USE OF IN-SITU PERMEABILITY TESTS FOR INFILTRATION FACILITY PERFORMANCE PREDICTION

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INTRODUCTION

The flow from infiltration facilities to unsaturated soil can be adequately represented by Richards' equation. Since there are no analytical solutions to the flow equation, estimates of outflow are made from approximate formulae based on the classical free surface flow theory in which the entire flow is assumed to take place inside the saturated zone thus neglecting the capillary effects and the resulting unsaturated flow component. A much improved estimate can be made from direct solution of Richards' equation using numerical simulation methods. For these techniques a prior knowledge of the soil moisture characteristics in the form of moisture-suction ($\theta - \Psi$) and conductivity - suction ($k - \Psi$) relations are required and they should be measured for a given location as these properties vary from soil to soil as well as spatially. It has been observed that $\theta - \Psi$ relation can be measured from small field soil samples quite reliably while it is laborious and time consuming to measure the more sensitive $k - \Psi$ relationship in a similar manner. This paper examines in-situ permeability test requirements and compare experimental results of flow rates from field infiltration facility tests with those predicted based on the soil parameters derived from in-situ tests. Double cylinder test is used to create and analyse the one-dimensional flow characterstics and borehole test is used to study the two-dimensional flow aspects.

IN-SITU PERMEABILITY TESTS

One-Dimensional Infiltration Test

Philip's series solution has been widely used to analyse the infiltration experiments carried out on infiltrometers. The applicable solution takes the form of a power series of $t^{1/2}$:

$$I = S t^{1/2} + A t + t^{3/2} \int_{\lambda} + t^2 \int_{\omega} + \ldots\ldots \qquad \text{---- (1)}$$

where I is the cumulative infiltration rate and S, A, $\int_{\lambda}$, $\int_{\omega}$, are each integrals of solution of ordinary differential equations and their numerical values depend on the soil-moisture characteristics as well as initial and boundary conditions.

As the series (1) converges very rapidly only the first few terms are required and it is customary to use the first two terms only to analyse the infiltration rate variation for relatively short times. Even though there is no theoretical proof, many researchers estimate saturated hydraulic conductivity value, K_0 as 1/3 A . We shall first examine the applicability of this formula for the soil-moisture characteristics of Kanto-Loam soils. Since the infiltration rate, i, from (1) does not reach K_0 as $t \to \infty$, even the complete solution of (1) has limited applicable time before it starts diverging off. Philip(1969) has introduced this converging time limit as tgr given by

$$tgr = [\, S / (K_0 - Kn) \,]^2$$

where Kn is the conductivity corresponding to initial moisture content.

Our computations showed that for Loam soil characteristics tgr varies from about 4 min for K_0 = .01 cm/sec, 7.5 min for K_0 = .005 , 37 min for K_0 = .001 at about 20% degree of saturation to about 2 min for K_0 = .01, 4 min for K_0 = .005 , 20 min for K_0 = .001 at about 65% degree of saturation. As we expect the K_0 to be of order .005 cm/s, the applicable time of the series (1) is quite small. A second point was that due to the relative close magnitudes of the coefficients the series cannot be truncated at two terms and terms up to at least three are needed for accurate estimate of the infiltration rate. Similar coefficient values for a sandy soil have been reported by Haverkamp et al.,(1977). From a number of field tests conducted we could not obtain reliable flow rates within the first 1-2 min and therefore we conclude that even though the 2-term solution is useful for soils with low saturated conductivity, it has limited application for the analysis of infiltrometer data for soils with high K_0 values such as Kanto Loam.

In our study an optimising scheme was formulated to identify the k - Ψ relation from the solution of Richards' equation based on sensitivity analysis. The variable selected for observation is the infiltration rate at the soil surface under constant head, denoted by q. The corresponding sensitivity equation is given by

$$q - \hat{q} = \frac{\partial \hat{q}}{\partial P_i} (\Delta P_i) \quad i=1, m \quad \text{--(2)}$$

where $\hat{q}$ is the computed flow rate corresponding to the observation q ; P_i is the ith parameter of the k - Ψ relation, m is the number of parameters and ΔP_i is the improvement required in the ith parameter.

Equation (2) is written for several points along the infiltraion - time curve and the resulting matrix equation is solved by regression as described by Decoursey and Snyder(1967).

The selected function to represent k - Ψ relation is

$$k = K_0 \{ (\theta - \theta r) / (\theta_0 - \theta r) \}^n \quad \text{---(3)}$$

where K_0 = the saturated hydraulic conductivity, θ_0 = saturated moisture content, θr = residual moistrue and n = a constant for the soil. K_0 and n are treated as unknowns while θ_0 ,θr are determined from laboratory measurements of small soil samples.

For the successful application of the above scheme an accurate numerical model for simulation is an imperative and we adopted a finite difference fully implicit Local Balance model of Richards' equation after rigorous testing. The coefficients ∂θ/∂Ψ and k values were taken at mid time steps through an iterative procedure. Accuracy was ensured by keeping the mass balance normalised with respect to inflow from surface to be <1% at all time steps.

Validation of the algorithm for a sandy soil is shown in Fig.1. Following analytical expressions were used for characterising the soil.

$$\theta = \alpha (\theta_0 - \theta r) / \{ \alpha + | \Psi |^{\beta} \} + \theta r \quad ;$$

θ_0 = .287, θr = .075, $\alpha = 1.611 \times 10^6$, β = 3.96 and k - Ψ by Eq.(3) with K_0 = .00944 cm/sec, n = 3.26

First infiltration-time curve was obtained for 30 min, using the above parameters for a water head of 10 cm with initial moisture at 50% saturation corresponding to Ψ = -95 cm. Five data points were taken as observations from this curve, and parameters were recalculated by using the above described algorithm. Initial parameter estimates for the solution were taken as K_0 = .015 and n = 5. In three iterations nearly the original parameters were obtained , and in 5 iterations the computed flow rates were exactly the same as the observations. Fig.1 shows the convergence of the solution while Fig.2 shows the corresponding changes of k - Ψ curve.

Field experiments were carried out at the experimental station of the Institute at Chiba. Moisture - suction measurements were made in the laboratory from small field samples and the best fitting analytical expression is given by

$$\theta = \alpha (\theta_0 - \theta r) / \{ \alpha + (\ln | \Psi |)^{\beta} \} + \theta r \quad \text{---(4)}$$

$$\theta_0 = .7547, \quad \theta r = .6232, \quad \alpha = 591.5, \quad \beta = 5$$

Fig.5 shows the measured data points and the analytical curve.

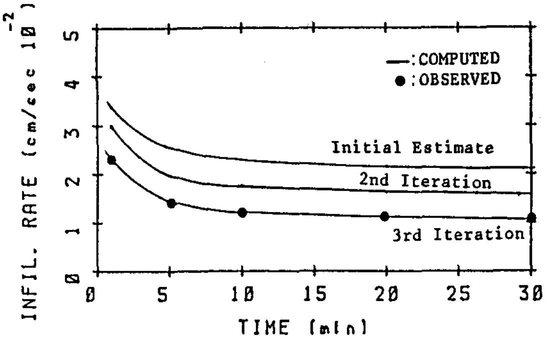

Fig.1 Validation of optimising algorithm.

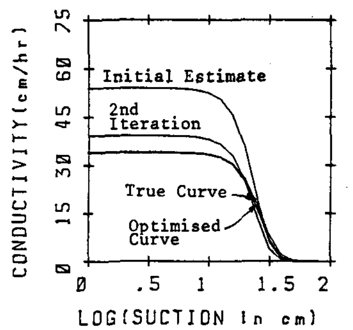

Fig.2 Convergence of k - Ψ relation.

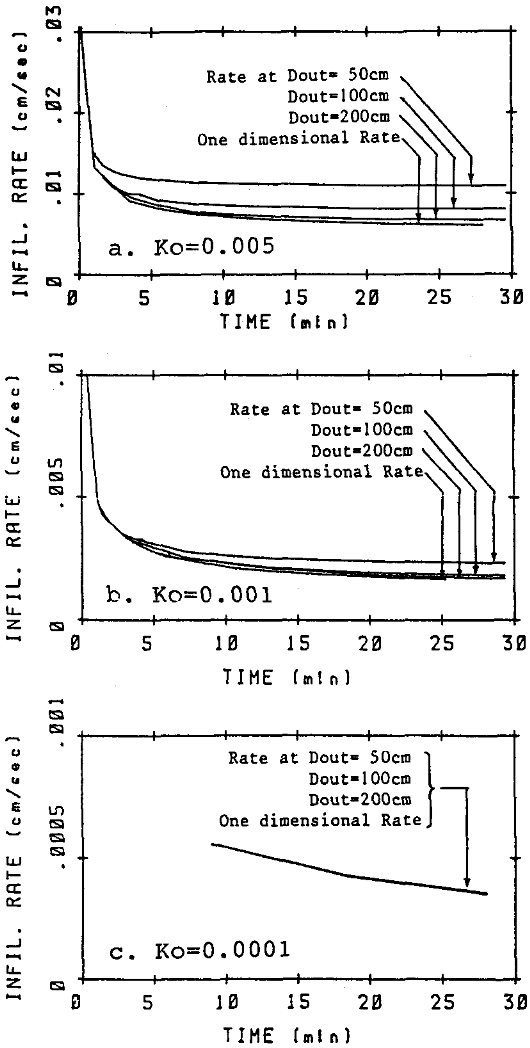

Fig.3 Effect of Dout on inner ring infiltration rate - Simulated results.

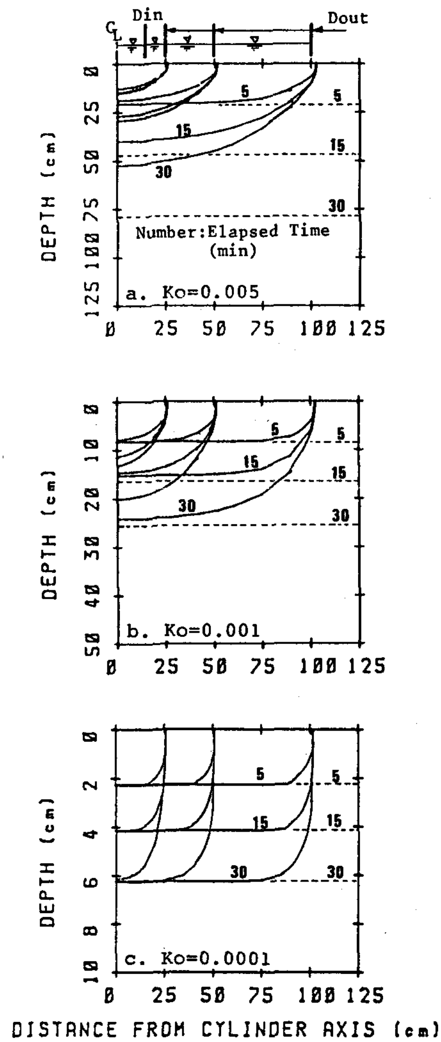

Fig.4 Time evolution of saturated profiles for different Dout.

Double cylinder experiments were carried out in the same location and it was observed that the estimated K_0 values change with the outside ring diameter. Closer examination of the phenomena through numerical simulations of the whole experiment showed that the flow from the inner cylinder remains one-dimensional only for a short period before two-dimensional unsaturated flow starts. The profiles corresponding to $\Psi = 0$ spread downwards during the initial period after which it reaches a steady state and the flow rate becomes almost constant. The outflow then takes place in the form of increasing moisture in the unsaturated zone.

The most sensitive parameter that affects the saturated bulb dimensions is K_0 while water head, the slope of $k - \Psi$ curve and initial moisture condition are the other important factors. Figs. 3 and 4 summarise these characteristics for Kanto-Loam expressed by Eqs.(3) and (4) with n=1.5, water head=15cm and initial moisture at 50% degree of saturation. The suction profiles of $\Psi = 0$ are shown for outside ring diameters D = 50, D=100, and D = 200 cm for time levels t=5, 15 and 30 min. Figs. a, b and c correspond to the K_0 values .005, .001 and .0001 cm/s respectively. Dotted lines of the figures correspond to profile of $\Psi = 0$ for the case of one-dimensional flow. Fig.4 shows the infiltration rates computed for an inside cylinder of 15cm diameter for each of these cases and the bottom most line shows the rate which corresponds to the one-dimensional flow. While the general pattern shown in these figures are applicable to all soil types, the exact amount of overestimation caused by different outside ring diameters is decided by the soil moisture characteristics as well as the initial moisture content.

Fig.6 shows the double cylinder experimental results and optimised flow curve. Top curve corresponds to a test with inside cylinder diameter=20 cm and outside diameter Dout=50 cm while for the bottom curve they were 15 cm and 174 cm respectively. The parameters obtained from the bottom curve were $K_0 = .00367$ cm/sec and n=1.5. The result is shown in Fig. 7. For the inverse solution initial condition was taken as constant moisture at 30% saturation. These parameters are taken to be representative of the soil.

Borehole Test

The soil is not expected to be isotropic and a two-dimensional infiltration test is required to obtain the horizontal saturated conductivity parameter. The borehole test is selected for this purpose even though this test is usually conducted to identify a single parameter in an isotropic medium. Even for a single parameter, as summarised by Stephens and Neuman(1982) the existing test formulae are based on the free-surface flow assumptions and the capillary flow is neglected. An attempt to obtain a general expression for borehole discharge was made by Philip(1985) including the capillary discharge, but since the resulting formula is not well suited for parameter estimation and is derived for an isotropic medium, we adopt the same parameter optimising technique for the general two-dimensional Richards' equation in radial cordinates. Theoretically all the parameters could be optimised, but due to the poor sensitivities of these parameters we take only the horizontal saturated conductivity Kh_0 as the unknown and use the vertical saturated conductivity Kv_0 and the n values determined from the previous one-dimensional test. The results of an experiment conducted close to the location of the previous experiment is shown in Fig.8. The estimated Kh_0 was .00091 cm/s (Fig. 7.). The borehole diameter used was 22 cm while the water head used was 15 cm.

FIELD EXPERIMENTS

Experiments were conducted on field models located 5 - 6 m from the location of the in-situ tests. The infiltration well used for the experiment is shown in Fig.9. Water head was kept constant inside the well by the use of solenoid valves and measurements were made at head=35 cm and h=110 cm. Flow rates required to keep constant heads were measured at intervals of 1 min at the beginning of the infiltarion and at 2-3 min intervals as the flow rate levelled off. An implicit finite difference formulation of the Richards' equation in radial coordinates based on ADIPT scheme was used for the simulation. Two sets of parameters were used for the simulation in which the first set is the parameters obtained from the in-situ

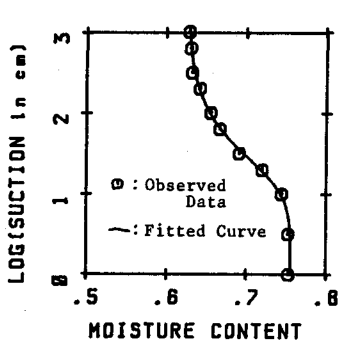

Fig.5 θ - ψ relation of in-situ test site.

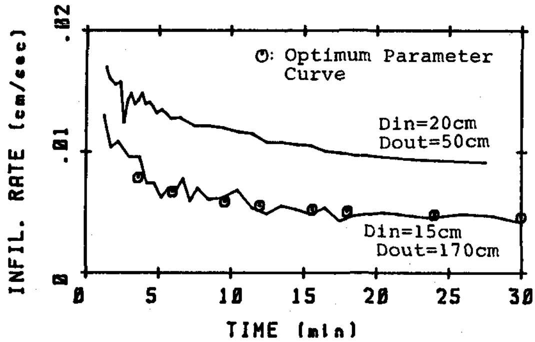

Fig.6 Double cylinder test results.

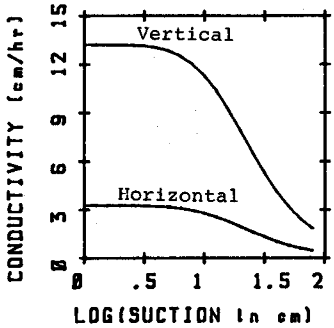

Fig.7 Estimated k - ψ relations.

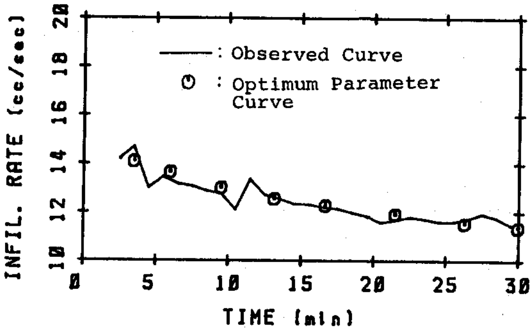

Fig.8 Bore-hole cylinder test results.

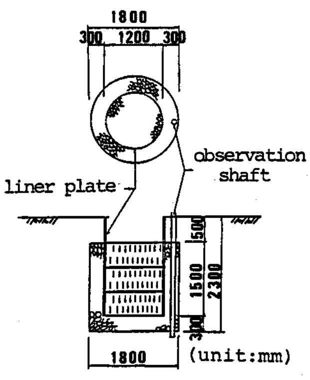

Fig.9 Field infiltration facility - Well.

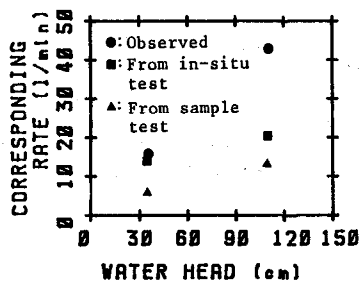

Fig. 11. Experimental and simulated results - Well.

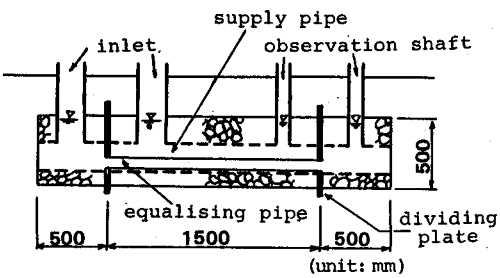

Fig.10 Field infiltration facility - Trench.

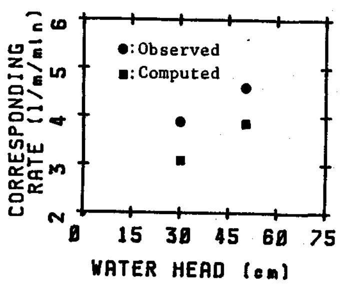

Fig. 12. Experimental and simulated results - Trench.

test described above. For the second set the saturated hydraulic conductivity was measured from the small field samples in the laboratory using the falling head method. Three samples were tested which gave K_0 values of 8.2, 7.8 and 8.1 x 10^{-4} cm/s, and their average was taken for the simulation. In this case both the horizontal and vertical parameters were taken as equal. The results are shown in Fig. 11. The values given are the nearly steady rates observed after 30 min and 40 min respectively.

A second test was carried out in a field trench model of which the geometry is shown in Fig.10. Two outer compartments were made at either side to minimise the corner effects so that flow rates for a unit length could be obtained from the inner compartment. Infiltration tests were carried out similar to the well for water heads at 30 and 50 cm. For the simulation, parameter set obtained from the in-situ tests was used and the results are summarised in Fig. 12.

RESULTS AND CONCLUSIONS

The results show that the estimated rates were lower than those measured experimentally for the infiltration facilities. This means that the estimated parameters were lower than a set of macro parameters required for the prediction of actual infiltration process. For the case of well we see that the in-situ parameters give a better estimate than the laboratory test parameters . While a conservative estimate is on the safer side from a design point of view, it is seen from the discussion on double cylinder test that overestimates could easily result if one-dimensional parameters were deduced from a flow which is not purely one-dimensional.

The performance of the in-situ test parameters for estimation can be viewed in the following manner. For the well, the low head simulation was better than the high head simulation which suggests that Kh_0 is a lower estimation. In the outflow from cylindrical sources the horizontal component plays a major role and in our borehole test we used only a head of 15 cm which may not have been high enough to reflect the horizontal flow component adequately.

For the trench the prediction is lower probably due to the parameter variation at different depths. From the relative magnitueds of sample tests at different depths it was observed that the saturated conductivity becomes smaller with decreasing depth. The in-situ tests were conducted at a location about 1.3 meters below the ground level while the trench was located from about 30 cm to 80 cm. below the ground.

In this study the parameters were estimated based on two in-situ tests. As we have observed large field variations of parameters even at the same depth at other locations, a better field representation could be made if a number of tests are carried out scattered around the location.

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