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A model study of mole drain spacing and performance

M. Rodgers[a,*], J. Mulqueen[b], J. McHale[a]

[a]*Department of Civil Engineering, National University of Ireland, Galway, Ireland*
[b]*Teagasc Walsh Fellow, Department of Civil Engineering, National University of Ireland, Galway, Ireland*

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Abstract

A model study on the spacing of mole drains and their influence on pore-water pressure heads was carried out using the finite element package SEEP/W for both transient-state and steady-state conditions. The aims were: to optimise mole drain spacing by modelling two drain spacings and to contribute to the understanding of mole drain performance; to compare pore-water pressure heads generated over a 12-day rainfall period by the model with those measured by a multipoint tensiometer in the field; to compare watertables for the two spacings under a range of steady-state rainfalls and hydraulic conductivity of the several soil layers. The drained field soil was three-layered, with a 150 mm thick permeable clay topsoil overlying a quasi-triangular wedge of permeable loosened clay soil over the mole drains that were drawn in a virgin clay subsoil of very low hydraulic conductivity. Mole drains of 0.075 m diameter were installed in the field at a depth of 0.45 m and tensiometer data were available for a spacing of 1.07 m; two spacings of 1.075 and 2.0 m were used in the modelling. There was good agreement between the pore-water pressures generated by the model and those measured by a multipoint tensiometer in the field for the 12-day sequential rainfall period. In the steady-state analysis, steady rainfalls of 5, 12 and 30 mm per day were imposed on a range of hydraulic conductivities of the soil layers for the two drain spacings. The close spacing of 1.075 m was shown by the model to give good control of the watertable while the more distant spacing of 2.0 m failed to control the saturation of the topsoil under a steady-state rainfall of 5 mm per day. For Irish soil and rainfall conditions, a mole drain spacing of 1 m or less is required to provide satisfactory control of the watertable in contrast with 2–3 m spacing commonly employed in the low-rainfall east of UK.

Keywords: Drainage; Finite element; Forestry; Mole; Spacing; Trafficability

* Corresponding author. Tel.: +353-91-750462; fax: +353-91-750507.
E-mail address: michael.rodgers@nuigalway.ie (M. Rodgers).

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1. Introduction

Soils with slow drainage characteristics comprise 21% of the soils of Ireland (Gardiner and Radford, 1980). These soils commonly have a permeable topsoil, 0.1–0.3 m thick, overlying a very slow draining structureless clay, silty clay or silt that may be many metres thick. The hydraulic conductivity of the topsoil generally varies from 1×10^{-6} to 5×10^{-6} m/s while the subsoil has values generally in the range 1.0×10^{-8} to 1.0×10^{-10} m/s. Drainage design in these soils entails placing the drains in the least permeable layer so as to control the watertable at sufficient depth below the ground surface for increased bearing capacity as required by trafficability, forest tree stability and crop growth; a steady-state drainage criterion commonly employed to meet these objectives is a watertable 0.3 m below the ground surface with a drain discharge of 10 mm per day. In order to promote rapid inflow to the drains and rapid drawdown of the watertable during and after rainfalls the subsoil above the drains must be loosened to increase its hydraulic conductivity (K). This can be seen in Eq. (1) which analyses the falling watertable induced by parallel ditches dug to an impervious layer once rainfall has ceased, using Dupuit–Forchheimer assumptions (Youngs, 1999).

$$\frac{1}{h_t} - \frac{1}{h_0} = 4\frac{K_s t}{pL^2} \tag{1}$$

where h_0 is the initial high watertable, h_t the watertable after drawdown in time t, t the time span of watertable drawdown, K_s the saturated hydraulic conductivity of the upper permeable layer, p the specific yield (drainable porosity) of the upper permeable layer, L the drain spacing.

Eq. (1) shows that a large K_s is required to induce rapid fall of the watertable for a given drain spacing and specific yield in a defined time span. Cost effective drain spacing for the above geometry can only be provided by mole drainage; mole drains 75 mm in diameter are commonly installed at a depth of 0.45 m below the ground surface in Ireland.

The design and performance of mole drains have been studied and reviewed for Irish conditions by Mulqueen (1998) and Robinson et al. (1987) and in general, by Spoor and Leeds-Harrison (1999). The depth and hydraulic conductivity of the upper permeable layer have a large effect on drain spacing requirements (Youngs, 1965, 1976); for Irish conditions with thin permeable topsoils a drain spacing of about 1 m is required with loosening of the subsoil layer between the topsoil and the mole drains, while spacings of 2–3 m are commonly used in UK to achieve rapid perched water drawdown and to include a factor of safety in the event of some mole channels failing (Spoor and Leeds-Harrison, 1999). Mathematical models of drainage systems are now widely used to facilitate the comparison of alternative solutions in a short time scale, for example, during the planning stages of a drainage project and also to extrapolate experimental results to a wide variety of soil, climate, crop and chemical management conditions. These models can also be used in the real-time operation of drainage systems (Nieber and Feddes, 1999).

Numerical simulation models have a particular relevance to the design and performance of drainage schemes for variably saturated flow systems because at the present time no analytical solutions exist for these (Nieber and Feddes, 1999). Agricultural drainage systems entail the flow of pore water through both unsaturated and saturated soil. Ignoring the compressibility of water and soil, the flow of water through a variably saturated soil into drains is described by the two-dimensional Richards equation for anisotropic conditions (Richards, 1931).

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta x}\left[K(x)\frac{\delta H}{\delta x}\right] + \frac{\delta}{\delta y}\left[K(y)\frac{dH}{\delta y}\right] + q \tag{2}$$

where θ is the volumetric moisture content (m^3/m^3), t the time (s), $K(x)$ the hydraulic conductivity in the x-direction (m/s), $K(y)$ the hydraulic conductivity in the y-direction [vertical direction] (m/s), H the total hydraulic head (m), q the applied boundary flux, e.g. rainfall or irrigation (m/s).

For isotropic conditions $K(x) = K(y) = K$. The form of the Eq. (2) shown can treat both saturated and unsaturated flow as well as flow in heterogeneous soils (Nieber and Feddes, 1999). However, the equation is highly non-linear due to the strong dependence of K on the pore-water pressure head. Accordingly, the equation must be solved by numerical methods or it must be linearised. A numerical finite element computer package SEEP/W developed by GEO-SLOPE (2001) is available to model flow into drains using Eq. (2) and was used in this study; a linearised procedure was adopted for unsaturated flow by Elrick and Reynolds (1986) using the matric flux potential as the variable for the Kirkhoff transformation and assuming an exponential relationship between the matric potential dependent unsaturated hydraulic conductivity, $K(\psi_m)$, and the field-saturated hydraulic conductivity, K_{fs} (Gardner, 1958). A full discussion on solutions for combined unsaturated and saturated flow in soils is given by Nieber and Feddes (1999).

The aims of this study were: to model two mole drain spacings of 1.075 and 2.0 m using the combined saturated/unsaturated flow theory to optimise the drain spacing and to improve the understanding of drain performance; to provide a transient-state analysis of watertable depths for a wet period and compare the output with data measured in the field by a multipoint tensiometer; and to compare the pore-water pressure heads for a range of steady-state rainfalls using the above spacings.

2. Materials and methods

A field plot experiment on the performance of mole drains in comparison with an undrained plot was reported by Burke et al. (1974) and further analysed later by Robinson et al. (1987). The mole drains were 0.075 m diameter and were drawn at a depth of 0.45 m and at a spacing of 1.07 m. The mole plough comprised a towed frame on which was mounted a thin vertical leg carrying a foot or mole with a trailing slightly larger expander at the base (Spoor and Leeds-Harrison, 1999; schematic diagram, page 1062). As the plough was drawn, the soil above the critical depth was loosened, while the mole and expander working just below the critical depth formed the mole channel. In the Irish context, mole drainage permits the installation of very closely spaced drains at economic cost while at the same time loosening the soil over the mole and either side of the leg. Mole drains in this clay have a life of 10 years or more but the soil loosening may have to be repeated.

Control of the watertable by mole drains improves the bearing capacity of soils and results in a 15–25% increase in grass growth in the spring, autumn and in wet summers,

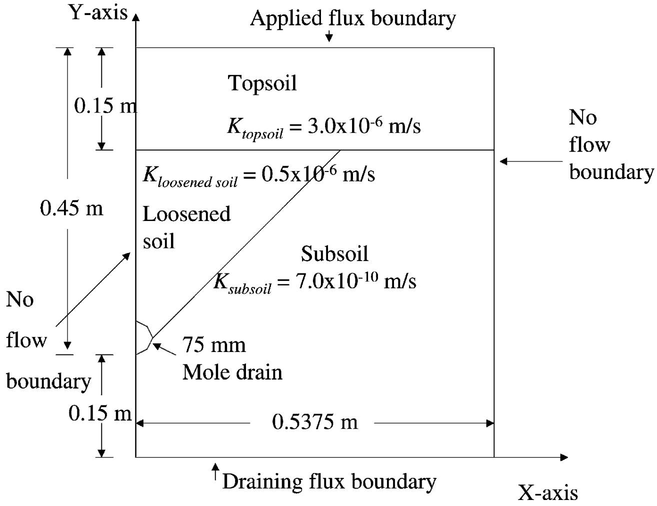

Fig. 1. Geometry and boundary conditions of a vertical semi-section of soil used in the finite element model with mole drains spaced at 1.075 m centres.

thereby extending the grazing season by 1–2 months (Mulqueen and Roche, 1975). Because soils suitable for mole drainage have clay and silt textures, mole drained lands require careful management. In forestry, mole drainage practically eliminates the development of excess pore-water pressures and piping induced by wind, results in increased depth and improved distribution of rooting and as a result stabilises forests against windthrow (Rodgers et al., 1995; McHale, 1998).

The tests were carried out on a two-layered clay comprising permeable clay topsoil, 150 mm deep, overlying structureless clay, down to 15 m thick. The K_s of the topsoil ($K_{topsoil}$) was measured at about 3×10^{-6} m/s and that of the clay subsoil ($K_{subsoil}$) at 7×10^{-10} m/s and these values, amongst others were used in the model study. During the course of drawing the moles a quasi-triangular wedge of soil at approximately 45° to the vertical was sheared, loosened and broken, over and about the mole as illustrated in Fig. 1, giving rise to an increased hydraulic conductivity, $K_{loosened\ soil}$. Due to a 17% slope, the moles in the test plot were always nearly empty. A multipoint tensiometer—reading to an accuracy of 10 mm—was placed midway between two adjacent mole drains to measure the pore-water pressure at various depths in the soil, including 0.15 m below the ground surface at the top of the subsoil.

A finite element software package SEEP/W by GEO-SLOPE (2001) was used to model the movement of pore water and its pressure distribution within the soil when mole drained. The package contains three separate programs that allow the drainage problem to be defined, solved and viewed graphically; these are Define, Solve and Contour respectively. The Define program involves drawing up the geometry of the drainage, selecting and defining the soil, generating the finite element mesh, assigning the boundary conditions and specifying the type and accuracy of the analyses etc. The Solve program computes the following parameters: total hydraulic and pore-water pressure heads at each node, velocities and hydraulic gradients at nodal points in each element, and flux quantities. The Contour program graphs the computed parameters.

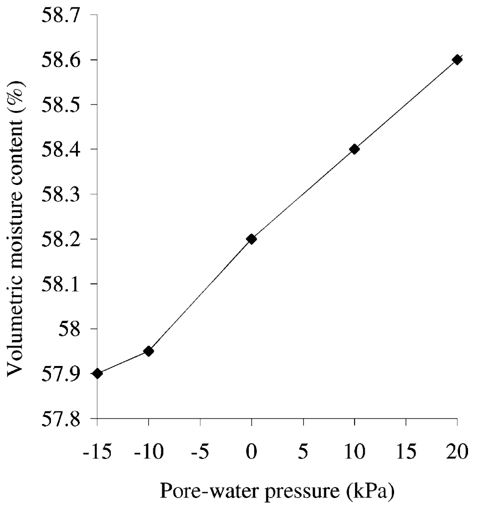

Fig. 2. Volumetric moisture content of clay subsoil against pore-water pressure (Mulqueen, 1990; GEO-SLOPE, 2001).

Two spacings of mole drains were used in the model, viz. 1.075 m, close to that employed by Burke et al. (1974) and 2.0 m as employed in a forest drainage experiment at Ballyfarnon, Co. Roscommon (Hendrick, 1989). In each case, the mole drains were 0.075 m diameter, with the invert at a depth of 0.45 m. The maximum depth employed in the model geometry was 0.60 m as the soil below this depth is essentially impervious. The geometry of the mole drain model for the 1.075 m spacing is shown in Fig. 1 and that for 2.0 m spacing was similar. The finite element mesh comprised quadrilateral and triangular elements, 12.5 mm high and 6.75 mm wide, with the nodes at the corners of the elements. Fig. 1 shows the boundary

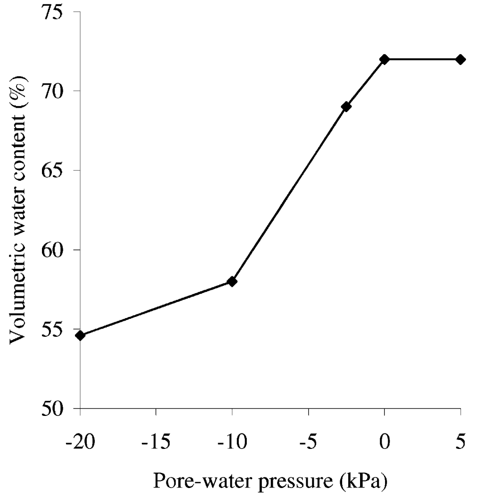

Fig. 3. Volumetric moisture content of topsoil against pore-water pressure (van Lanen and te Nuyl, 1997).

conditions employed, viz. no flow on the left and right hand boundaries and an applied flux on the upper and lower boundaries; on the lower boundary an exiting flux of 2×10^{-10} m/s was used, about 0.3 that of the $K_{subsoil}$ because the hydraulic gradients of 0.3 were commonly measured below the invert of the mole during the study period. The $K_{loosened\ soil}$ of the loosened soil wedge was varied in the finite element modelling until the pore-water pressure head results from the analyses were close to the field results. Other parametric studies were also carried out by varying the K values of the topsoil and loosened subsoil.

To define the soil properties, functions for the volumetric moisture content (θ_v) and the moisture-dependent K, $K(\theta)$ against pore-water pressure must be inputted in the Define program. Where the θ_v function only is known, the $K(\theta)$ function can be estimated from it using a method in Green and Corey (1971), and that procedure was used in this study. θ_v functions were taken to be similar for the topsoil and loosened soil; data for the topsoil and the virgin clay are shown in Figs. 2 and 3 respectively.

3. Results and discussion

Transient-state analyses were carried out for a 12-day rainfall period with daily rainfalls for the 12 consecutive days as shown in Fig. 4. The rainfalls were transformed into rates of meters per second over time in seconds. For example, a rainfall of 22.5 mm on Day 8 corresponded with a steady rate of 2.604×10^{-7} m/s over the time 604,800−691,200 s and

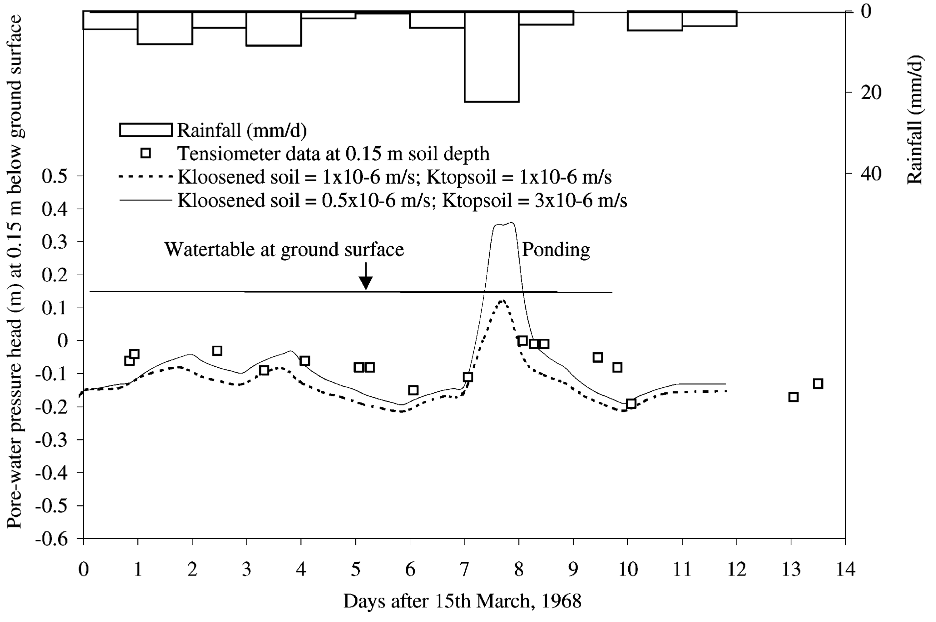

Fig. 4. Comparison of pore-water pressure heads (m) at 0.15 m below ground surface from SEEP/W analyses and tensiometer field measurements midway between mole drains at 1.07 m centres using rainfalls over 12 days in March 1968.

so on. In Fig. 4, the pore-water pressure heads at 0.15 m below ground surface computed by the transient-state analysis are compared with those measured by the multipoint tensiometer placed midway between the two mole drains. There was good agreement between the model output and the measured values from the field when $K_{\text{loosened soil}}$ in the model was taken at 0.5×10^{-6} m/s. Fig. 4 also indicates that the K value of the loosened soil is the critical parameter determining the control of the pore-water pressure in the surface soil layer. Most of the heavy rainfall on Day 8 was concentrated over a 3 h period that occurred shortly after the tensiometer was read in the morning. This rainfall could have led to saturation and ponding later on in the day as indicated by the model results. When the tensiometer was read on the following day—Day 9—the pore-water pressures indicated the water table was again below the ground surface. As the soil had gone through the winter period of wetting up, the loosened soil and topsoil would have reached very low K values

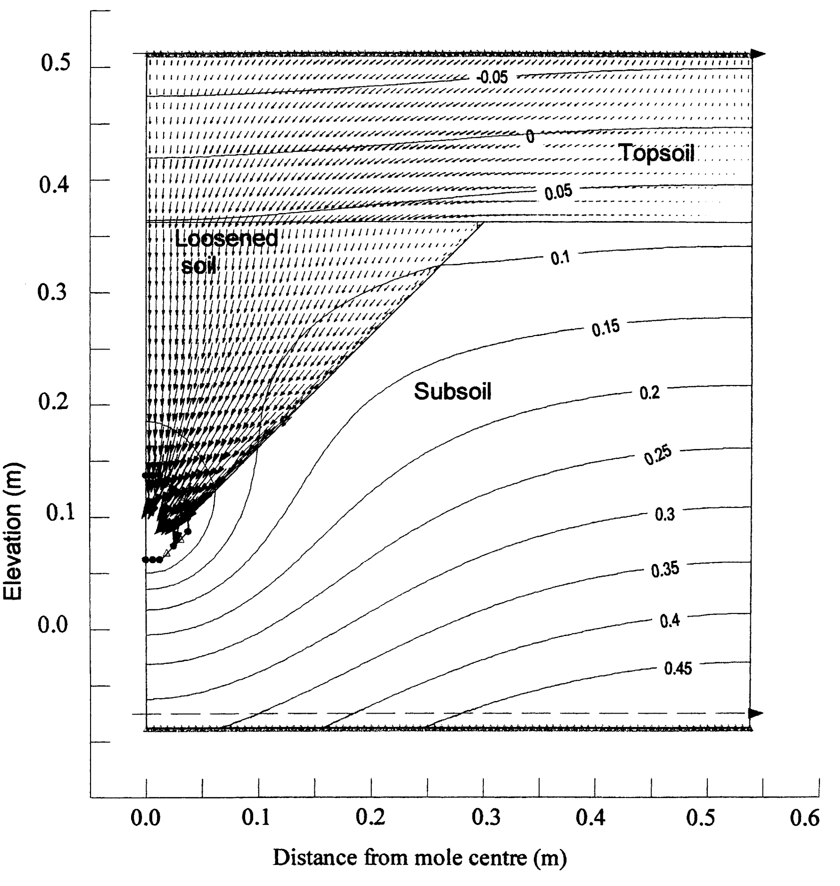

Fig. 5. Steady-state flow and pore-water pressure heads in soil with mole drains at 1.075 m spacing for a rainfall of 12 mm per day. Hydraulic conductivity values used were: $K_{\text{topsoil}} = 3.0 \times 10^{-6}$ m/s, $K_{\text{loosened soil}} = 0.5 \times 10^{-6}$ m/s and $K_{\text{subsoil}} = 7.0 \times 10^{-10}$ m/s. The watertable is indicated by the zero pore-water pressure head contour.

for this rainfall period leading to attenuation of peak flows through the drains (Robinson et al., 1987) and maximising surface run-off to 2–11% of rainfall (Burke et al., 1974).

In the transient-state analysis, 80 time steps were used over the 12-day period. Other numbers of time steps in the range 40–80 did not change the response significantly. Steady-state analysis with the watertable at 0.5125 m below the ground surface was used to establish initial conditions for the transient-state analysis.

Steady-state analyses were also conducted using three different rainfall fluxes, viz. 5, 12 and 30 mm falling uniformly throughout each day (5.8×10^{-8}, 1.4×10^{-7} and 3.5×10^{-7} m/s respectively). Typical outputs are shown in Fig. 5 for 1.075 m spacing and a recharge of 12 mm per day and in Fig. 6 for 2.0 m spacing and a recharge of 5 mm per day using the same K_s values for the soil component layers. A comparison of Figs. 5 and 6 shows that the watertable is about at the same position midway between the drains for both spacings i.e. within 100 mm of the soil surface; however, the recharge for the 1.075 m spacing was 2.4 that for the 2.0 m spacing. Neither drain spacing was able to control the watertable at 0.3 m below the ground surface for a steady rainfall of 12 mm per day as was also verified by surface run-off hydrographs (Burke et al., 1974). However, the drain spacing of 1.075 m was able to do so for a steady rainfall of 5 mm per day (Table 1), and in accordance with Eq. (1) would result in a rapid fall of the watertable on cessation of rainfall unlike the 2.0 m spacing since the rate of drawdown is inversely proportional to the square of the drain spacing. This rapid fall on reduction of rainfall is also illustrated in Fig. 4 on Day 9 for the model results.

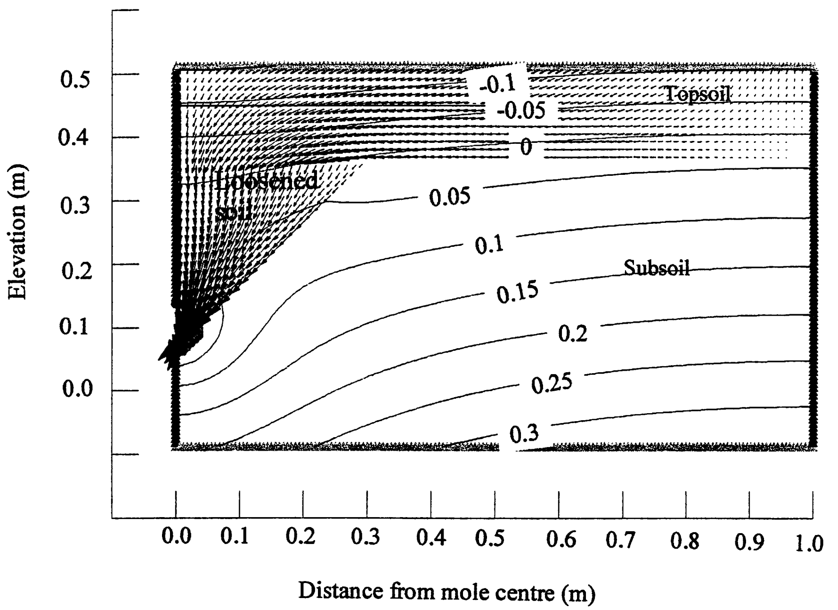

Fig. 6. Steady-state flow and pore-water pressure heads in soil with mole drains at 2.0 m spacing for a rainfall of 5 mm per day. Hydraulic conductivity values used were: $K_{topsoil} = 3.0 \times 10^{-6}$ m/s, $K_{loosened\,soil} = 0.5 \times 10^{-6}$ m/s and $K_{subsoil} = 7.0 \times 10^{-10}$ m/s. The watertable is indicated by the zero pore-water pressure head contour.

Table 1
Depth (m) to the crest of the watertable for two drain spacings, three steady rainfall rates and saturated conductivities of: $K_{topsoil} = 3.0 \times 10^{-6}$ m/s, $K_{loosened\,soil} = 0.5 \times 10^{-6}$ m/s, $K_{subsoil} = 7 \times 10^{-10}$ m/s and q (discharge at base) $= -2 \times 10^{-10}$ m/s

Rainfall (mm per day)	Drain spacing	
	1.075 m	2.0 m
5	0.30 m	0.11 m
12	0.06 m	Ponded
30	Ponded	Ponded

4. Conclusions

1. Transient-state analyses in real time over a 12-day rainfall period gave pore-water pressures that agreed well with those measured in a field test plot.
2. Mole drains spaced at 1.075 m centres gave moderate control of the watertable in the model study in late-winter/spring and because of higher K values in autumn/early winter would give better control then; mole drains at the more distant spacing of 2.0 m did not.
3. Both the model and experimental results demonstrate that mole drain spacing in Irish soils under prevailing climatic conditions must be at or closer than 1 m.
4. The hydraulic conductivity of the loosened soil over the plane of the mole, along with that of the topsoil, is the dominant parameter determining mole drain performance.

The primary factors that influence the performance of mole drains in the study soils with very shallow topsoils are: the spacing at which the drains are drawn—through its influence on the extent of loosened soil caused by brittle failure; the drain spacing through its influence on watertable response to rainfalls; the hydraulic conductivity of the loosened soil and topsoil; and the intensity of rainfall. The hydraulic conductivity of very slow draining subsoils has practically no effect on mole drain performance under Irish soil and climatic conditions.

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