



Design and Crop Response Parameters of Mole Drainage Systems in Heavy Clay Soils - A Review

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Abstract: Drainage needs to reclaim its rightful position as an indispensable element in the integrated management of land and water. Although draining heavy clay soils poses special problems, reasonable solution can be found on soil conditions and local factor. Mole drainage systems have proved much more efficient and economical than pipe/tile drainage systems in heavy clay soils. Mole drains are unlined cylindrical channels which function like clay or plastic pipes and are formed using an implement called a mole plough. This paper presents a review of design parameters for mole drainage system and their effectiveness for crop production. The study revealed that several researchers, mostly outside India have studied the design parameters for mole drain formation and influence of mole drainage on crop production.

Keywords: Mole drains, Drain spacing, Drain depth, Production, Vertisols

The sustainability of irrigated agriculture is under threat due to widespread occurrence of water logging and soil salinity. Drainage can be viewed as the “price to pay” for the sustainability of irrigated agriculture if considered in a holistic approach in the framework of integrated in water management improvement strategies and as part of rural development at large. Drainage is an effective tool in combating the negative effects of salinity and water logging (Vardhan *et al.*, 2014).

Vertisols (clay soils) occupy over 320 mha (2.5%) of the global land area and found under a wide range of climates with major part (about 83%) under semiarid and arid conditions. Vertisols offer good prospects of production when adequately drained since they suffer from flooding, surface ponding and or waterlogging. Characteristics of Vertisols (FAO, 1990) include (i) small size particles and large surfaces area, (ii) very poorly permeable, (iii) low to very low hydraulic conductivity, (iv) very hard and difficult to cultivate when dry and very sticky when wet. In India, maximum area of *vertisols* is found in *Maharashtra* (29.9 mha) followed by *Madhya Pradesh* (16.7 mha). Surface and sub surface drainage technologies can be adopted to control the water table. However, surface drainage is limited by the fact that a natural outlet should be present in the vicinity of field to be drained. Sub-surface drainage system is the only option to realize the full potential of crop production by creating artificial drainage to control the soil salinity and managing the water table below the root zone (Vardhan *et al.*, 2014). Though, sub-surface

drainage system with tiles, perforated plastic pipes is a technique by which water table can be controlled by collecting water in a sump and subsequently pumping them out, it involves huge initial investments. An alternative, cheaper system is mole drainage and this system has proved very successful under non-irrigated conditions in countries such as the United Kingdom and New Zealand. Mole drains are cylindrical channels artificially produced in the subsoil without digging a trench from the surface. They are similar to pipe drains except that they are not lined with tile or other stabilizing materials. Moling is a temporary method of drainage where soil conditions are suitable mole function efficiently for the few first years and then gradually deteriorate. Mole drainage alone, on the hand, usually offers a good solution to drainage problems in most clayed soils. Soil loosening by deep ploughing or subsoiling to improve hydraulic conductivity is only justified in situation where mole drainage would be unsuccessful. The major soil properties influencing the suitability of soils for pipeless drainage are clay content, clay mineralogy, nature of exchangeable cations, type of deposit and bulk density (Spoor *et al.*, 1982a). The most favourable condition for pipeless drainage are homogeneous, clay-rich soils at optimum soil water status (Nicholson, 1953; Hudson *et al.*, 1962; Cooper, 1965). Ideal clays for moling are calcareous, stone-free clays of the smectite group of mineral and which are subject to an appreciable soil water deficit during the dry season (Farr and Henderson, 1986). This paper reviewed the design & crop

response parameters of mole drainage **systems** in heavy clay soils.

Selection of design parameters for mole drainage system: Mole drain depth and spacing are usually not computed. The low installation cost, in general does not justify the expense of investigations and allows for a close spacing with a great safety margin. Although the spacing is related to soil texture in some countries in Eastern Europe, it is largely determined based on local experience in most countries (Jha and Koga, 2002).

Spacing of mole drains: To ensure proper fissuring of the soil through the area, the spacing of mole drains varies from 2 to 5 m is commonly applied (Theobald, 1963). If the spacing is less than 2 m, there is a danger of damage of the previously constructed drain where as if the spacing is greater than 5 m the fissuring effect may not cover the intervening space. However, it depends on the soil permeability and the necessity of drainage also. Mole drains constructed at 2m, 4m and 6m spacing and depth 60cm drains are functioning well since last five years and more effective in soybean crop (Ramana Rao *et al.*, 2009b).

Depth of mole drains: Mole channel should be deep enough to be protected from the load of heavy farm machinery and from the climatic phenomena. Moreover, the deeper the channels are, the greater is the extent of fissuring. However, installation costs increase with depth. Suitable depths are found to be 45-55 cm in New Zealand and 70-90 cm in Eastern Europe (Raadsma, 1974). Pipeless drains should be installed in the depth range of 55-80 cm i.e. at a depth at which they will attain the highest stability (Soucek, 1965). Pipeless drains are limiting in depth depending on the power available to construct drains and efficiency of the drainage system (Cavallars, 1974). In practices, a mole drains depth of 40 to 60 cm from the soil surface is normally adopted (Jha and Koga, 2002).

Length of mole drains: The length of mole channels depends on the grade of the mole drains formed, soil type, shape, size and topography of the field. Flat slope requires shorter drain. Generally adopted/accepted maximum effective length of moles is 200 m. Safe drain lengths vary from 20 to 80 m and should be decided on the basis of local experience (Smedema and Rycroft, 1983).

Outlet of mole drains: Just after the mole drains installation, the loose soil should be removed from the outlet and 1 to 3 m pipe should be inserted into the mole drain channel to prevent outlet destruction and soil erosion (Husson *et al.*, 1962).

Moling parameters: Childs (1943) pointed out that a study of the mechanics of the mole drainage brings out chiefly the point that the cartridge, if properly set, tends to maintain itself at the set depth, ignoring local surface bumps and

depression. The function of producing regular falls despite surface irregularities is best left to the cartridge, without making use of the beam as a bridging device, because the latter arrangement can cause serious channel fault. The true value of a long beam is that it enables full use of the self adjusting power of the cartridge (Schwab, 1947). The principal factors that affect the power requirement are speed of the power unit, depth and size of torpedo, soil type and moisture content. He reported that the power requirement was 30 and 70 hp for moling depths of 0.6 and 0.9 m, respectively. Movement of soil during the moling operation was carried out by Wells (1951). He found that the passage of mole plough caused a wedge of soil to be disturbed in front and to the side of the plough standard. He also pointed out the way in which the fissures are connected directly into the mole channel, which facilitate water entry into the channel. Primary aim of pipeless drainage is not control the groundwater level, but to remove excess water from the field or the topsoil where it may form a perched water table. Water flow to the mole channels is usually by preferential flow through the leg fissures or cracks developed at the time of drain installation reported by Childs (1943), May (1976), Goss *et al.* (1983), Spoor and Leeds-Harrison (1999), Schwab (1957) and Cavelaars *et al.* (1994) reported that the initial cost of pipe less drainage is as low as $1/10^{\text{th}}$ of that of tile drains, but the short life is the main disadvantages.

Norum and Gray (1964) observed that the pull in sandy loam soil was 2250 kgf at a moling depth of 42.5 cm and moisture level 15%, whereas, in clay loam soil, it was 6300 kgf at a moling depth of 60 cm and moisture level 11%. Cooper (1965) specified the torpedo length of between 37.5 and 90 cm and the diameter from 2.5 to 15 cm. A good mole plough should produce a 8.8 cm hole, cline and round at a depth of 65 cm. Twocock (1970) reported that moling is generally unsuccessful unless there is soil moisture deficit at the time of operation wet condition make the operation more difficult and damage the soil surface. Under such condition shattering will not occur and only the plough leg produces a smeared slot. In this case the only way water can enter the mole channel is by flowing over the surface or by along the plough layer, and then down the slot into the channel. Furthermore the soil disturbance and crack development above the mole channel during installation is more upon the prevailing moisture conditions than is channel formation itself. Trafford and Rycroft (1972) investigated the water table behavior in drainage experiment on heavy clay soils and found that the water table dropped quickly to the mole channel invert level after rain stopped, whereas the water table fall was much slower on the tile drained plot. This difference in water table behavior could have been due to a

rapid flow of water into the mole drain caused by cracks or it could have simply been due to close drain spacing on the moled plot or both. According to Cavelaars (1974) depth of drains depends on the power available to construct drains and the efficiency of the drainage system. In practice, a drain depth of 40 to 60 cm is adopted. They reported that the size of mole drain is determined by local experience rather than the required hydraulic capacity. The size of mole channels may vary from circular to an oval shape depending upon the subsoiling moisture and the set of machine. He also reported that since the pipe less drainage system has to be renewed from time to time, the accompanying fissuring gradually creates a better structure in the soil and improves its permeability. Raadsma (1974) and Sommerfolt (1987) found that several attempts have been made to strengthen mole channels by lining the walls with plastic strips concrete, bituminous fiber, hot bituminous, and other stabilizing emulsion. The main purpose of lining was to enhance the life of mole drains and to make mole drainage application under less favorable conditions. Forero (1975) found that 2 m spacing was the most effective in leaching compared to 4 to 8 m drain spacing; leaching effect were insignificant in the latter case. Singh (1978) measured pulling forces in the Bangkok clay soil as 2.08 and 1.48 tons, respectively when the soil moisture was respectively 38.7 and 29.7% by weight. Furthermore, Hassan (1981) observed that the force required to pull the mole plough at 40, 50 and 60 cm depths was more than 3 tons. Based on the field experiment in Bangkok clay soil, Hassan (1981) found that mole drains constructed at 3 m spacing 50 cm depth were more stable and more effective in terms of extent of fissures and drain-outflow behavior. In fact, owing to the relatively low cost of moling, the cost is not normally a major consideration for selecting the spacing of pipeless drains.

Mole channels gradually lose their effectiveness. Their working life time in fair to good condition is of the 3 to 15 year (FAO, 1971). However, much shorter and much longer lifetime (e.g. 30 to 40 years) has also been recorded (Smedema and Rycroft, 1983; Mueller, 1988; Spoor and Leeds-Harrison, 1999). The only method of repair is to reconstruct mole channels. Sommerfeldt *et al.* (1987) carried out a study to determine the bulk density distribution of soil around mole drains and also the smear and conditions at the surface of the mole. Drains were installed at 50, 70 and 90 cm depths in a clay loam soil. Three water treatments were used on the soil: not flooded (D), flooded 1wk prior (F1) to installation, and flooded 1 day prior (F2) to installation of the drains. The water treatments affected the conditions of the moles, the fracturing of the soil above the moles, and the bulk density of the soil around the moles. The greatest amount of

smearing around the perimeter of moles was observed in the F2 treatment and the least was in the D treatment. Visible fracturing of the soil above the drains was affected by depth of installation as well as by water treatment. In 50-cm-deep drains, fracturing started at the side of the mole and fanned out upward to the surface. In 90-cm drains there was minimal fracturing, starting at about the 50-cm depth. Most fracturing occurred under the D water treatment, whereas fracturing was least in the F2 treatment. The mean bulk density of the soil above the moles was smaller than that below the moles, where it was similar to that of the undisturbed soil. Compaction of the soil around the mole, though significant, should not impede drainage. Drag between the bullet and the soil should remove segments of the smeared skin, leaving sufficient areas of unsmeared soil through which water can easily enter the drains. Thus, water entry into the moles should not be restricted by compaction or smear, regardless of depth of installation or water content of the soil during installation.

Weil *et al.* (1991) examined the condition of mole drains having various slopes and depths using a borescope over a three year period; three years after their installation, most mole drains were in good condition and had remained at least half open on both sites. Water table drawdown was significantly faster in the mole drained plots compared to undrained plots and an adjacent tile drained plot. Freeze-thaw cycles were not detrimental to mole drain effectiveness. Hann (1994) in his study suggested that while maintaining a constant grade is often not essential, reverse gradient that induce water ponding and sudden grade changes need to be avoided in order to minimize the risk of mole channel collapse. Cavelaars *et al.* (1994) reported that the type of leg slot and leg fissures development and mole channel connection required at the time of installation depend upon the particular drainage problem or moling application. The desired water flow routes to the mole channel vary from almost 100% localized flow through the leg slot and fissures, to the situation where flow is largely through the soil mass between the mole drains with little flow through the fissures.

Christen and Spoor (1999) conducted field experiment in southeastern Australia to investigate the efficiency of various methods for reducing irrigation water flow rates into mole drains and the subsequent effect on mole channel stability. It was found that localized crack sealing methods using a trailing wedge behind the mole plough, followed by tractor wheeling or rotavation was unsuccessful. However generalized surface tillage to create a fine surface tilth about 100 mm deep was successful in reducing mole drainage discharge and improving stability. Preventing discharge from mole drains during irrigation was particularly effective in

reducing mole flows and was not found to reduce mole channel stability compared to high rates of drainage throughout an irrigation event. Furthermore, sprinkler irrigation was found to result in lower mole drainage than flood irrigation, and improving mole stability. Positioning the mole away from areas where water is ponded on the soil surface for irrigation. Such as furrow, also result in lower drain flows and stability.

Rodgers *et al.* (2003) carried out a model study on the spacing of mole drains and their influence on pore-water pressure heads using the finite element package SEEP/W for both transient-state and steady-state conditions. The drained field soil was three-layered, with 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.

Crop response to mole drainage systems: Spoor *et al.* (1982a) concluded field and laboratory studies to examine the various stresses that can arise in the vicinity of a mole channel from its formation to ultimate collapse. It was observed that the major types of mole channel deterioration in the field include reduction in channel diameter, changes in channel shape, slurry formation, roof collapse, siltation and wall erosion. Proposed potential failure mechanisms are: (1) unconfined swelling, cyclical swelling/shrinking, swelling following crack infill, swelling after remolding; (2) elastic recovery following compression, relief of pore pressure, relief of low pressure within channel; (3) time-dependent flow/creep; (4) soil structure collapse, de-flocculation; and (5) excessive crack development, soil infill, erosion, siltation, soil surface loading. The major soil properties associated with these failure mechanisms are: (1) shear strength, shear stress/strain relationship, consolidation property; (2)

swelling/shrinking behaviour; (3) apparent viscosity; and (4) aggregate stability. Spoor *et al.* (1982b) found that the major soil properties influencing the suitability of soils for pipeless drainage are clay content, clay mineralogy, nature of exchangeable cations, type of deposit, and bulk density. Unfortunately, it is impossible to define necessary limiting values or ranges for the individual soil properties since they are all interactive and in many cases the interactive effects are additive. In addition, their interactions with climatic and installation factors also play a major role in determining the final over all stability. Leeds-Harrison *et al.* (1982) studied the mechanism by which water flow to a pipeless drain. It was observed that large cracks created during mole drain installation fill and empty at very low suction and provide a direct route for water flow to the mole channel. This results in a rapid water flow to the mole channel. However, if no such cracks exist, the efficiency of the drainage system is solely dependent on the natural hydraulic conductivity of the undisturbed subsoil. Such a situation may arise in the field due to ineffective fissuring of the soil during the moling operation or subsequent crack sealing due to soil swelling or the action of an expender. Thus, the contribution of crack flow is of great importance in most mole able soils.

According to Smedema and Rycroft (1983) moling is best suited to clay soils with minimum clay content of about 30%. They reported that the critical depth occurs at a depth corresponding to an ratio (tine depth/tine thickness) of the order of 5:7. The attraction of pipeless drainage lies in its low installation cost and its efficacy in places where conventional subsurface drainage systems (e.g. pipe/tile drains) are physically not feasible it is worth mentioning that a pipeless drainage should not be simply considered as a cheap, shallow closely spaced unlined version of a pipe drainage system rather, it is a soil and drainage improvement measure, whereby the latter supports the former, and vice versa, based on cracking subsequent improvement of the subsoil and on the provision of lateral outflow facilities for impeded flow through mole channel. Robinson and Beven (1983) reported that the results of a plot experiment to determine the effects of mole drainage on the hydrological response of a swelling clay soil under pasture are described. It is shown that the response is very dependent on antecedent moisture conditions, and that higher peak flows may be generated under relatively dry conditions on the (drier) drained plot. This appears to be related to the generation of flows in interpedal macropores supplying water to the mole drains. Under wet conditions, the hydraulic efficiency of the macropores is reduced by swelling of the clay and surface saturation develops on the undrained plot. This results in generally higher peak discharges than from

the drained plot. Recession discharges and total water yields are almost always higher from the drained plot. The implications of this work are that it may be very difficult to detect or model the influence of clay land drainage on river flows. Harris (1984) in experiments on good moling soil, observed about 20% reduction in the hand, on some of the very stable paddy soils in Jiansu Province of China, submergence for 60 days does not appear to cause serious deterioration (Spoor and Leeds-Harrison, 1999). Farr and Henderson (1986) found that it is of great importance that the moisture conditions of the soil be favorable during the mole drain installation because dry clay are hard and brittle, while moist clay are soft and plastic. Good mole drainage requires a stable, well formed channel connected to the by leg fissures. The fissures are formed at an angle of 45 degree to the direction of travel. The best condition occurs when the soil around the moling depth is in the plastic state and the above is in a friable state. The surface soil must also be dry enough to ensure proper traction during construction. When moled in this condition, a cleaned smooth channel and a slot are formed and the passage of the blade leaves and fractures a cone shaped zone above resulting in an increase in the permeability and soil porosity to a marked extent. Dewey *et al.* (1987) conducted field/labatory study for five years. They found out that the use of unlined mole channels as an alternative for, or a supplement to conventional subsurface drainage, could be considered. Mole drainage is more successful in the heavy Rensburg and Willowbrook soil farms than in the variable duplex soils such as those of the Kroonstad and Longlands farms. The factors of slope, antecedent and current soil moisture content, soil bulk density, and soil type are important in determining the success of the installation and performance of a mole drainage system. Various guidelines are outlined for the use of mole drainage in the sugar industry. Eggelsmenn (1987) reported an increase in crop yield from 20 to over 100% due to pipeless drainage. Mueller and Schindler (1992) also found a significant increase in crop yields due to pipeless drainage over 10 years. Pipe less drainage was earlier called mole drainage or earth drainage. It was first developed in England, today it is successfully used in many countries as cited by Egglesman (1987) renamed "mole drainage" as "pipe less drainage" after the positive experience at home and abroad and consequently acknowledged it as a fully accepted drainage methods on the same footing as the pipe drainage. The old practice of pipe less drainage which has existed prior to the manufacture of tile was considered to be a temporary method. Spoor and Ford (1987) carried out field and laboratory investigations to identify potential soil and climatic factors influencing mole channel and fissure stability.

It was found that, of seven distinct potential channel failure mechanisms, four are directly connected with implement disturbance. These are wall, expander, and sub-soiler and topsoil failure. Although soil factors have the greatest influence on the cyclical swell/shrink, unconfined swelling, and slurry failure, the mole plough has important indirect effects. Differences in soil condition during installation produce marked differences in subsequent channel stability. Hence, modification to the implement to change the type of soil disturbance under given installation conditions, to have the potential to significantly increase the channel life. In addition, weather and hence soil moisture condition, following installation, also have a major influence on the initial stabilization of the channel and on the rate at which subsequent deterioration occurs. The timing of the first significant channel wetting following formation as well as extremes of weather are particularly important influences on the channel life. Through it may not be possible to control the weather; possibilities exist in certain circumstances through implement modification and tillage, to delay the onset of first wetting. It is concluded that moling qualities of soil cannot be defined solely on the basis of soil properties. Mac Ewana *et al.* (1992) reported that waterlogging is a major problem of dryland agriculture in many areas of Australia. Yellow duplex soils, especially those with bleached A2 horizons, are the soils most commonly associated with waterlogging. The problem is principally the development of perched water tables in the A horizons after rain, due to the restricted downward drainage of water caused by the restricted downward drainage of water caused by the and mole drainage techniques are briefly reviewed, and experience with subsoil drainage in yellow duplex soils in Victoria is outlined. Mueller and Schinder (1992) after several year studies on pipeless drainage in alluvial soil clay found that young mole channels have a hydraulic efficiency considerably higher than required in moderate climates. Disintegration of mole channels leads to a reduced hydraulic performance, but normally the hydraulic function of disintegrated channels remains sufficient even after 3-4 years. Furthermore, a hydraulically effective channel diameter of 7 mm is required for sufficient hydraulic function of mole drains.

Jha (1992) and Jha and Koga (1995) carried out a field experiment in conjunction with soybean crop in the central plain of Bangkok to examine the impact of pipeless drainage on soil properties and plant growth. Pipeless drainage were installed at a depth of 55 cm, spaced 2 m apart and at 1% slope by using a mole plough having a torpedo of 8.5 cm and an expander of 9.5 cm in diameter. The effects of pipeless drainage on soil physical and chemical properties were found

to be very significant: basic infiltration rate increased by about 2.7 fold, porosity increased by 14% at 25 cm depth and by 19% at 40 cm depth, soil aeration improved markedly, saturated hydraulic conductivity increased by 34 fold at 25 cm depth and by 61 fold at 40 cm depth, and pipeless drains with liming showed long-lasting improvement in soil pH and E_c in the lower soil profile. Because of these improvements in the soil properties it was found that the soybean crop responded very well to pipe less drainage. There was about 46% increase in grain yield and 118% increase in the dry matter per plant. Jha and Koga (1996) conducted a field study in the acid sulphate clayey soils of Bangkok to assess the hydraulic performance of pipeless drainage system. In addition crack observation by dye tracing technique, *in situ* hydraulic conductivity measurement and pertinent chemical analyses of drained effluent were also carried out. The drain discharge hydrographs were found to be highly influenced by the surface cracks caused by long term drying. These cracks enhanced the drain discharge by 15 to 20 times the normal drain discharge. Such enhanced drain discharge is not desirable, and hence it should be avoided. The staining test (dye tracing technique) further confirmed the presence macro-pores up to an appreciable depth in the drained plot. Consequently *in situ* hydraulic conductivity increased by a factor of 4.3. Moreover, the pipeless drainage system together with lime proved effective for attenuating the acidity and/or toxicity of acid sulphate soils. It was also found that the total water loss through the drains during irrigation was about 2% of the total water applied, indicating that the irrigation requirement is not significantly affected by this discharge system.

Mulqueen (1998) reported that the draught of a mole plough and the spacing 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 wind throw 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 water table control and tree stability. Christen and Spoor (1999) reported that subsurface drainage in irrigated agriculture presents an interesting challenge in that rapid drainage is required after an irrigation or rainfall event to alleviate any waterlogging, but during irrigation events drainage is undesirable. High rates of drainage during an irrigation event will lead to poor application efficiency. Also, when using mole drains, which rely entirely upon soil cohesion to retain their structure, high rates of water flow can lead to their rapid collapse. This paper compares various methods of reducing rates of irrigation water flow into mole drains and the subsequent effect on mole stability. Localized crack sealing methods using a trailing wedge behind the mole plough, followed by tractor wheeling or rotovation, were unsuccessful. However, generalized surface tillage to create a fine surface tilth about 100 mm deep was successful in reducing mole flow rates and improving stability. Preventing discharge from mole drains during irrigation was particularly effective in reducing mole flows and was not found to reduce mole stability compared to high rates of drainage throughout irrigation. Sprinkler irrigation was found to result in lower mole flow rates than flood irrigation, and improved mole stability. Positioning the mole away from areas where water is ponded on the soil surface for irrigation, such as furrows, also resulted in lower flows and improved stability. Cavelaars *et al.* (1994) Spoor and Leeds-Harrison (1999) also found that to avoid excessive deep percolation losses directly to the drain during flood irrigation, leg slot and fissures development should be minimal. In certain situation with stable mole channels, closing drain outlets during irrigation will also reduce percolation losses without inducing channel collapse. A field study conducted in southeastern Australia, Christen and Spoor (2001) investigated the effect of an angled leg mole plough on the direct inflow of irrigation water and the stability of mole channel. The leg of angled leg mole plough comprised an upper vertical section to which an angled section carrying the mole foot attached at a 30 degree angled. The trials were carried out on two contrasting clay soil in a flood - irrigated area. One of the soil type was structurally stable on wetting, and other stable. The quality of the mole channel formed at installation using the straight leg plough was good, but using the angled leg plough was only moderate due to some instability problems with the equipment. This was caused by the mole foot pitching and thus forming an oval channel. After applying irrigation to the mole channels the angled leg mole proved more stable than

the straight leg moles in the unstable soil. This was due to reduced water flow rates into mole channels causing less erosion and to the prevention of leg slot opening up directly into the mole channel, through shrinkage, during dry period. The latter prevented significant soil wash and ingress into the channel during the following irrigation. The improved stability is of great importance in that it may allow the adoption of mole drainage on sodic and swell/shrink soils where previously mole drainage would have been ineffective. Moreover, in the structurally stable soil, the stability of the angled leg moles was found to be slightly worse than those installed with the straight leg mole plough. This was probably due to inadequate soil packing in the mole channel roof during installation. Finally, it was concluded that the mole channels installed with angled leg plough have the potential for much greater stability on sodic and swell/shrink soils than the moles installed with current straight leg mole ploughs. Before this potential can be fully achieved, further development of the mole plough and moling technique for installing angled leg mole channels is required to ensure that high quality mole channels are consistently formed during installation.

Jha and Koga (2002) review the design and practice of pipeless drainage system and reported that pipeless drainage systems have proved much more efficient and economical than pipe/tile drainage system in heavy clay and loamy soils, and in highly decomposed peats. A number of results and guideline for ameliorating heavy soils exist worldwide. However, most practices are site specific and require local practical experiences. This paper presents a state of arts review of the pipeless drainage system. Firstly, the widely accepted theory and practice of pipeless drainage system. Finally, a comprehensive review of the pipeless system, covering its various aspects, is presented. This study revealed that a well established package and practices of the pipeless drainage system are available in some parts of Europe, New Zealand and Australia, however the same is unavailable in Asia. Experiences gained in this area in clayed soils of Thailand, together with experiences worldwide could help develop feasible practices for the pipeless drainage system in Asian countries. More field oriented studies (with and without crops) in this direction are required to be carried out in different parts of the Asia. Mishra *et al.* (2000) conducted a laboratory study at Indian Agricultural Research Institute, New Delhi to assess the suitability of clay soils for moling and to evaluate the performance of mole drains constructed under wide variety of initial soil moisture and bulk density conditions by simulating the field situations in a Hale-Shaw Model. The soil properties at the time of construction of mole channels significantly affected the performance of mole drains, channel stability, development of cracks and fissures

and the force required for moling. At an initial soil moisture content of 20 per cent (v/v) and bulk density of 1.4 g/cm³ the drainage performance was quite satisfactory. At low density (1.25 g/cm³) it was difficult to construct the mole channels due to too loose packing. Also, deformations in mole shapes were predominant when the same were subjected to saturation. At higher moisture content no major cracks and fissures developed to act as the secondary channels for carrying water to the mole drains.

Ramana Rao *et al.* (2005a) reported that at Central Institute of Agricultural Engineering, Bhopal a mole plough was designed to study the feasibility of mole drainage in vertisols. The dimensions of mole plough are leg having a size of 1000 X 250 X 25 mm and 100 mm foot with 110 mm bullet diameter. The total weight of the plough is 85 kg. The liquid limit of the experimental plot was worked out as 47.81% and plastic limit was found to be 22.7%. A 75 hp tractor was used in the formation of mole drains at 2, 4 and 6 m spacings and at a constant depth of 0.60m. In each spacing 4 lateral drains were formed. The length of each mole drain is 60 m. At the time of mole drain formations the soil moisture content is 22.5% at moling depth. For measuring mole drain discharge in different spacings three sumps were constructed with water pumping and measuring system. Soybean crop performance under mole drainage was monitored during recent monsoon season. The plant growth parameters such as plant population, plant height and number of branches were observed to be more in mole drain plot as compared to control. The average soybean yield obtained in 2, 4 and 6 m spacings are 6.7, 6.7 and 6.1 q ha⁻¹, respectively, whereas in control it is 3.0 q ha⁻¹. The initial study indicated that mole drainage can be effectively utilized in draining *vertisols* for soybean crop cultivation under temporarily waterlogged conditions.

At Central Institute of Agricultural Engineering Bhopal field studies were carried out on influence of mole drainage on soybean crop production. The drains were installed at an average depth of 0.6 m with 2, 4 and 6 m lateral spacing. The results of the study indicated that the soybean yields increased from 50–60% over control (Ramana Rao *et al.*, 2005b). James *et al.* (2007a) studies the drainage of sports surfaces of natural turf. Commonly, these surfaces are situated on soils of low hydraulic conductivity, which require the installation of remedial drainage to bypass the flow of water from the surface to an outfall. This is usually achieved with sand slit drainage, which is costly. A number of these soils are suitable for mole drainage at a much lower cost. Using an actual football pitch in a field-scale experiment on a smectitic, calcareous clay and their study determined that mole drainage was effective in reducing soil moisture content

at 100-mm depth, but the reduction was not as great as sand slit drainage in the first year after installation. Despite peak soil moisture deficits of 101 and 157 mm in 2005 and 2006, mole leg-slots did not re-open in the 2 years following installation. There was significant slumping of the sand slits, however, because of soil shrinkage. This prevented play on the sand slit area to safeguard players.

James *et al.* (2007b) reported that the use of mole drainage techniques for the improvement of clay soil sports surfaces has been limited by concerns over drainage-channel longevity and surface disruption. A review of the engineering of agricultural mole drainage machinery and practice was conducted with the objective of identifying key design and operation factors to maximise drain lifespan and performance, whilst minimising surface disturbance in the mole drainage of sports surfaces. An outline design for a reduced draught force, floating beam, and grade controlled, sports surface mole plough was proposed. Key operating parameters included soil suitability, operation timing, working depth, drain spacing and post-installation management.

Jihad *et al.* (2008) carried out the study to regulate a depth of water table in heavy clay soil prevalent on the Syrian coast using mole drainage. It shows a reduction in the bulk density of soil above the mole drain by (0.14 g/cm^3), an increase of the volume of air space porosity which has a diameter large than $10 \mu\text{m}$ by 7%, an increase of the hydraulic conductivity of saturated soil by 0.74 m/d , and an increase of the volume of pores holding available water ($0.2\text{--}10 \mu\text{m}$) by 2.87%, compared with the non-moled treatment. The executed mole drain has reduced the depth of water table and has increased moisture suction of the soil above mole drains (drying soil); this is associated with an increase in potato (var. *Sponda*) production by 35%. The results demonstrated that the suitable range for mole drain spacing is $0.5\text{--}2.2\text{m}$, and the optimum between mole drains is 1.4m . Ramana Rao *et al.* (2009a) reported that at CIAE, Bhopal feasibility of mole drainage for draining excess rain water in vertisols was studied for the last five years. A 75 hp tractor was used in the formation of mole drains at 2, 4 and 6 m spacings and at a constant depth of 0.60 m . At the time of mole drain formation the soil moisture content at moling depth was 24 % (db) and the tractor was operated at 0.8 kmph . In each spacing, 4 lateral drains were formed to a length of 60 m . The cost of formation of mole drains at 2, 4 and 6 m drain spacings are Rs. 3100, Rs.1800 and Rs. 1100, respectively per ha. The cost of installation of mole drains was recovered in the first year of installation of drains due to enhanced soybean yield. For the last five years the drains are functioning well as a result of which the soybean yields are increased about 40-50% in mole drain area over control (no

drainage). Early maturity of at least 15-20 days and less weed problems were observed in mole drain area as compared to control. Due to improvement in soil physical properties, the rabi crop yields under mole drained area were also higher (12-15%) than the control area. The technology being successfully demonstrated in six farmers' fields of Raisen and Vidisha Districts of Madhya Pradesh. In the present study techno-economic feasibility of mole drainage systems in vertisols were established for enhancing crop production in temporary waterlogged vertisols of Madhya Pradesh.

Ramana Rao *et al.* (2009b) a 4-year (2004-2009) field experiment was carried out at Central Institute of Agricultural Engineering (CIAE), Bhopal feasibility of mole drainage for draining excess rain water in vertisols. A 56 PS wheel tractor was used in the drawing of mole drains at 2, 4 and 6 m spacings and at a constant depth of 0.60m at grade of 0.8% . The soil moisture content was 22.5% at moling depth. The quantity of drained water from the plots under each of drain spacing was monitored using water meter. The drained area between each was 480 m^2 , 960 m^2 and 1080 m^2 for 2, 4 and 6 m drain spacings respectively. The crop yields increased by about 50% in the mole drained plots as compared to the control. The field capacity of mole plough during formation of mole drains at 2,4 and 6 m drain spacing were 0.14 , 0.28 and 0.42 ha h^{-1} , respectively while the cost per ha for construction of mole drains at 2,4 and 6m drain spacing were Rs. 3200, Rs 1800 and Rs. 1200, respectively.

Kanmuri *et al.* (2010) reported that percolation rates of soil layers above mole drains and at the midpoint of mole drains were measured in rotational paddy fields under varied land use and crops. In addition, soil layers above mole drains were observed in these fields. Percolation rates above mole drains were kept high at the rate of $350\text{--}480 \text{ mm h}^{-1}$ in upland fields and in paddy fields without puddling. On the other hand, in the paddy field with puddling, percolation rates decreased by each puddling practice. The percolation rate above the mole drain is affected by in-situ vertical cracks formed during subsoiling practices, rather than the residual void area of the mole drain hole. The characteristics of the drainage-function in rotational paddy fields with mole drains are that: (1) the percolation rate increased right above the mole drain with the subsoiling practice, (2) upland crop culture increased the percolation rate at the midpoint of mole drains, (3) the percolation rates above the mole drain and at the midpoint of mole drains decreased with puddling practices in the paddy field. Their results indicate that, to keep the drainage-function of the paddy field high, the mole drain needs to be re-installed after two paddy culture. Paulo *et al.* (2010) reported that simulations with HYDRUS2D software demonstrate that the

winter rainfall, combined with surface drainage is not, in itself, efficient in reducing the salts accumulated during the irrigation period. Rainfall, together with a surface drainage system, combined with mole drains is more efficient for the purposes of soil conservation and decreasing the risk of salinity, especially if the amount of winter rainfall is considerably higher than the average. Within the present framework of climate change, with decreasing rainfall in the winter, irrigation in semi-arid areas increases concerns with regard to the accumulation of salts, and it is noted that the winter rainfall is not enough to maintain low salinity levels. The flow capacity in situations of greater rainfall is higher in combined drains and therefore there is a greater removal of salts in this case. The use of mole drains is effective in reducing salinity levels by about 20% compared with the levels observed in simple drainage. Future studies can quantify the amount of rainfall and/or the increase in efficiency of irrigation, first with regard to salt removal capacity and second with regard to reducing the salt load. The simulations indicate that the winter rainfall is not enough to remove the excess salt, even if there is an increase in intensity of about 50%. Again, in this scenario, CD is more efficient in removing the salts.

El-Adl (2011) reported that the effects of different types of mole drains on some clay soil properties and wheat yield were tested in this study. The experimental studies were conducted in heavy clay soil. Moles were composed of 3 different materials; compost, sand and mixture of compost with sand (1:1). Two depths of moles (0.3 and 0.5m) and three distances among moles (10, 15 and 20m) were investigated in this work. The results indicated that the piezometric head increases as the distance among moles increases and vice versa. At each mole spacing, the Piezometric head decreases as the time advances after irrigations. However, the 10 m mole spacing achieved the best significant results over the 15 and 20m spacing. The highest yield (2737 kg fed⁻¹) was obtained by using compost, 10m distance among moles and 0.5m moles' depth. Decreasing distance among moles, increases yield penetration resistance (PR), hydraulic conductivity (Kh) and infiltration rate. Increasing mole depth, increases yield (Kh) and infiltration rate while decreases (PR). Kolekar *et al.* (2011) study that the effect of mole drains spacing on the crop parameters on summer groundnut. A tractor 65 HP was selected to make drains of 2, 4 and 6m. The plant height, number of branches plant⁻¹, number of pods plant⁻¹, weight of pods plant⁻¹ and total yield were height in 4m drain spacing followed by 6m, 2m and control and total yield in 4 m drain was 69.2% more than the control.

Ramana Rao *et al.* (2012) reported that studies carried

out by various agencies indicated that large areas under vertisols in Madhya Pradesh are kept fallow during rainy season (July-September) every year due to temporary waterlogging and associated problems. To drain out the temporarily waterlogged vertisols, drainage technologies are essentially to be adopted. With low adoption of costly pipe drainage technologies an alternative to the pipe drainage i.e., mole drainage (pipe less) was demonstrated in a total of 21 farmers' fields in Madhya Pradesh State, India. The plant height (45 DAS), flowering date, number of pods branch⁻¹, chlorophyll content of leaves and yield values respectively for mole drained area and control (no drainage) are: 71 cm, 35th day, 30, 3.91 mg g⁻¹, 1.2 t ha⁻¹; 45 cm, 43rd day, 12, 1.41 mg g⁻¹ and 0.65 t ha⁻¹. Bulk density of the soil was also reduced from 1.75 g cc⁻¹ to 1.61 g cc⁻¹ at moling depth. About 13-15% of higher crop (wheat) yield was also observed from subsequent crop due to improvements in soil physical properties.

Dhakad *et al.* (2014a) reported that mole drains can be formed in vertisols under different treatment, when the average soil moisture content was between 22.36% and average clay content is 52.36% at moling depth. Field capacity of mole plough for drains formation recorded highest under S₄D₁ (mole drains at the spacing of 8 m on the depth of 0.5 m) and lowest under S₁D₁ (mole drains at the spacing of 2 m on the depth of 0.5 m). Mole drain with S₁D₁ (spacing of 2 m at the depth 0.5 m) was found better in comparison with all other mole drain spacing as well as over control. Effect of mole drainage on the growth parameters and productivity of soybean in various mole drains treatments were found better in comparison with control (No mole drain). Dhakad *et al.* (2014b) reported that mole drain with S₁D₁ (spacing of 2 m at the depth 0.4 m) was found better in comparison with other spacing and depth as well as the control. Net return and B:C ratio of mole drain with S₂D₁ (spacing of 4 m at the depth 0.4 m) & S₁D₁ (spacing of 2 m at the depth 0.4 m) were found most profitable during 1st year and 2nd year of experiment respectively for soybean crop. Dhakad *et al.* (2015a) concluded that adoption of mole drainage technology for draining temporary waterlogged vertisols was proved to be techno-economically viable technique. However, its design parameters such as mole drain spacing and mole drain depth are location specific, as these parameters have bearing on the crop performance. In this study, mole drain with a spacing of 2m installed at a depth of 0.4m from ground surface was found better in comparison with other spacing and depths in vertisols of Central India for soybean crop in temporary waterlogged vertisols. Dhakad *et al.* (2015b) reported that mole drain formation has bearing on the crop performance, which is also influenced by mole drain spacing and drain

depth. Mole drain with S_1D_1 (spacing of 2m at the depth 0.4m) was found better in term of the root length, root nodules plant⁻¹, leaf area index, crop growth rate and economic of soybean crop in comparison with other spacing and depth as well as the control. Effect of mole drainage technology on the root and physiological parameters of soybean under temporary waterlogged conditions was found better. Dhakad *et al.* (2015c) concluded that observation on physiological parameters like days to germination, days to 50% flowering and days to 75% maturity showed non-significant differences due to different treatments (spacing of mole drain, depth of mole drain and interaction of these two) and maximum values of all the parameters were observed under mole drain spacing S_1 (2 m) and mole drain depth D_1 (0.4 m) in most of the cases. Dhakad *et al.* (2016) concluded that net return is the best index of profitability of crop production and higher net return Rs. 64725 ha⁻¹ and Rs. 28325 ha⁻¹ were recorded for lentil and soybean crop respectively under mole drain areas, whereas, the lower net return Rs 31300 ha⁻¹ and Rs 11900 ha⁻¹ was recorded under control (No mole drain system) for these crops. From the study, it can be concluded that the mole drains are best option for the water logged vertisols and it is the most appropriate, profitable and productive practice in these soils not only for *kharif* crops but also for *rabi* crops.

CONCLUSION

Heavy soils of low hydraulic conductivity (less than 0.01 m day⁻¹) often require very closely spaced drainage systems (2-4 m spacings) for satisfactory water control in *kharif* season. Mole drainage has been proved very economical and most efficient for achieving water regime and crop response under heavy soils. Mole drainage technology though proved as a cheaper alternate to pipe drainage. Experiences gained in the vertisol of Madhya Pradesh concluded that effect of mole drainage on the growth parameters and productivity of soybean in various mole drains treatments was found better in comparison with control (No mole drain) and concluded that the mole drains are best option for the water logged vertisols and profitable practice in these soils not only for *kharif* crops but also for *rabi* crops.

REFERENCES

- Cavalaars JC 1974. Subsurface field drainage systems. In: *Drainage Principles and Applications*. Publication No. 16, vol. IV, International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands, pp. 1-65.
- Cavalaars JC, Vlotman WF and Spoor G 1994. Subsurface drainage systems. In: H.P. Ritzema (Editor-in-chief), *Drainage Principles and Applications*. ILRI Publication 16, 2nd Edition, International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands, pp. 827-929.
- Childs EC 1943. The mechanics of mole drainage. *Empire Journal of Experimental Agriculture* **10**(39): 169-181.
- Cooper T 1965. Practical Land Drainage. Part-4, Land Drainage. Leonard Hill, London, pp.192.
- Christen EW and Spoor G 1999. Controlling irrigation water flow to mole drains. *Journal of Irrigation and Drainage Engineering* **125**(2): 59-63.
- Christen EW and Spoor G 2001. Improving mole drainage channel stability in irrigated areas. *Agriculture Water Management* **48**(3): 239-253.
- Dhakad SS, Ramana Rao KV, Agrawal Vijay and Verma SK 2014a. Effect of different mole drain spacings on the growth characters and yield of soybean in Raisen district of MP. *Research in Environment and Life Sciences* **7**(1): 23-25.
- Dhakad SS, Ramana Rao KV, Mishra KP and Verma SK 2014b. Economic feasibility of mole drains for soybean crop. *Green Farming* **5**(6): 1146-1149.
- Dhakad SS, Ramana Rao KV and Mishra KP 2015a. Influence of Mole Drain Spacing and Depth on Yields Attributes and Yield of Soybean (*Glycine max* L.). *Ecology, Environment and Conservation* **21**(4): 1823-1828.
- Dhakad SS, Ramana Rao KV and Mishra KP 2015b. Effect of mole drainage technology on root and physiological parameters of soybean (*Glycine max* L.) in temporary waterlogged vertisols of Madhya Pradesh. *International Journal of Agricultural and Statistical Sciences* **11**(1):167-173.
- Dhakad SS, Ramana Rao KV 2015c. Visual parameters of soybean (*glycine max* L.) as influences by mole drain spacing and depth in vertisols of Madhya Pradesh. *Scientific Journal Agricultural Engineering* **XL**(2): 107-115.
- Dhakad SS, Ramana Rao KV, Umat Rajiv, Ambawatia GR, Khedkar NS and Verma Gayatri 2016. Economic feasibility of mole drainage system in waterlogged vertisols in Malwa region of Madhya Pradesh. *Ecology, Environment and Conservation* **22**(September Suppl.): 307-311.
- Dewey FJ, Meyer JH and George JA 1987. An evaluation of the suitability of soils for mole drainage in the South African sugar industry. *South African Sugar Technologists' Association* (June 1987), pp. 133-139.
- Eggelsmann, R 1987. Subsurface Drainage Introductions. *Bulletin of the German Association for Water Resources and Land Improvement*, Verlag Paul Parey, Hamburg, Germany, pp. 83-120.
- EI-Adl MA 2011. Effect of different types of mole drains composition on some clay soil properties and wheat yield. *Journal of Soil Science and Agric. Engineering* **2**(1): 109-120.
- FAO 1971. Drainage of heavy soils, irrigation and drainage paper 6, Rome, pp.109.
- FAO, 1990. Guidelines for soil description. 3rd Ed. (revised). Soil Resources, Management and Conservation Service, Land and Water Development Division. FAO, Rome. 70 pp.
- Farr E and Henderson WC 1986. Land Drainage. 1st Edn., Longman, London, pp. 175-189.
- Forero JA 1975. Effectiveness of mole drains in leaching heavy soils. M.S. thesis, Department of Agriculture and Irrigation Engineering, Utah State University, Logan, U. S. A. (unpublished).
- Goss MJ, Harris GL and Howse KR 1983. Functioning of mole drains in a clay soil. *Agricultural Water Management* **6**(1):27-30.
- Hann MJ 1994. *Soil implement and interactions influencing mole drainage channel stability*. Ph. D. thesis, Cranfield University, Silsoe, U.K.
- Harris GL 1984. Effect of mole submergence on the life of mole channels. *Agricultural Water Management* **8**(4):361-374.
- Hassen AA 1981. A field test of mole drain to investigate the design parameters with application to Bangkok clay. M. Eng. Thesis no. AE-81-14, AIT, Bangkok, Thailand (unpublished).
- Hudson AW and Hopewell HG 1962. The Drainage of Farm land.

- Massey Agriculture College, Pelmerton. North, New Zealand.
- James IT, Blackburn DWK and Godwin RJ 2007a. Mole drainage as an alternative to sand slitting in natural turf sports surfaces on clays. *Soil Use and Management* **23**: 28-35.
- James IT, Hann MJ and Godwin RJ 2007b. Design and operational considerations for the use of mole ploughing in the drainage of sports pitches. *Biosystems Engineering* **97**: 99-107.
- Jha MK 1992. *Studies on mole drainage in Bangkok clay soil*. M. Eng. Thesis no. AE-92 -51, AIT, Bangkok, Thailand (unpublished).
- Jha MK and Koga K 1995. Mole drainage: prospective drainage solution to Bangkok clay soil. *Agriculture Water Management* **28**(3):253-270.
- Jha MK and Koga K 1996. Performance evaluation of pipeless drainage: A case study in the central plain of Thailand. *Irrigation Engineering and Rural Planning* **30**: 94-107.
- Jha MK and Koga K 2002. Design and practices of pipeless drainage systems: A review *International Agricultural Engineering Journal* **11**(2 & 3):59-91.
- Jihad Ibrahim, Arslan Dr. Awides and Hassen Naser 2008. The effect of regulating the depth of water table by mole drainage on soil physical properties and on productivity of potatoes on the syrian coast. *Tishreen University Journal for Research and Scientific Studies - Biological Sciences Series* **30**(2):1-20.
- Kanmuri H, Iwasa I, Hoshi N and Kato M 2010. Durability and significance of mole drains for the drainage-function improvement in rotational paddy fields. Transactions of the Japanese Society of Irrigation. *Drainage and Rural Engineering* **250**: 107-115.
- Kolekar OL, Patil SA, Patil SB and Rathod SD 2011. Effect of different mole spacing on the yield of summer groundnut. *International Journal of Agricultural Engineering* **04**(01): 82-85.
- Leeds-Harrison P, Spoor GB and Godwin RJ 1982. Water flow to mole drains. *Journal of Agriculture Engineering Research* **27**(2): 81-91.
- Mac Ewana RJ, Gardner WK, Ellington A, Hopkins DDG and Bakker EAC 1992. Tile an mole drainage for control of waterlogging in duplex soils of south-eastern Australia. *Australian Journal of Experimental Agriculture* **32**:865-878.
- May JH 1976. Water movement to mole channels. Special Study Report, National College of Agriculture Engineering, UK, 50 pp. (unpublished).
- Misra AK, Sarkar TK and Bhattacharya AK 2000. Simulation studies of mole drain characteristics. *Journal of Agricultural Engineering* **37**(1): 39-54.
- Mueller L 1988. Efficiency of sub-soiling and subsurface drainage in heavy alluvial soils of the G.D.R. *Soil and Tillage Research* **12**(2):121-134.
- Mueller L and Schindler U 1992. Durability and hydraulic performance of mole channels in alluvial clay soils. International Conference on Agricultural Engineering (7-10 Dec) Bangkok, Thailand, pp. 889-896.
- Mulqueen J 1998. Depth, spacing and length of mole drains with applications to afforestation. *Irish Journal of Agricultural and Food Research* **37**(1): 39-49.
- Nicholson HH 1953. The principle of field drainage. Cambridge University Press, Cambridge, UK.
- Norum DI and Gray DM 1964. Unlined mole lines for irrigation. Paper presented at the Summer Meeting of ASAE, Colorado and Paper No. 64-212.
- Paulo JN, Ricardo Castanheira and Serralheiro P 2010. Impact of mole drains on salinity of a vertisol under irrigation. *Biosystems Engineering* **105**(01): 25-33.
- Raadsma S 1974. Current Draining Practices in flat Areas of Humid Regions in Europe. In: J.V. Schilfgaarde (Ed.), Drainage for Agriculture. Agronomy Monograph No. 17, American Society of Agronomy, Inc., Publisher, Madison, Wisconsin, pp. 115-143.
- Robinson M and Beven KJ 1983. The effect of mole drainage on the hydrological response of a swelling clay soil. *Journal of Hydrology* **64**: 205-223.
- Rodgers M, Mulqueen J and McHale J 2003. Model studies of mole drain spacing and performance. *Agricultural Water Management* **60**(01): 33-42.
- Ramana Rao KV, Kishore Ravi and Singh Ramadhar 2005a. Feasibility study of mole drainage in vertisols. 39th annual convention & symposium of Agricultural Engineering (9-11 March, 2005) Hyderabad, India pp. 29-40.
- Ramana Rao KV, Kishore Ravi and Singh Ramadhar 2005b. Mole drainage studies in vertisols of Bhopal region- a case study. All India Seminar on Reclamation of waterlogged saline soils through drainage (4-5 December, 2005) Kota, India, pp.124-132.
- Ramana Rao KV, Kishore Ravi and Singh Ramadhar 2009a. Mole drainage a viable alternate to pipe drainage – A case study. 60th International Executive Council Meeting & 5th Asian Regional Conference (6-11 December 2009) New Delhi, India pp. 1-6.
- Ramana Rao KV, Kishore Ravi and Singh Ramadhar 2009b. Mole drainage to enhance soybean production in waterlogged vertisols. *Journal of Agricultural Engineering* **46**(4):54-58.
- Ramana Rao KV and Singh Ramadhar 2012. Pipe Less Drainage (Mole Drainage) Studies Under Actual Farmers' Field Conditions-A Case Study in India. 11th ICID International Drainage Workshop on Agricultural Drainage Needs and Future Priorities (September 23 – 27, 2012) Cairo, Egypt (Paper No.35) pp.1-6.
- Schwab GO 1947. Power requirements, limitations and cost of mole drainage in some Iowa soils. M. S. thesis, Iowa State College, Ames, Iowa.
- Schwab GO 1957. Mole Drains. In: J. N. Luthin (Ed.), Drainage of Agricultural Lands. Agronomy Monograph No. 7, American Society of Agronomy, Inc., Publisher, Madison, Wisconsin.
- Singh AKP 1978. Effectiveness of Mole Drains in the Improvement of Bangkok clay. M.E. thesis no. 1078, AIT, Bangkok, Thailand (unpublished).
- Soucek O 1965. Present stage and perspective of use of non-reinforced mole drainage in Czechoslovakia. International Symposium on Hydrological and Technical Problems of Land Drainage. Prague, pp. 305-319.
- Spoor G, Leeds-Harrison, PB and Godwin RJ 1982a. Some fundamental aspects of the formation, stability and failure of mole drainage channels. *Journal of Soil Science* **33**(3): 411-425.
- Spoor G, Leeds-Harrison PB and Godwin RJ 1982b. Potential role of soil density and clay mineralogy in assessing the suitability of soil for mole drainage. *Journal of Soil Science* **33**(3): 427-441.
- Spoor G and Ford RA 1987. Mechanics of mole drainage channel deterioration. *Journal of Soil Science* **38**(2):369-382.
- Spoor G and Leeds-Harrison PB 1999. Nature of heavy soil and potential drainage problems. In: R. W. Skaggs and J. van Schilfgaarde (Editor), Agricultural Drainage. Agronomy Monograph No.38, American Society of Agronomy, Inc., Madison, Wisconsin, pp. 1051-1081.
- Smedema LK and Rycroft DW 1983. Land Drainage. First edition, Batsford Academic and Education Ltd., London, pp.77-97.
- Sommerfeldt JG and Chang C 1987. Desalinization of an irrigated, mole drained, saline clay loam soil. *Canadian Journal of Soil Science* **67**(2):263-269.
- Theobald GH 1963. Method and Machines for Tile and other Tube Drainage. Agricultural Development Paper 78, FAO, Rome.
- Trafford and Rycroft DW 1972. A review of literature on mole draining. Technical Bulletin 72/10, Field Drainage Experimental Unit, Cambridge, U. K.
- Twocock, J 1970. The feasibility of secondary drainage treatment in high rainfall areas. MAFF, field drainage experimental unit (FDEU) Annual Report, Cambridge, pp.69-74.

Vardhan Vishnu Sidlagatta, Chilamkuthy Sreenivas, Reddy Chinta Venkat and Sreedevi, Pandraju 2014. Impact assessment of drainage water management in salt affected soils of Godavari Western Delta on a pilot scale in India. *Scientific Journal Agricultural Engineering* **XXXIX**(3): 63-71.

Wells AA 1951. *Soil mechanics and tillage*. Ph.D. thesis, University of Cambridge, Cambridge, U.K. (Unpublished).

Weil C, Natho-Jina S, Chambers R and Wires K 1991. Mole drainage in silicate clay soils subject to freezing. *Transaction of ASAE* **34**(4):1693-1698.

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