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Depth, spacing and length of mole drains with applications to afforestation

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The draught of a mole plough and the spacings of mole drains for soil loosening and control of the groundwater table were calculated from theory and compared with measured values in two gley soils with stratification. The stability of mole channels against loads on the soil surface was also considered. There was good agreement between calculated and measured values of draught and drain spacing. Maximum measured draughts of the mole plough were low, in the range 30 to 40 kN. Mole drain spacing for soil loosening and control of the watertable was similar at about 1 m apart; this spacing conforms with tree planting practice in rows 2 m apart. The depth at which mole drains are drawn should be related to the soil profile. Surcharge loads from machinery are unlikely to cause roof failure of mole channels in soils with significant friction. The results are discussed in relation to the role of mole drainage in the prevention of windthrow in forests on gley soils and in particular to the need for soil loosening for effective drainage. Practical aspects of the installation of mole drains on gley soils in relation to slope, mole length and stability, erosion and ageing of the mole channels are considered. Further research is required on the effects of closure of the mole channel in some soils over time on watertable control and tree stability.

Keywords: Afforestation; mole drains

Introduction

Mole drainage is an effective and economical system of drainage for impervious soils with high silt and clay contents (gley soils). These soils commonly comprise a permeable organic topsoil (0.15 m deep) overlying a thick impervious overconsolidated subsoil high in silt and clay. The topsoil and subsoil have hydraulic conductivities of about 0.3 m/day and 1×10^{-3} to 1×10^{-4} m/day, respectively. Mole drains installed in these soils at the proper depth and spacing in dry conditions can control the watertable at 0.3 to 0.4 m below ground surface (Robinson, Mulqueen and Burke, 1987). Gley soils comprise about 21% of the land area of the Republic of Ireland

(Gardiner and Radford, 1980). They are mainly developed on soil parent materials high in silt and clay derived from shales, shaly sandstones and earthy limestones. Large blocks of these gleys are associated with Namurian rock formations in the drumlin belt and with Westphalian (Coal Measure) formations in Cos. Clare, Kerry and Limerick and the Castlecomer Plateau. Less extensive areas are found scattered throughout the country (Gardiner and Radford, 1980).

Effective mole drainage improves agricultural conditions through improved trafficability and reduced poaching, earlier and more grass with minimal rush growth (Mulqueen and Roche, 1975), improved efficiency of fertiliser and reduced liver fluke disease. Mole drainage practically eliminates surface run-off and nutrient enrichment of surface waters (Burke, Mulqueen and Butler, 1974). Due to reform of the Common Agricultural Policy of the European Union and other factors, mole drainage for agriculture has declined to negligible quantities in recent times.

Extensive afforestation is now taking place on these silt and clay soils. After rapid growth in the first 15 to 20 years there is widespread windthrow of the trees especially after thinning, due to poor anchorage. Mole drainage can control this windthrow. By controlling the watertable, mole drains result in deeper rooting (Coutts and Philipson, 1978; Hendrick, 1989), increasing the soil loading on the root plate. Mole drainage eliminates saturation with the resulting increase of effective stress on the root plate. In saturated conditions, high pore water pressures are built up in the soil by the sway of the trees (Rodgers *et al.*, 1995). These high pore water pressures lead to hydraulic fracture of the soil beneath the root plate in windy weather and result in windthrow. Mole drains must be installed before the crop is planted.

Mechanical and Hydraulic Aspects of Installing Mole Drains

There are two requirements which must be met in order to control the watertable by drainage in impervious silt and clay soils: (i) the drains must be installed at close spacings and (ii) the hydraulic conductivity of the subsoil slab above the drains must be increased to the order of magnitude of that of the topsoil.

Mole drains are installed by a mole plough that is drawn through the soil by a heavy duty wheeled or tracked tractor. A mole plough consists of a frame on which is mounted a narrow leg carrying at its bottom a cylindrical mole with an inclined leading face. As the mole channel is formed by the mole at the operating depth, the plough leg makes a vertical slit in the soil from which fractures at an angle of about 45° open up at both sides. The fractures point in the direction of forward travel of the mole plough in herringbone fashion. When the mole is drawn at the optimum depth, the fractures and loosening intersect the perimeter of the mole and increase the hydraulic conductivity of the subsoil slab above the plane of the mole and so allow surplus soil water to flow sufficiently fast into the mole drain. To loosen the entire slab, the plough must be drawn at such spacings that the loosening and cracking induced by each of two adjoining pulls of the plough at least meet midway and overlap. When the residual hydraulic conductivity induced by the plough is known, the spacings of the drains can be determined from drain spacing formulae using the boundary conditions and a design rainfall.

As the mole plough is drawn through the soil, the upper layers of soil above a plane, called the critical depth (Godwin and Spoor, 1977; Spoor and Godwin, 1978), are split and lifted upwards toward the soil surface and cracks may occur; the lower layers are displaced to the sides of the tool and move in a horizontal plane (Godwin and Spoor, 1977; and Figure 1) and compaction may occur in compressible soils. However, compaction is unlikely due to the over-consolidation and plastic state of subsoils in Ireland. When the soil is dry, there is brittle failure with much cracking in the upper soil layers above the critical depth which depends on the tool geometry and the stiffness of the soil. Below the critical depth, the energy to let the soil flow horizontally past the mole and leg is less than that necessary to lift and fail the soil in an upward direction. The ideal is to locate the mole just into the zone of horizontal flow with the leg in the lifting zone. In this configuration, the slab of soil over the mole is lifted, loosened and cracked with an increase in volume and hydraulic conductivity. Loosening is essential for the effective drainage of gleys in Ireland (Galvin, 1983; 1986). Because of higher and more frequent rainfalls and lower evapotranspiration in the growing season in Ireland, Irish silt and clay soils are wetter and less stiff than the clay soils of the east of England where mole drainage is common. Accordingly, mole drainage is a summer operation in Ireland in contrast to autumn and early winter installation in eastern England. In contrast with the clay soils in the east of England which are high in swell-shrink smectitic clay minerals, Irish clay and silt soils are substantially quartzose with much less swell-shrink and consequent differences in behaviour.

In this paper the draught of a mole plough and the drain spacing for soil loosening in two gley soils are calculated

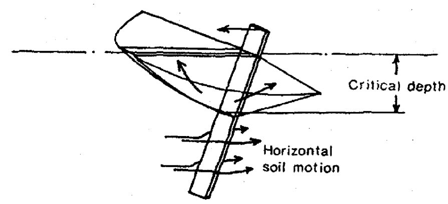

Figure 1: Soil movements about the leg of a mole plough (after McKyes, 1989).

from mathematical equations derived from the above theory (Godwin and Spoor, 1977; McKyes, 1989) and compared with measured values. The resistance of mole drains to roof failure from surface loads is also considered. The drain spacing for control of the watertable is derived from drain spacing formulae and compared with experimental values. Practical applications of the results are discussed.

Theory of Mole Plough Draught, Soil Loosening and Drain Spacing

The draught of a mole plough can be derived by calculating that due to the lifting action of the plough on the soil above the critical depth and that due to the horizontal deformations of the soil below the critical depth and summing. Mathematical expressions for the draught due to the lifting action of the plough on the soil have been derived by the application of the theory of lateral earth pressures on retainer walls in passive failure; it is assumed that directly ahead of the mole and leg there is a prismatic wedge of soil of constant width moved forwards and upwards while to each side of this prism there is a circular crescent edge section of the same radius as the prismatic wedge also moved but sidewards, forwards and upwards (Godwin and Spoor, 1977). A decrease in the rake angle (angle from the forward horizontal to the inclined blade) of the leg leads to an increase in the critical depth. The narrower the leg, the larger the circular crescents are relative to the central prism. Employing the assumed failure patterns of Meyerhoff about driven piles (Lambe and Whitman, 1969), it has been possible to derive a mathematical expression for the draught of the plough due to the horizontal deformations of the soil (Godwin and Spoor, 1977).

The spacing of the mole slots for mechanical loosening of the soil can also be calculated using the assumptions in Godwin and Spoor (1977). If it is assumed that loosening and cracking of the soil is limited to the moved soil above the critical depth, then the maximum permissible spacing of the mole drains for soil loosening can be estimated from the product of the critical depth and certain mathematical functions of the rake angle of the plough leg and the angles of internal friction of the soil and of soil-metal friction (Godwin and Spoor, 1977; McKyes, 1989).

Mechanical stresses from surface traffic can lead to roof failure in the mole. This could arise in site preparation for afforestation where tracked excavators are used to excavate collector drains across mole drains. The surcharge arising from loading by the tracks could cause roof failure which would be especially harmful at the outfall ends of moles. It is possible to analyse the effect of surcharges on the roof of a mole taking a worst case scenario of a wedge shear along radii such as mole plough cracks. The surchage load leading to failure of the roof can be calculated from theory that can be found in Bolton (1979), using both cohesive and frictional models.

The spacing of the mole drains for control of the watertable can be calculated or derived from a nomogram of Toksoz and Kirkham (1961). The design of land drainage entails the specification and installation of drains in the soil at such depth and spacing to control the elevation of the groundwater table at a predetermined depth below ground level against a design intensity of rainfall. The depth to the crest of the watertable is specified in relation to the depth and distribution of rooting and anchorage in forestry, and trafficability and plant growth in agriculture. However, the depth to which the watertable can be lowered in gleys, by mole drainage, is controlled by the critical depth of loosening where the subsoil is practically impervious. Drain spacing for a given depth of drain is determined primarily by the hydraulic conductivity of the soil, the design rainfall and the depth to the impervious layer below the drain.

Mathematical equations derived from the theories outlined above were used to calculate the values given in this paper.

Experimental Methods

Experimental measurements of draught of a mole plough were made on two gley soils near Ballinamore, Co. Leitrim. Soil 1 is a clay comprising a 0.15 m organic topsoil overlying an inorganic clay that is commonly plastic below about 0.25 to 0.3 m. Soil 2, a silt, comprises a 0.15 m organic topsoil overlying a hard angular gravelly inorganic clayey silt layer that changes to a plastic silty clay at about 0.4 m. These soils have been classified as Ballinamore Series and Garvagh Series, respectively, by Walsh (1974).

Relevant properties of both soils were measured. Texture was measured by wet sieving and sedimentation by the pipette method. Plastic and liquid limits were measured using the BS 1377 (1990) procedure. Bulk density, dry bulk density, void ratio and air voids were measured by soil sampling and by nuclear gauge with gamma and neutron sources in the field. Field moisture content was measured by sampling and oven drying. Cohesion and angle of internal friction were measured in a direct shear box. Adhesion and angle of soil-metal friction were measured in a direct shear box by drawing a smooth metal plate over the soil. In the gravelly silt soil the latter values were estimated. Values of cohesion, adhesion and friction angles were also available for another silt soil at Inagh (Kilrush Series in Finch, 1971), and are shown for comparison purposes and discussed in relation to stability of the mole.

The mole plough used in the tests had a 0.025 m wide leg to which was attached a 0.075 m diameter mole. The working depth for the mole drainage in both soils was 0.45 m. The critical depth was estimated as 0.25 m for the clay soil and 0.35 m for the silt soil. To measure the draught, a dynamometer was placed between the drawbar of a tracked tractor and the tow point of the mole plough. Readings of force were taken over 50 m long mole drains in both soils. The mole was then removed and the plough was drawn at the same setting to obtain the draught on the leg alone. The draught on the mole was then obtained by subtraction.

Results

Texture of the two test soils is shown in Table 1 along with plasticity values for the clay. The clay soil has the highest liquid limit of any glacial drift found in Ireland. The gravelly silt layer of the silt soil can contain 20 to 50% angular chert gravel.

Table 2 shows typical field values for bulk density and moisture contents of the two soils after dry weather. Bulk density and particularly dry bulk density increase with depth; the topsoils of both soils are very light. Repeat measurements by nuclear gauge in the silt soil showed that the clayey silt layer (0.3 to 0.45 m) is variable, probably due to differing gravel content.

Some mechanical values for the two test soils and the silt soil near Inagh (Co. Clare) are given in Table 3. The values are variable for the different soils and soil layers. The cohesion of the hard gravelly layer of the silt test soil is high.

Average and range of measured draughts are compared with calculated values for both soils in Table 4. Calculated values are larger than experimental values mainly because of the light brittle topsoil (when dry). Values of a similar order have been measured in New Zealand (Bowler, 1980) and by Godwin, Spoor and Leeds-Harrison (1981) in a range of four soils in England. The calculated values for the loosening draught force are 12.9 kN and 27.0 kN, respectively, for the clay and silt soils.

Below the critical depth, the soil is moved to the sides of the leg and mole. The draught force over the 0.125 m of leg and over the 0.075 m mole in this zone

Table 1. Texture and plasticity values for the clay and silt soils in the layer adjoining the topsoil

Soil	Composition (%)			Plastic limit ($\% H_2O$)	Liquid limit ($\% H_2O$)	Plasticity index ($\% H_2O$)
	Sand	Silt	Clay			
Clay	9	42	49	24	59	35
Silt	32	34	34	–	–	–

Table 2. Some physical properties of the clay and silt soils

Soil	Layer (m)	Bulk density (kN/m^3)	Dry bulk density (kN/m^3)	Water[1] (%)	Void ratio	Air voids (%)
Clay	0–0.075	12.6	7.4	70.0	2.03	21
	0.15–0.45	17.0	13.0	30.0	1.04	11
Silt	0–0.10	11.6	7.0	66.0	2.40	24
	0.05–0.10	12.6	8.3	47.5	1.85	22
	0.15–0.30	15.1	12.6	19.5	1.10	–
	0.30–0.45	17.9	14.9	20.0	0.74	9
	0.30–0.45	20.2	17.0	19.0	0.53	2

[1]Field moisture content

amount to 6.8 kN and 12.2 kN, respectively, for the clay soil. The total draught force for the leg is 19.7 kN and 31.9 kN for the mole and leg. The calculated mole draught comprises 38% of the total draught compared with 40% measured in field tests. Similar calculations for the silt soil indicate a leg draught force of 28.7 kN and a mole draught force of 15.7 kN making a total draught of 44.4 kN. The calculated draught on the mole is 35% of the total draught compared with 47% measured in the field tests.

The results of the calculations are sensitive to errors in estimating the values of the angles of soil internal friction and soil metal adhesion. A draught of about 45 kN may be adopted for practical purposes. Suitable allowance must be made for boulders and stones in the soil; in the clay soil, draughts of up to 40.1 kN were required to remove boulders and in one case a sustained draught of 47.7 kN failed to dislodge a boulder, with refusal due to skid.

Spacing of mole drains for soil loosening

Measurements for loosening in the clay soil indicate loosened widths of 0.75 to 1.2 m (Rodgers, Mulqueen and Kyne, 1989) and 1.07 m (Burke *et al.*, 1974). The calculated widths (s) of the side crescents for the clay and silt soils are 0.7 and 1.07 m, respectively, and the maximum permissible drain spacings are twice these values (Table 4). The values for s are sensitive to errors in estimating the critical depth, which is sensitive to changes in soil density and angle of internal friction. If neighbouring crescents are forced to overlap, as would be required to insure a factor of safety, the drain spacings should be closer than those in Table 4, e.g. about 1 m.

Table 3. Some mechanical properties of the two gley soils and Inagh silty clay

	Clay[1]	Silt			Inagh silt[1]
Layer (m)	0.15–0.45	0.05–0.10	0.15–0.30	0.30–0.45	0.15–0.45
Cohesion (kPa)	20	12	37	15	28
Internal friction (°)	34	29	27	39	19
Adhesion (kPa)	2	–	4[2]	2[2]	9
Soil-metal friction (°)	27	–	21[2]	23[2]	12

[1]Kyne (1988); [2]Estimated.

Table 4. Mean and range of measured draughts compared with calculated values for a mole plough working at a depth of 0.45 m

Soil	Mean (kN)	Range (kN)	Calculated (kN)	Ratio[1]	Drain spacing[2] (m)
Clay	22.1	29.0–13.4	31.9	1.10	1.4
Silt	32.0	37.9–24.5	44.4	1.17	2.1

[1]Calculated/maximum; [2]Maximum drain spacing for soil loosening.

A spacing of 1 m may be adopted as a practical measure and this is compatible with forestry planting practice of 2 m centres for trees.

Depth of the mole drain

The depth of the mole drain must be related to the soil profile conditions. The ideal is that the leg should be located in brittle soil while the cylindrical mole is in plastic soil. In clay soils such as that of Table 3 and SWG3/G3 soils as classified by Cruickshank (1997) in Northern Ireland, the invert of the mole drains could be located as shallow as 0.35 m and spacings could be as close as 0.6 m with trees planted beside every third mole. Mole drains drawn too deeply in plastic soils are not effective in controlling the watertable since the soil cracks do not intersect the wall of the mole drain and the single leg slit closes in over time.

Soil surface loading and the stability of mole channels

The effects of mechanical stresses from surface traffic on the roof of a mole channel can be analysed using a frictionless cohesive model and a frictional model (Bolton, 1979). Taking the cohesive model in Bolton (1979) and considering a soil of unit weight 17 kN/m^3 with an undrained shear strength of 20 kPa and a 0.075 m diameter mole drain at a depth of 0.45 m, the surcharge load leading to failure of the roof arch is 75.1 kPa. Under these conditions, the static surcharge load is quite low; this load can quite easily be exceeded by impact loads from the tracks during emptying an excavator bucket. There are gains from allowing mole-drained soil to age and dry out increasing the soil shear strength when dry weather is forecast before allowing traffic back on the land.

If on the other hand, a frictional model is used with a slight negative pore-water pressure (near zero) at the mole wall and using an angle of internal friction of 35° and a token resistance of 1 kPa in the wall of the cavity such as would be provided by the pore-water tension, then a surcharge of about 400 kPa would be required to fail the roof of the mole drain. This is large and unlikely to be obtained in practice at the depth of the mole.

Soil about the mole perimeter becomes wet and at or near liquid limit during drainage of free water. The perimeter soil may also experience a seepage force. Some soils under these conditions can experience creep, leading to a gradual reduction of the bore of the mole and eventually closure. Examples of such gradual closure were noted by the author in soils about Lisdoonvarna and Inagh in Co. Clare, for which some mechanical data are shown in Table 3. This soil has a low friction angle.

Hydraulic design: drain spacing

To apply the Toksoz and Kirkham (1961) nomogram to mole drainage of Irish gley soils, the following values for the parameters may be taken in the case of mole drains of 0.075 m diameter at a depth of 0.45 m:

1) depth below ground surface to the crest of the watertable midway between drains[1] = 0.35 m
2) depth to impervious layer below the centre of the mole drain = 0.0375 m
3) design rainfall rate = 0.012 m/day
4) hydraulic conductivity of the soil (after loosening) = 0.3 m/day

From the nomogram solution the drain spacing works out at 0.71 m. To fit in with forestry practice, this spacing may be relaxed to 1 m. Using mole drains at a spacing of 1.07 m, Burke *et al.* (1974) achieved good control of the watertable, practically eliminating surface run-off in grassland. The calculated hydraulic conductivity value derived from drain flow measurements in their experiment was 0.74 m/day. A mole drain spacing of 1 m appears about right.

Hydraulic design: length of mole drains
Considering only the transport capacity of the mole channel, long mole drains can be designed at spacings of about 1 m. In practice, there are limits to the lengths of moles, imposed by site and soil conditions. The main factors are uneven ground, stony soil and the soil properties affecting the stability of the loosening and mole channels. The length of mole drains can be controlled by the spacing of open collector drains which are excavated at about right angles to and deeper than the mole drains; these collector drains act as outfalls for the flow from the mole drains.

In ground of uneven gradients, backfalls can develop in the mole channels. These backfalls lead to ponding and waterlogging in the channel and result in premature failure through unconfined swelling (Spoor and Ford, 1987), structural collapse (Harris, 1984) and silting (Bowler, 1980). In uniformly sloping ground and in good moling soil, the length of mole drains may vary up to 50 m with 20 to 40 m being most commonly used in agriculture. In flat land and in steeply sloping ground, the length of mole drains is commonly 10 to 20 m but may be as short as 5 m in very unfavourable conditions e.g. stony soil and flat land with small depressions.

Mole drains drawn in dry conditions in the absence of free water and followed by dry weather have time to age and increase in strength (Spoor, Leeds-Harrison and Godwin, 1982). As a result, and apart from the effects of good cracking on hydraulic conductivity, mole drains drawn in dry conditions are better able to withstand stresses imparted to them by free water during drainage.

High flow velocities in the channel itself, as would be experienced in long moles on steep slopes, can give rise to wall erosion. Wall instability can also arise from the occurrence of sand lenses (from weathered sandstones) and gravel which can lead to failure of the channel and ponding in the mole. The erosion of a mole channel is a function of the hydraulic shear of the water flowing in the mole channel and two soil properties, the channel erodibility resulting from shear and the critical shear stress below which soil detachment is negligible (Schwab *et al.*, 1993). Hydraulic shear increases with slope and hydraulic radius. Mole erosion has been found on long mole drains when heavy rainfall occurred soon after drawing them (Mulqueen, 1974).

In suitable soils and sites under forestry, mole drains have a long life; at

[1]0.35 m is a watertable crest depth below ground surface with a discharge of 0.012 m/day commonly used for grassland in Ireland.

the Ballyfarnon forest near Riverstown, Co. Sligo, mole drains installed in 1971 at 2 m centres are still functioning well, 26 years later.

Discussion and Conclusions

Using classical soil mechanics and semi-empirical methods for solution, Godwin and Spoor (1977) have obtained equations that successfully predict the magnitude of forces on mole ploughs. These equations, when applied to two Irish moling soils with stratification, have given magnitudes of the right order for the draught of the mole plough and the drain spacing for the mechanical loosening of the soil. The results for two soils indicate that the theory can predict the maximum draught force, which is not very high. However, suitable allowance must be made for the occurrence of stones and boulders in the soil. The drain spacing for soil loosening and watertable control agree reasonably well, which is a rather helpful result.

Drain spacing theory and experiment show that very close drain spacings are required to control the watertable after the soil has been loosened (with a large increase in hydraulic conductivity) when drawing the moles. In an experimental investigation of the effects of loosening on flow to mole drains, Leeds-Harrison, Spoor and Godwin (1982) showed that, in a structured clay soil with a well-developed sub-angular blocky structure and a hydraulic conductivity of 0.022 m/day, mole drains overlain by mechanically loosened soil had a significantly faster response to rainfall than mole drains in the same soil not mechanically loosened. A subsequent theoretical analysis of the effects of fracturing by Youngs (1984/1985) showed that fracturing played an important role in increasing the rate of groundwater flow to mole drains; without the fissuring and loosening, groundwater flow to the mole drains is much slower and flow continues for much longer. In an Irish clay, Burke *et al.* (1974) showed that the discharge through mole drains with soil loosening averaged 505 mm/year over 5 years compared with 313 mm/year in surface run-off from an undrained plot. Galvin (1983; 1986) has highlighted the role of loosening in the drainage of Irish gleys. Installing drains by excavator involves little or no loosening of the soil with little or no increase in hydraulic conductivity (required to promote fast flow of surplus rainfall to the drains). The analysis and the studies indicate that mole drainage with soil loosening is the only practical and effective solution to the drainage of Irish gley soils of the type described. In the Ballyfarnon forest site with stable mole channels at 2 m centres, which gave reasonable control of the watertable, trees planted on mole drained land showed a large increase in rooting depth and more symmetrical rooting (Hendrick, 1989) and a significant increase in the ultimate overturning moment with negligible increase in pore water pressure compared with trees planted on undrained land [M. Rodgers, J. Mulqueen, J. McHale, E. Hendrick and M. Keane (unpublished)].

Soil profiles should be examined before deciding on the depth of mole draining in a field or farm. Clay and silt soils with plastic layers close to the soil surface should be mole drained at depths of 0.35 to 0.4 m and at spacings of about 1 m; greater depths (up to 0.6 m) are indicated on gley soils where the plastic soil layer is deeper.

The length of a mole channel between outfalls into open collector drains must be controlled by design, taking into account the slopes of the land to avoid backfalls on gentle slopes and erosion of moles on steep slopes, the stability of the mole channel, its resistance to erosion by flowing water and the stoniness of the soil in relation to interruptions in the bore of the mole channel. Blockages on long mole drains on slopes can result in large volumes of water breaking through onto the surface of the soil. Mole drain lengths of 10 to 40 m at spacings of 1 m are suitable for forest lands on many sites.

Where trees are planted in mounds, a collector drain spacing of 8 to 12 m is convenient as the drain spoil can be used to make the mounds. Blockages to the outfall ends of moles by machinery can be forestalled by offsetting the excavator on the downslope side of the collector drain when excavating. Lining the outfall ends of moles at collector drains with short lengths of plastic drain pipe removes the risk of closure of the mole outlets at the wall of a collector drain especially in soils of low stability.

Research is required to determine if mole drainage, which promotes deeper rooting in the early years of growth, confers a long-term benefit to tree stability in the event that the mole blocks up and to what extent the loosening effects above the mole channel contribute to improved drainage and tree stability in such an event.

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References

Bolton, M. 1979. 'A Guide to Soil Mechanics'. MacMillan Press Ltd., London, pages 310–315.

Bowler, D.G. 1980. 'The Drainage of Wet Soils'. Hodder and Stoughton, Auckland, New Zealand, page 165.

Burke, W., Mulqueen, J. and Butler, P. 1974. Aspects of the hydrology of a gley on a drumlin. *Irish Journal of Agricultural Research* **13:** 215–229.

BS 1377. 1990. Methods of Test of Soil for Civil Engineering Purposes. Part 2. British Standards Institution, London, pages 5–14.

Coutts, M.P. and Philipson, J.J. 1978. Tolerance of tree roots to waterlogging: 1. Survival of Sitka spruce and lodgepole pine. *New Phytologist* **80:** 63–69.

Cruickshank, J.G. (ed.). 1997. Soils and Environment: Northern Ireland. Agricultural and Environmental Science Division, Department of Agriculture for Northern Ireland and The Agricultural and Environmental Science Department, The Queen's University of Belfast, 214 pages.

Finch, T.F. 1971. 'Soils of Co. Clare'. Soil Survey Bulletin 23. An Foras Talúntais, Dublin, 246 pages.

Galvin, L.F. 1983. The drainage of impermeable soils in high rainfall areas. *Irish Journal of Agricultural Research* **22:** 161–187.

Galvin, L.F. 1986. Impermeable soils require stable channels and good crack formation for effective drainage. In: 'Hydraulic Design in Water Resources Engineering: Land Drainage' (ed. K.V.H. Smith and D.W. Rycroft), Springer Verlag, Berlin, pages 413–422.

Gardiner, M. and Radford, T. 1980. 'Soil Associations of Ireland and their Land Use Potential'. Soil Survey Bulletin 36, An Foras Talúntais, Dublin, 142 pages.

Godwin, R.J. and Spoor, G. 1977. Soil failure with narrow tines. *Journal of Agricultural Engineering Research* **22(3):** 213–228.

Godwin, R.J., Spoor, G. and Leeds-Harrison, P.B. 1981. An experimental investigation into the force mechanics and resulting soil disturbance of mole ploughs. *Journal of Agricultural Engineering Research* **26:** 477–497.

Harris, G.L. 1984. Effects of mole submergence on the life of mole channels. *Agricultural Water Management* **8:** 361–374.

Hendrick, E. 1989. Effect of cultivation method on the growth and root anchorage of Sitka spruce. *Irish Forestry* **46(1):** 19–28.

Kyne, M. 1988. An experimental investigation into the effects of ribbed blades on soil displacements induced by mole ploughs. *M. Eng. Sc. Thesis*, National University of Ireland, Galway, 194 pages.

Lambe, T.W. and Whitman, R.V. 1969. 'Soil Mechanics'. John Wiley and Sons Inc., New York, pages 498–506.

Leeds-Harrison, P.B., Spoor, G. and Godwin, R.J.

1982. Water flow to mole drains. *Journal of Agricultural Engineering Research* **27**: 81–91.

McKyes, E. 1989. 'Agricultural Engineering Soil Mechanics'. Elsevier, Amsterdam. Chapter 8, pages 192–221.

Mulqueen, J. 1974 . 'Drainage of Impeded Soils'. An Foras Talúntais, Dublin, 76 pages.

Mulqueen, J. and Roche, A. 1975. Land Reclamation and Drainage. In: 'Leitrim Resource Survey' Part 2, Chapter 2, An Foras Talúntais, Dublin, pages 3–25.

Robinson, M., Mulqueen J. and Burke, W. 1987. On flows from a clay soil - seasonal changes and the effect of mole drainage. *Journal of Hydrology* **91**: 339–350.

Rodgers, M., Casey, A., McMenamin, C. and Hendrick, E. 1995. An experimental investigation of the effects of dynamic loading on coniferous trees planted on wet mineral soils. In: 'Wind and Trees' (ed. M.P. Coutts and J. Grace), Cambridge University Press, Cambridge, pages 204–219.

Rodgers, M., Mulqueen, J. and Kyne, M. 1989. An experimental investigation into the effects of ribbed shanks on soil displacements induced by mole ploughs. *Proceedings of the 11th International Congress on Agricultural Engineering* **3**: 1627–1632.

Schwab, G.O., Fangmeier, D.D., Elliott, W.J. and Frevert, R.K. 1993. 'Soil and Water Conservation Engineering' (4th edition), J. Wiley and Sons Inc., New York, page 95.

Spoor, G. and Ford, R.A. 1987. Mechanics of mole channel deterioration. *Journal of Soil Science* **38**: 369–382.

Spoor, G. and Godwin, R.J. 1978. An experimental investigation into the deep loosening of soil by rigid tines. *Journal of Agricultural Engineering Research* **23(3)**: 243–258.

Spoor, G., Leeds-Harrison, P.B. and Godwin, R.J. 1982. Some fundamental aspects of the formation, stability and failure of mole drainage channels. *Journal of Soil Science* **33**: 411–425.

Toksoz, S. and Kirkham, D. 1961. A graphical solution to a new drain spacing formula. *Journal of Geophysics Research* **15**: 115–129.

Walsh, M. 1973. The soils. In: 'Co. Leitrim Resource Survey', Part 1 (Chapter V), Soil Survey Bulletin 29, An Foras Talúntais, Dublin, pages 18–43.

Youngs, E.G. 1984/1985. An analysis of the effect of the vertical fissures in mole-drained soils on drain performances. *Agricultural Water Management* **9**: 301–311.

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