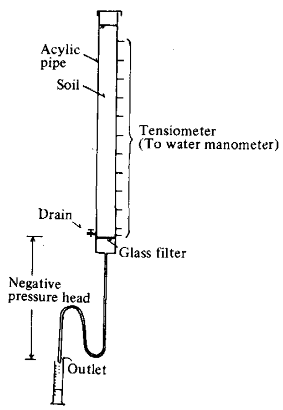

Fig. 3 Schematic diagram of experimental apparatus for one dimensional vertical drainage.

Table 1. Physical properties of sample soil.

Sample soil	Soil texture	Particle density (g/cm^3)	Sample bulk density (g/cm^3)	Particle size class (% by weight)			Saturated conductivity (cm/sec)
				Coarse S.	Fine S.	Silt	
Toyoura sand	Sand	2.56	1.56	99.2	0.8	0.0	1.6×10^{-4}
Kuroboku loam	F.S.loam	2.47	1.17	81.0	15.0	4.0	2.6×10^{-4}

$$\text{upper boundary} ;\ \frac{\partial h}{\partial z} + 1 = 0 \tag{9}$$

$$\text{lower boundary} ;\ h(z,t) = h(Hp,t) \qquad t > 0 \tag{10}$$

where z is the vertical co-ordinate defined as positive in the upward direction relative to the soil surface, L is the length of the soil column. The solution of Eq (*3*) subject to the initial and boundary conditions was obtained approximately by the numerical technique proposed by Wisler and Watson.[3] The relation between unsaturated hydraulic conductivity and pressure head was obtained through the non-steady drainage method.

(*3*) *Results and discussion*

Fig. 4 shows the pressure head distributions during the process of the negative pressure drainage. The solid lines show the measured distribution and the broken lines show the computed ones. Initially, after the gravity drainage, for *Kuroboku loam* the pressure head Ψ at the height x of the column from the filter is given by $\Psi = - x$, and for *Toyoura sand* $\Psi = - x, x < 65$ and $\Psi = - 65, x > 65$. Finally, after the negative pressure drainage, the redistributions are given by $\Psi = - x - 100$ for the loam and $\Psi = - 65$ for sand. The characteristic value of *65* (*cm*) for the sand is such that the pressure head fails in the continuous transmission of the negative pressure of the water. In two cases, the negative pressure drainage causes the same redistributions, as the gravity

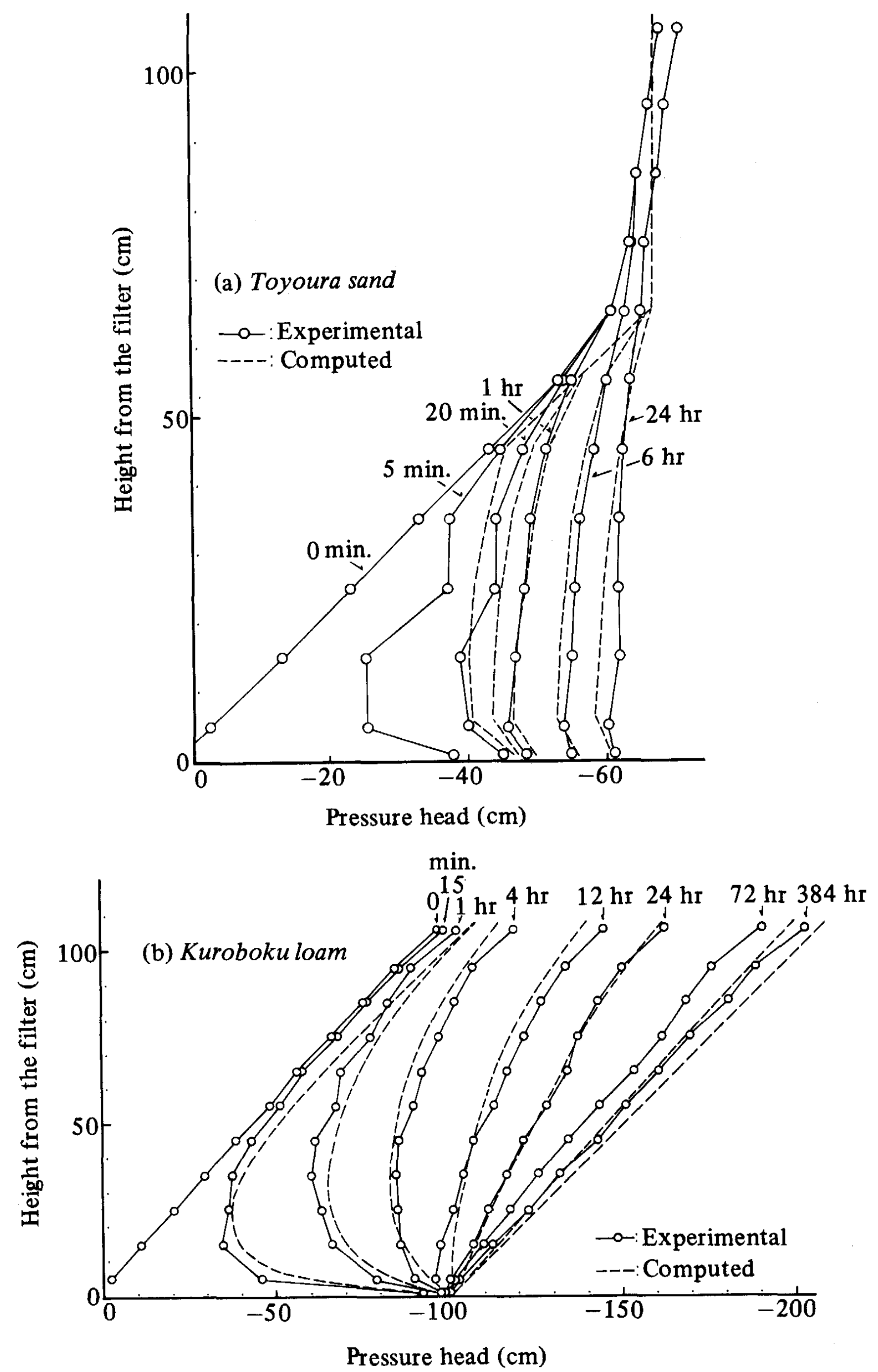

Fig. 4 Experimental and computed pressure head distributions for (a) *Toyoura sand* and (b) *Kuroboku loam* in one dimensional vertical drainage.

drainage does, when the water table is lowered further to the value of the given negative pressure.

In the case of *Kuroboku loam*, the sensor of the tensiometer at the height of 1 cm indicates the value of the given pressure head, *−100 cm*, right after the start of the drainage. While in *Toyoura sand* it gradually approaches the limited value of *−65 cm.* The hydraulic conductivity of the soil, compared to the porous material, affects the through the porous material. In this case, the glass filter has the hydraulic conductivity of the order *−4*, thus for *Toyoura sand* the given negative pressure is not transmitted efficiently to the soil through the filter.

3. The maximum outflow rate of two dimensional steady state drainage

There are three cases of the steady-state drainage with respect to the elevation of a porous pipe and that of the water table. We discuss the case which is shown in Fig. 1. Then Eq. (*6*), (*7*) and (*8*) apply.

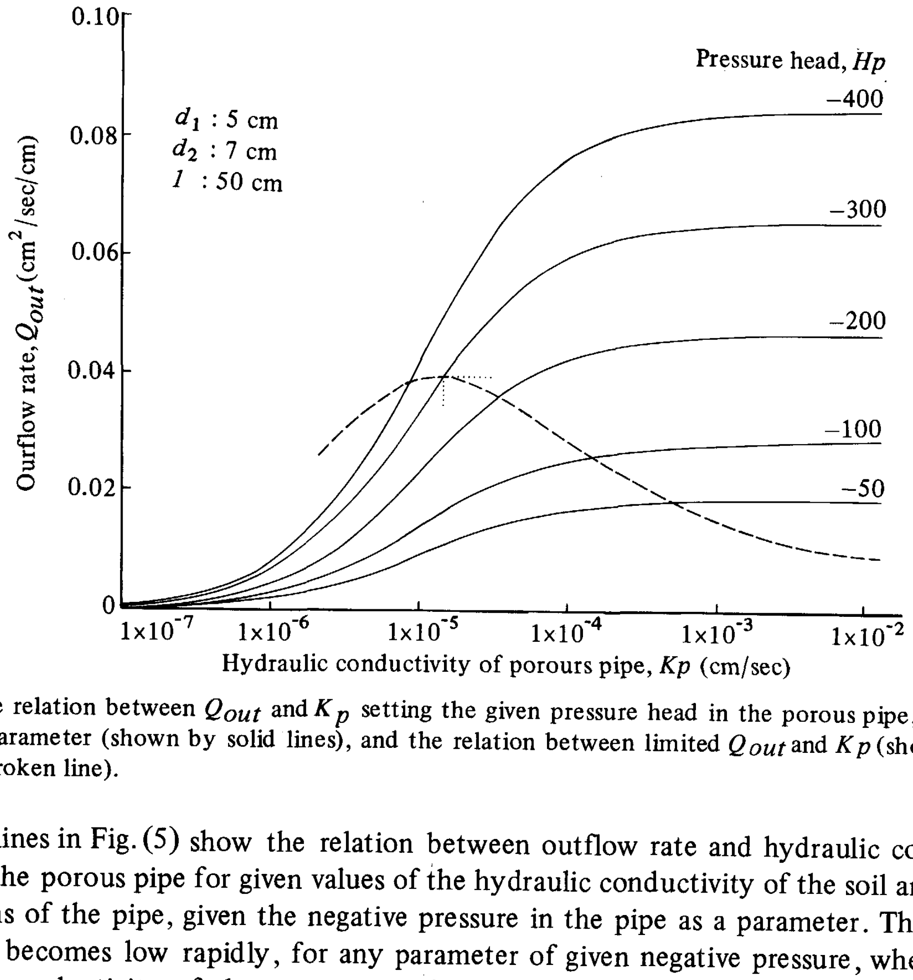

Fig. 5 The relation between Q_{out} and K_p setting the given pressure head in the porous pipe, Hp, as a parameter (shown by solid lines), and the relation between limited Q_{out} and Kp (shown by a broken line).

Solid lines in Fig. (5) show the relation between outflow rate and hydraulic conductivity of the porous pipe for given values of the hydraulic conductivity of the soil and the dimensions of the pipe, given the negative pressure in the pipe as a parameter. The outflow rate becomes low rapidly, for any parameter of given negative pressure, when the hydraulic conductivity of the porous pipe becomes less than that of the soil, 1×10^{-4}. And it seems to be effective to give higher negative pressure head to the pipe in order to gain higher outflow rate. However, porous materials have the property of high hydraulic conductivity but low anti-air permeability. Murashima *et al*[4] showed the relation between the both for the porous materials. For ceramic pipe, the relation takes the form of

$$K_p = 1.24\, S^{-2} \tag{11}$$

where S is the anti-air permeability in cm.

The anit-air permeability is the limited negative pressure head in the porous pipe. Consequently, the outflow rate has a limited value for a given negative pressure. The broken line in Fig. 5 shows this outflow rate with the hydraulic conductivity. It indicates that the outflow rate is maximum when $Hp = -300$ and $Kp = 1.4 \times 10^{-5}$.

4. Application to the experimental field

(1) Experimental procedure

Fig. 6 shows the location of the experimental lot in the glass field. Each lot has a dimension of 3 m X 8 m.Lot 1 and 2 are for negative pressure drainage, Lot 3 and 4 are for subsurface drainage of the tube drainage system and Lot 5 which has no drainage system is for control. At Lot 1 and 2, porous ceramic pipes extended by connecting vinyl hose-joints to the length of 8 m are buried at a depth of 40 cm and 60 cm respectively. The inside diameters of the ceramic pipes are 4.9 cm for Lot 1 and 7.3 cm for Lot 2. At Lot 3 and 4, corrugate-wall plastic drain tubes with, a 6.5-cm-diameter and an 8-m-length, are buried at a depth of 60 cm. Then gravel is utilized as the filter material. material.

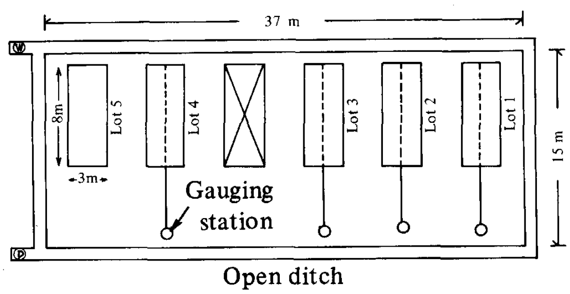

Fig. 6 Location of the experiment lot. Lot 1 and 2 are for the negative pressure drainage, Lot 3 and 4 are for tube drainage and Lot 5 is for control.

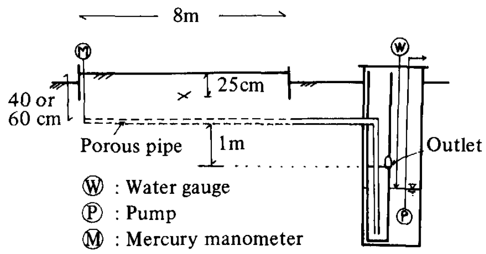

Fig. 7 Schematic diagram of the longitudinal section of the negative pressure drainage lot, Lot 1 and 2.

Fig. 7 shows the longitudinal section of Lot 1 and 2. The negative pressure head of 100 cm is given and kept in the porous pipe lines.

Surface soil from 25 to 30 cm in thickness which has the hydraulic conductivity of the order of *−4* is classified as *clay loam* and subsurface soil with the order of −7 is classified as *light clay*.

The water level of the open ditch is controlled to keep it about 60 cm below the soil surface.

Measurement of drainage discharge, rainfall and pressure head in the soil, by tensiometers, was done from August to november, 1979.

(2) Results and discussion

Quantitative description of the relation between rainfall and drainage is given in Table 2. Fig. 8 shows drainage hydrographs for rainfall on Sept. 28 and Oct. 6. First of all, these show that the water is drained by the negative pressure drainage method. Compared to the tube drainage as shown in Fig. 8, the water drained in low peak discharge but in long duration. Consequently, the drainage percent is the same degree for two drainage methods. Fig. 9 shows the pressure head changes with time during the same period as the drainage changes in Fig. 8. The effects of the negative pressure drainage are found.

There are several technical problems with respect to the construction and maintenance of this drainage method while it has drainage effects. Some of these problems are caused by the breakable porous pipe itself. Because of the breakability the vinyl joints are needed to connect pipes and this adds difficulties to the construction of the system.

The second is the problem to maintain the negative pressure throughout the system. There are, especially, troubles at the upper end of the porous pipe line where the value of the negative pressure is checked. Finally, a decrease in the permeability of the porous pipe will cause lower drainage efficiency. To solve this problem, it is necessary to utilize filter materials.

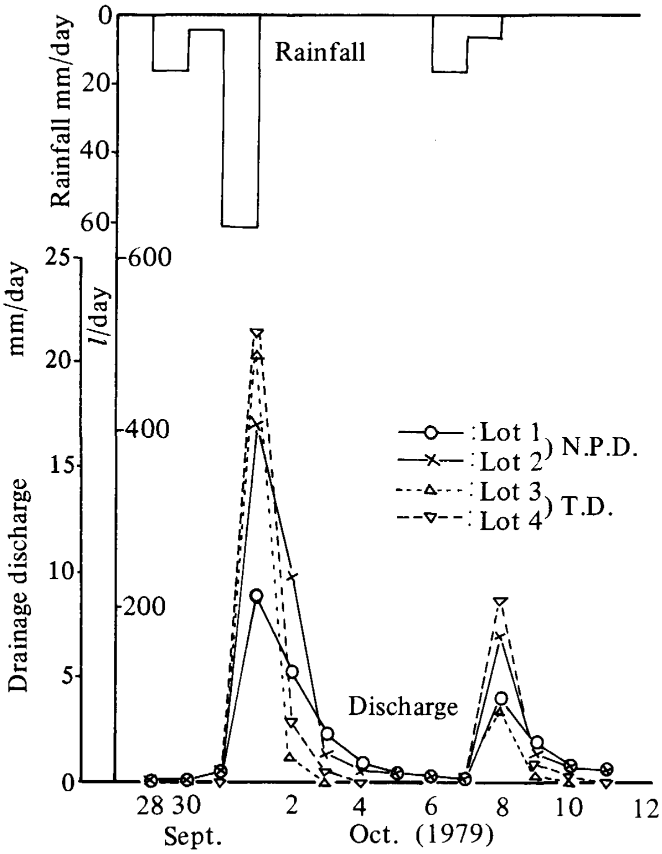

Fig. 8 Drainage hydrographs.
N.P.D. stands for negative pressure drainage, and T.D. tube drainage.

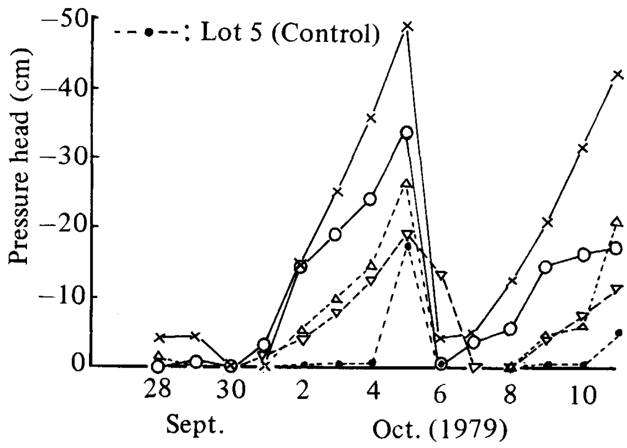

Fig. 9 Pressure heads with time.
Pressure heads were measured by tensiometer at the depth of 25 cm in the center of each lot.

Table 2. Quantitative description of the relation between rainfall and drainage.

No.	Rainfall		Negative pressure drainage						Tube drainage					
	Date and duration	Total infall	Lot 1			Lot 2			Lot 3			Lot 4		
			Q	q	f	Q	q	f	Q	q	f	Q	q	f
	day	mm	mm	l/day	%	mm	l/day	%	mm	l/day	%	mm	l/day	%
1	Aug. 27, 1	22.5	113.4	80.9	20.9	—	—	—	—	—	—	42.9	41.2	8.0
2	Sept. 1, 5	28.0	80.6	28.4	12.1	—	—	—	2.7	2.2	0.4	10.1	7.0	1.5
3	Sept. 17, 2	26.5	42.9	18.1	6.8	75.4	46.4	11.7	0.2	0.2	0.0	0.0	0.0	0.0
4	Sept. 28, 3	82.0	450.0	215.1	22.9	725.6	414.9	36.8	527.9	496.0	26.8	591.2	515.9	30.0
5	Oct. 6, 2	22.5	188.4	93.5	35.1	250.0	171.4	46.2	100.8	89.1	18.7	236.7	208.1	44.0
6	Oct. 17, 3	57.0	281.2	67.6	20.5	—	—	—	—	—	—	783.4	454.0	57.2
7	Nov. 9, 8	92.0	392.0	27.7	17.8	1027.4	138.0	48.4	823.8	280.4	37.3	1857.9	316.6	87.5

Q is total drainage discharge, q is peak drainage discharge, and f is drainage percent.

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