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Soil Disturbance Generated by Deep-working Low Rake Angle Narrow Tines

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The soil disturbance generated by low rake angle and trenchless drainage tines working under a wide range of depths and soil conditions is described. Detailed soil movement studies are presented from which soil deformation mechanisms are proposed. The factors controlling the actual nature of the disturbance are identified and discussed.

1. Introduction

Low rake angle narrow tines are used for a wide range of agricultural operations including soil loosening, mole drainage and trenchless drain pipe laying. Work by Spoor and Godwin[1] and Godwin, Spoor and Leeds-Harrison[2] shows that, with given implements, the effectiveness of soil loosening and the stability of mole channels is working-depth dependent. Naarding,[3] Olesen[4] and Eggelsman[5] all report varying performance efficiencies of pipe drainage systems, after installation using the trenchless technique. In all cases these differences in implement behaviour and field performance have been attributed to changes in the nature of soil disturbance at depth as the conditions changed.

The major emphasis in previous narrow tine studies has been directed towards force assessment and prediction, and to defining the general soil disturbance pattern and major soil failure planes. Kostritsyn,[6] Zelenin,[7] O'Callaghan and Farrelly[8] and Godwin and Spoor[9] have shown that soil wedges develop on the face of plane tines, and that the nature of the general soil disturbance depends upon soil conditions, tine rake angle and working depth. Their work suggests that below certain working depths, termed critical depths, soil movement changes from a predominantly forward and upward form, crescent failure, to a mainly forward and sideways one, lateral failure. These failure modes have been used successfully in force prediction models.

The critical state soil mechanics concept, see Roscoe, Schofield and Wroth,[10] suggests that soil density may be decreased or increased depending on whether brittle or compressive soil failure occurs. The nature of the failure is dependent upon the degree of soil compressibility and the magnitude of the confining stresses. Confining stresses change with increasing depth and, hence, the possibility exists of a change in failure type with depth. Compressive failure would be detrimental for soil loosening and to drain performance (see Spoor and Fry,[11] Fry and Spoor[12]) but essential for subsequent mole channel stability.

It can be concluded from previous work that changes in the nature of soil failure occur with changing tine working depth and soil conditions. To date, however, no detailed investigations have been made to determine the exact three-dimensional nature of soil disturbance generated by low rake angle narrow tines or the factors which control it. This paper examines this disturbance and the major determining factors.

2. Investigational methods and procedures

Experiments were carried out at different working depths in both field and laboratory, using a range of trenchless drainage machines and 45° rake angle plane narrow tines. The soil conditions

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investigated were selected to give a range of shear strengths, and details of soil densities and degrees of moisture saturation are given in Table 1.

TABLE 1

Laboratory and field soil conditions

	Soil texture, structure and condition	*Dry bulk density, t/m³*	*Moisture content, %*	*Saturation, %*
Laboratory	Moderately loose homogeneous sandy loam	1·18	10·9	22
	Moderately compact homogeneous sandy loam	1·50	12·5	30
	Very compact homogeneous sandy loam	1·7	11·2	61
	Moderately compact sandy loam with large vertical cracks	1·43	11·2	35
Field	Moderately compact fine sandy loam	1·40	24·0	64
	Weak structured silty clay loam containing numerous macropores	1·07	51·3	92
	Clay with moderate, angular blocky structure	1·45	27·6	88
	Chalky boulder clay with moderate/strong prismatic structure	1·7	17·5	86
	Clay, structureless (massive)	1·68	22·0	101
	Clay, structureless (massive)	1·3	38·25	92

Assessments of soil disturbance were made using three independent approaches: the location of the shape, position and extent of soil failure planes, assessment of changes in hydraulic conductivity in the disturbed zone and a determination of the trajectory and movement of soil particles and aggregates within the entire disturbance area.

The major soil failure planes were located by excavation, immediately following the passage of the tine. Profile meter and surveying techniques were used to quantify the limits of the soil failure profile, as detailed in Spoor and Fry.[11]

Hydraulic conductivity measurements were made on undisturbed soil samples taken in the field from alongside and beneath tine working depth to identify any smeared or compacted zones generated by the tines. A falling head permeameter technique, similar to that described by Spoor and Fry,[11] was used for the assessment.

The trajectory and relative movements of soil particles and aggregates during deformation with the tines was measured using a bead tracer technique. Laboratory soils were prepared in layers and 6 mm diameter coloured beads accurately positioned in rows at various depths. Bead positions, before and after each test, were recorded to an accuracy of $\pm 0{\cdot}25$ mm in the X, Y and Z planes using a Vernier X, Y, Z plotter.

Uniform compaction in a small soil bin was achieved by subjecting each layer to a predetermined number of blows from a 1·3 kg mass applied through a 0·052 m² wooden block on the soil surface. The beads were positioned in the required compacted layer during preparation by bedding them, using light pressure, in the bottom of a V-shaped groove approximately 1·25 bead diameters deep. After bedding, their position was recorded and the groove filled with sieved soil and compacted between the beads using a spatula. Relocation of the beads after a test run was by careful excavation using a spatula, and it was found the beads tended to sit securely in the socket formed at installation and so were relatively resistant to disturbance. The beads in the direct line of movement of the tine could not be accurately relocated.

No significant bead movements were recorded as a result of soil preparation in the denser soil conditions (densities of 1·2 t/m³ or more), although slight downward movement sometimes occurred in low density soil (1·0 t/m³). Where movement did occur it was found to be vertical and uniform across the bin, and so an appropriate correction could be made to the initial bead positions. Beads were always positioned beyond the limits of movement in the tests and these beads, at least six per placement depth, were used each time to check for movement during preparation.

Bead movements during soil preparation were significant in the larger soil bin, up to 2 mm, where soil compaction was achieved using a heavy roller. The movements were, however, uniform, so that appropriate corrections could be made to the initial bead positions. The majority of the investigation was carried out in the small soil bin, where accuracy was high and movements due to preparation were rare in the range of soil density used. Tests in the larger, less accurate, soil bin were used mainly to check the validity of the trends measured in the small bin. *Fig. 1* shows final bead positions at different depths after a soil bin test.

In the field trials, following the removal of vertical soil cores, 36 mm diameter plastic balls, with short plastic tails to assist in relocation, were introduced into the undisturbed profile. The holes were refilled at the appropriate soil density following placement. Initial and final ball positions were monitored using surveying techniques, to an accuracy of ±5 mm, in X, Y and Z directions.

The method used to estimate relative net compaction or loosening effects was based on the assumption that any beads located initially at the same depth (Z) and lateral distance (Y) from the tine, in the direction of tine travel (X), will behave in a similar manner. This assumption is valid for homogeneous soils. Using X, Y, Z co-ordinates, if a bead in position A (X_0, Y_0, Z_0) in *Fig. 2* is displaced to A′ (X_0+a, Y_1, Z_1) it follows that a bead at A_1 (X_1, Y_0, Z_0) will be displaced to A'_1 (X_1+a, Y_1, Z_1). Other beads will be displaced in a similar manner, generating shape changes such as those illustrated in *Fig. 2*. The volume of such shapes can be determined by multiplying the cross sectional areas in the YZ-plane by the distance between the opposite sides in the X direction (perpendicular to YZ-plane). As the distance a between the opposite ends in the X direction does not change during deformation, any volume change is directly related to changes in cross sectional area in the YZ-plane. This area can be determined directly by using the values of lateral (Y) and upward (Z) movements measured using an X, Y, Z plotter. For the bead grid spacing used an experimental error of approximately ±5% may arise in estimates of volume changes, due to measurement errors. Larger grid squares or the summing of several grid square changes will reduce the percentage error in volume change assessments.

Much of the laboratory work was carried out in a small soil bin with the soil surface surcharged, to simulate greater working depths than those actually used. A uniformly distributed pressure of 1 kN/m^2 was used to effectively increase the soil depth by approximately 70 mm in the sandy loam soil of dry bulk density 1·5 t/m^3. The surcharging loads and their positions, see *Fig. 3*, were selected to give soil failure planes similar in shape and dimension to those monitored at depth in the unsurcharged, deeper soil bin tests.

Surcharging weights were not positioned directly above the tine. However, since the soil failure planes at depth were consistently similar to the unsurcharged failure planes and the main area of study was beyond these planes, the surcharging arrangements effectively enabled deep-working tines to be analysed in a relatively shallow soil bin.

3. Experimental results

The results are presented in two sections: the general soil failure profiles and the detailed soil disturbance studies.

3.1. *General soil failure profiles*

Fig. 4 shows, in vertical elevation, the extent and shape of the soil failure planes developed at either side of a 45° rake angle plane tine working at a range of depths in a uniform sandy loam soil. The general shape of these profiles is very representative of other profiles formed by trenchless machines and other low rake angle tines, working under a wide range of soil conditions, see Spoor and Fry.[11] Comparing the shallow and deep profiles, *Fig. 4* and *Figs 5* and *6*, those at the

Fig. 1. Tracer beads after tine disturbance showing soil movement at different depths: (top to bottom) depth below surface 50, 100, 140, 200 (working depth) mm, respectively

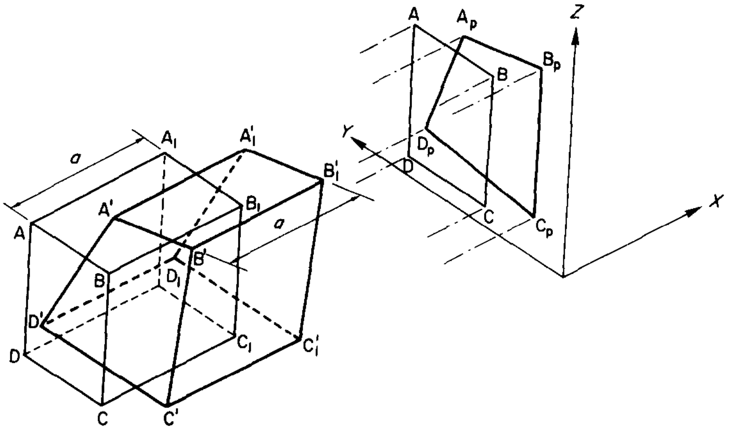

Fig. 2. Schematic of bead movement showing projected area (A_p, B_p, C_p, D_p) on YZ-plane. Percentage volume change = $[(A, B, C, D - A_p, B_p, C_p, D_p)/(A, B, C, D)] \times 100$

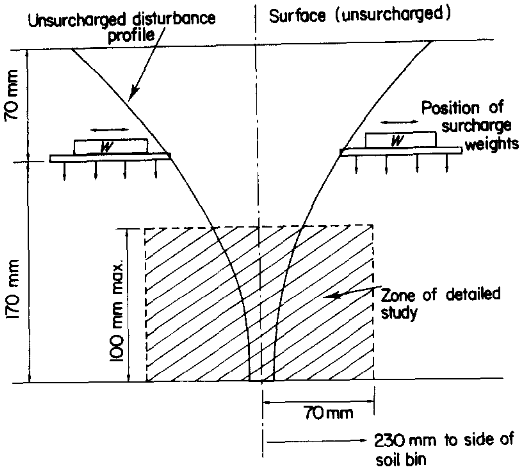

Fig. 3. Position of soil bin surcharge weights in relation to unsurcharged disturbance profile

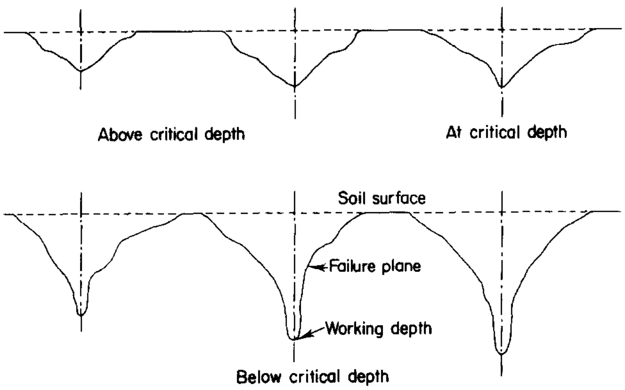

Fig. 4. Soil disturbance at different tine working depths

greater working depths show a marked decrease in the lateral extent of the failure planes below a certain depth, the critical depth as defined by Godwin and Spoor.[9] The actual critical depth is dependent upon tine geometry and soil conditions. Significant soil surface heave occurs within the limits of the failure planes, created by soil slip along a succession of these planes generated by the tine at regular intervals.

Examination of the field and laboratory profiles, together with the conclusions of other workers suggested that the nature of soil disturbance beyond the failure boundaries may vary between locations, even though the geometries of the boundaries remain similar.

Fig. 5. Soil disturbance, tine above critical depth

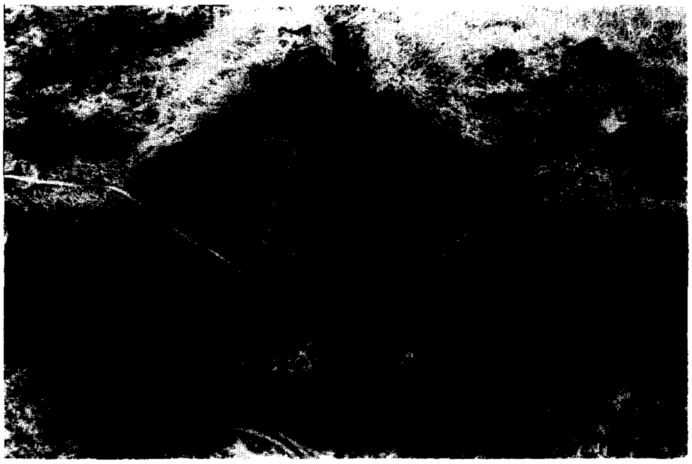

Fig. 6. Soil disturbance, tine below critical depth

3.2. *Detailed soil disturbance studies*

3.2.1. *Homogeneous soil conditions*

(a) *Effect of working depth. Figs 7* and *10* show the disturbance caused by a 12·5 mm wide, 45° rake angle tine working in the soil bin at 125 mm deep unsurcharged, and 170 mm deep surcharged, (240 mm equivalent depth) in the medium density sandy loam soil. The extent of vertical and sideways movement at different depths below the surface in a vertical plane at right angles to the direction of travel is shown, together with the horizontal movement and major soil failure planes. The quantities expressed between the bead positions indicate the percentage volume change within that particular area; positive values indicate net loosening and negative values indicate net compaction.

The shallow tine operating above its critical depth (*Fig. 7*), causes minimal soil disturbance beyond the major failure planes and the soil within the planes is effectively loosened. Working below critical depth, considerable soil disturbance now occurs beyond the failure planes near working depth, with soil in that area being subjected to some compaction, see *Fig. 10*.

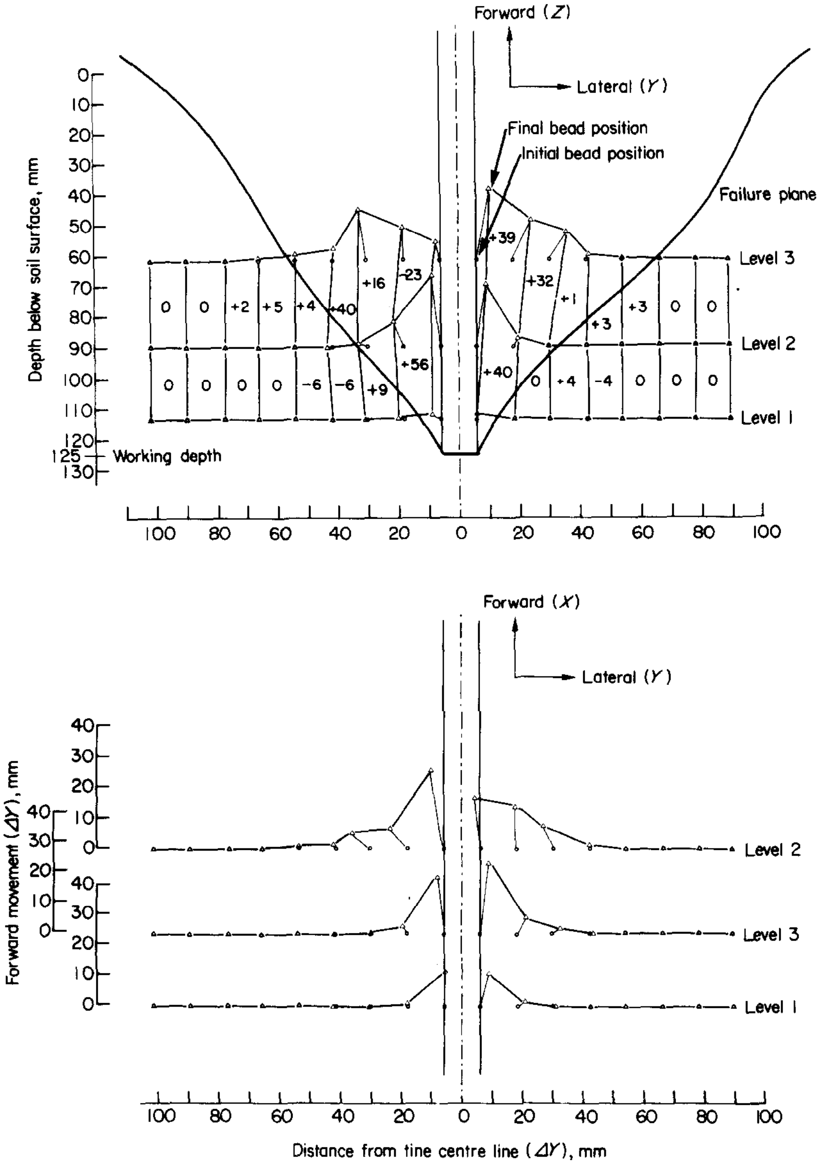

Fig. 7. Soil disturbance and net volume change, tine above critical depth. Dry bulk density 1·4 t/m³. + ve, net loosening; — ve, net compaction

Results from field trials, see *Fig. 8*, in a fine sandy loam confirm the above soil bin results. The trenchless drainage machine used had a curved blade, 175 mm wide with a 15° share rake angle and was operated at 1·1 m deep, slightly above the critical depth. *Fig. 8* shows very little soil disturbance beyond the failure planes, with loosening between the planes. No changes in hydraulic conductivity were detected beyond the failure planes, see Spoor and Fry.[11]

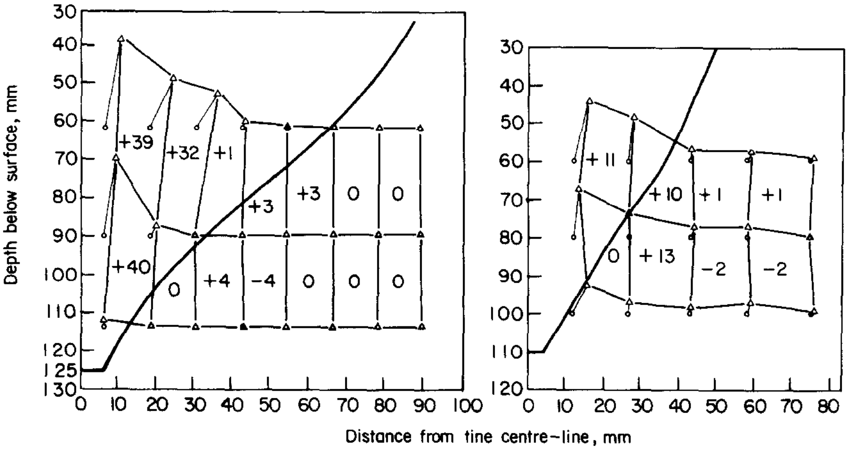

Fig. 8. Soil disturbance and net volume change, tine above critical depth. (Left) Soil bin, dry bulk density 1·34 t/m^3; (right) field, dry bulk density 1·39 t/m^3

(b) *Effect of soil density (tines below critical depth).* Comparison of *Figs 9, 10* and *11* from soil bin tests in a sandy loam at low (1·2 t/m^3), medium (1·45 t/m^3) and high (1·7 t/m^3) densities, respectively, shows in all cases that the soil disturbance at depth extends well beyond the main soil failure planes. The lateral extent of the total disturbance zone is similar at all soil densities, although there is a slight trend towards greater disturbance at depth in the lower density soil. The forward component of soil movement is always greater than the upward and sideways components and its magnitude, particularly close to the tine, tends to increase with decreasing soil density.

A comparison of the percentage volume changes in the different locations shows that at all soil densities, loosening has taken place near the tine, within the main failure planes. The loosening effect is greatest in the high density soil.

Volume change in the area beyond the failure planes with this below-critical-depth disturbance is dependent upon location and initial soil density. There is little evidence of any compaction in the high density soil, *Fig. 11*, the trend throughout being towards some net loosening. The lower density soils, *Figs 9* and *10*, have, however, been compacted slightly at depth, compaction occurring closer to the soil surface in the soil of lowest density. These differences in percentage volume change are clearly illustrated in Table 2, which shows the average percentage change in volume beyond the major soil failure planes, within three and six tine widths of the edge of the tine.

The percentage volume change measured in many of the individual sections is frequently within the experimental error band of ±5% and, therefore, its significance must be questioned. Where, however, positive or negative values consistently appear in succession it can be concluded that some definite volume change has occurred.

The compacted zone within the low density soils is concentrated towards the working depth area of the tine. Compaction decreases as the soil surface is approached with a transition from net compaction to loosening. The transition depth moves closer to the soil surface as initial soil density decreases.

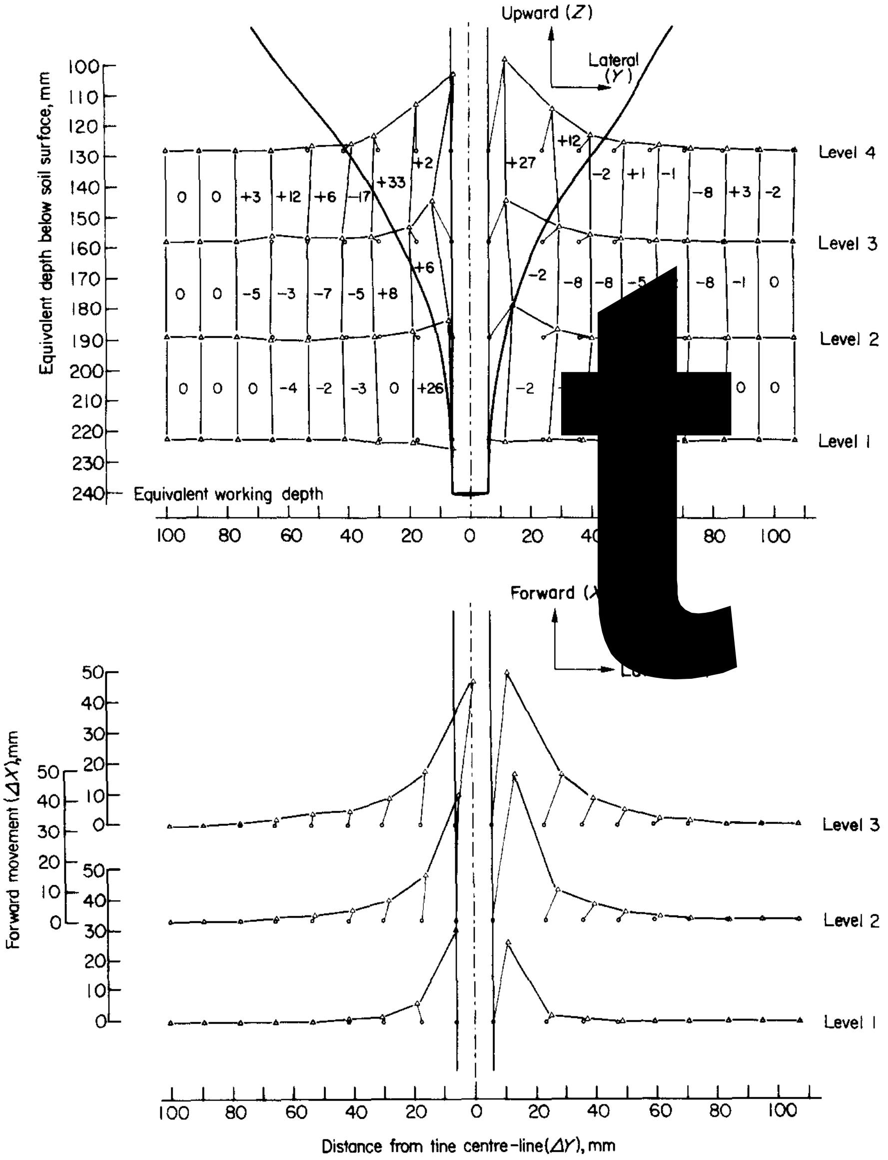

Fig. 9. Soil disturbance and net volume change, tine below critical depth (low density soil, 1·2 t/m^3)

(c) *Effect of tine width.* Increasing tine width at the same working depth, with all tines working below critical depth, increases both the total soil movement and its lateral extent. This can be seen in *Fig. 12*, which compares relative bead movement at one depth, after disturbance with tines of 6, 12·5 and 25 mm width, working at an equivalent depth of 240 mm in the medium density sandy loam.

3.2.2. *Heterogeneous soil conditions*

(a) *Laboratory results (tines working below critical depth).* Soil conditions simulating the presence of large air-filled cracks were created in the laboratory by packing the moderately compact sandy

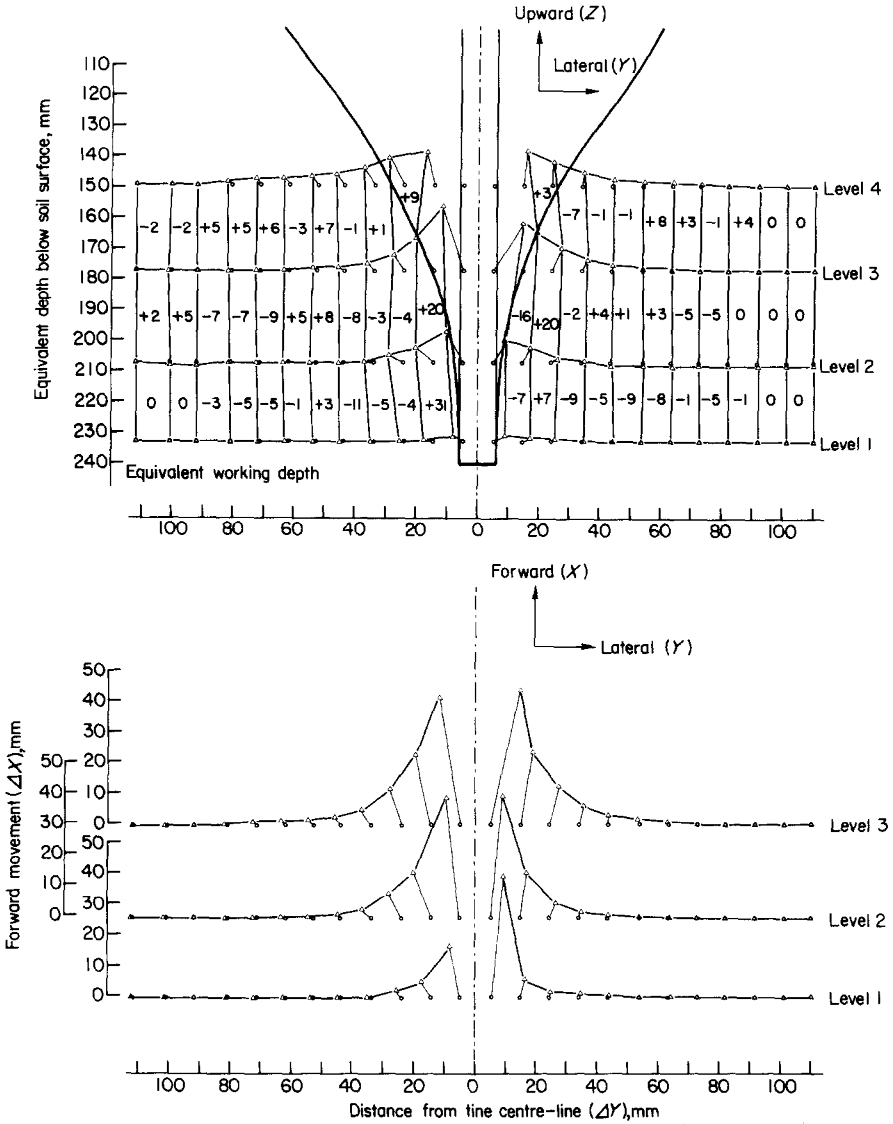

Fig. 10. Soil disturbance and net volume change, tine below critical depth (medium density soil, 1·45 t/m^3*)*

loam in the presence of Perspex strips. These strips were carefully removed from the front face of the soil after soil preparation, creating vertical cracks of varying length, thickness and distance from the tine. The vertical extent of the cracks also varied, with some cracks having continuity to the surface where Perspex strips were removed from above.

Fig. 13 shows the soil disturbance generated by a 12·5 mm wide tine operating in an otherwise homogeneous profile except for the presence of 3 mm wide discrete vertical cracks, positioned 45 mm from the tine edge. The large volume reduction in the region of the cracks is immediately obvious, indicating almost complete crack closure. This degree of volume change can be compared with the relatively minimal volume change in *Fig. 10*, where cracks were absent. Little movement occurred within the bottom row of beads in *Fig. 13*, indicating little crack fill due to compaction near the working depth. This is in contrast to the considerable lateral movement of

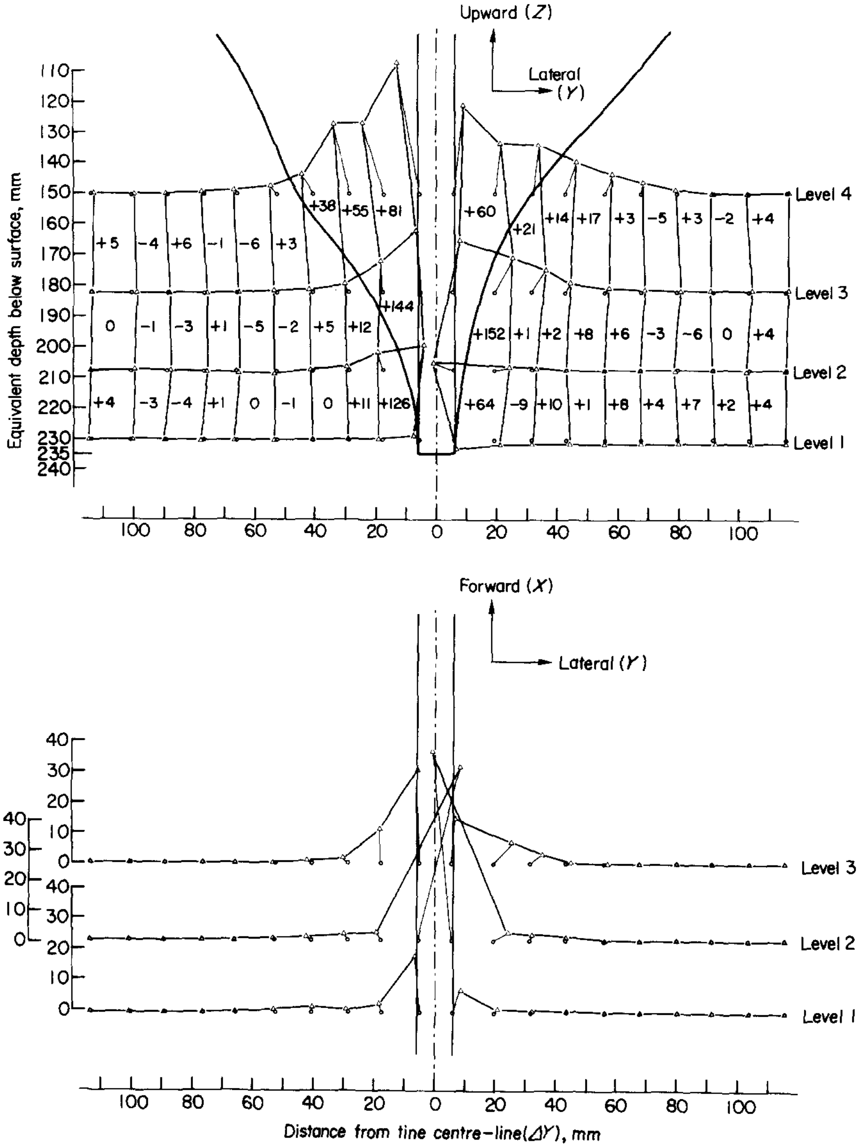

Fig. 11. Soil disturbance and net volume change, tine below critical depth (high density soil, 1·7 t/m^3)

beads, with virtually no upward movement, towards the crack at the second and third levels. Bead movement above the cracks is almost wholly forward and upwards.

A series of experiments with vertical cracks positioned at different distances from the edge of the tine have shown the percentage reduction in soil volume near the crack to be almost inversely proportional to the distance between the crack and the tine, see *Fig. 14.* In tests with decreasing tine widths a stage appears to be reached where the tine becomes incapable of generating sufficient lateral strain to displace soil by mass flow into discrete cracks a given distance from the tine. The closer the cracks to the tine, the greater the chance of crack closure at working depth.

TABLE 2

Volume change beyond failure planes; tine below critical depth

Average height above tine working depth, mm	*Average percentage volume change*			*Extent beyond failure planes*
	Initial soil density, t/m^3			
	1·2	1·45	1·7	
75	+5·5	+0·7	+24·7	Three tine widths
50	−4·0	+1·7	+4·3	
25	−2·3	−4·5	+2·0	
75	+3·3	+1·2	+12·0	Six tine widths
50	−3·7	−1·0	+2·1	
25	−2·5	−5·0	+2·1	

Measurement error in volume change assessment: three tine widths, ±2%; six tine widths, ±1·5%

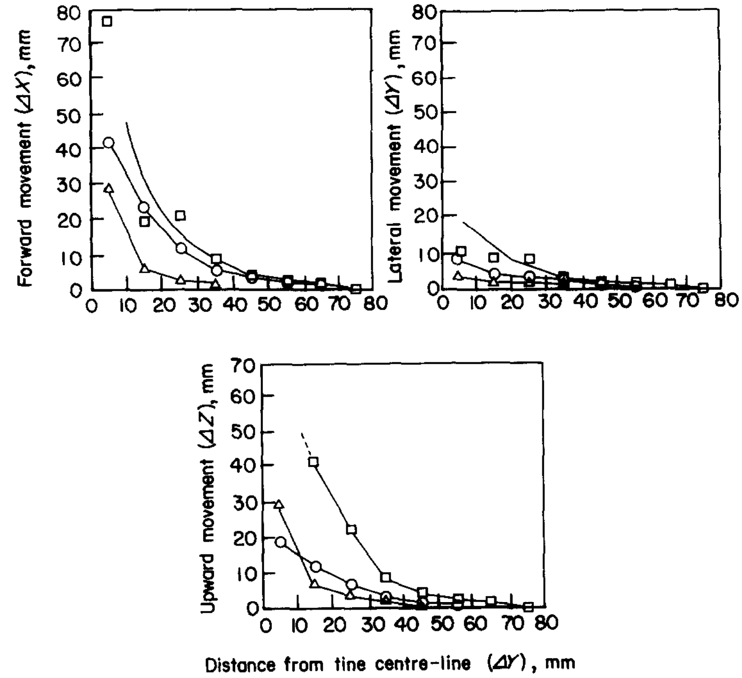

Fig. 12. Influence of tine width on soil movement (60 mm above working depth), tines below critical depth. Sandy loam, dry bulk density 1·3 t/m^3. □, 25 mm; ○, 12·5 mm; △, 6 mm wide tine

(b) *Field results*

(i) *Soil containing discrete macropores.* In a low shear strength almost saturated silty clay loam subsoil (Chatteris/Agney Series[15]) containing numerous large (1–3 mm dia) vertical root channels, the disturbance effects of a trenchless drainage tine were quantified by counting the number of root channels/unit horizontal area, and measuring changes in the soil hydraulic conductivity. The trenchless tine was working just below critical depth and was fitted with a slightly pointed cone-shaped share, which would tend to increase the chances of lateral soil movement at depth.

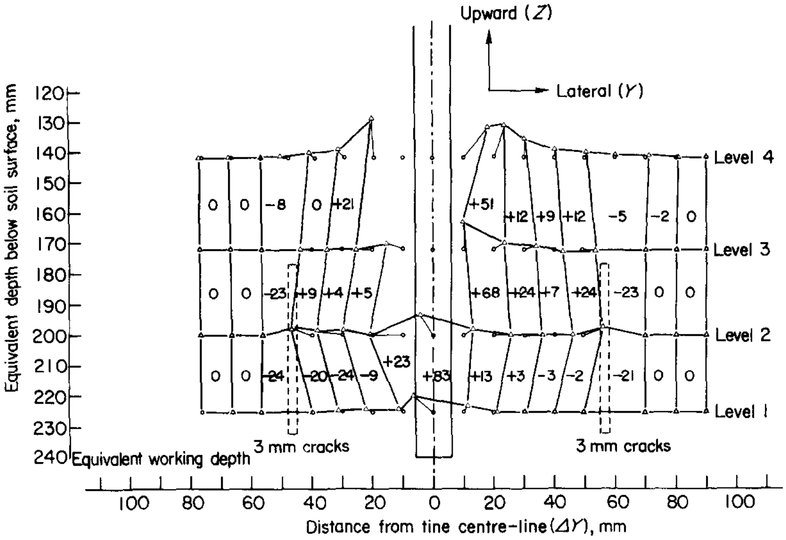

Fig. 13. Soil disturbance and net volume change in soil containing vertical cracks, tine below critical depth. Dry bulk density 1·4 t/m³

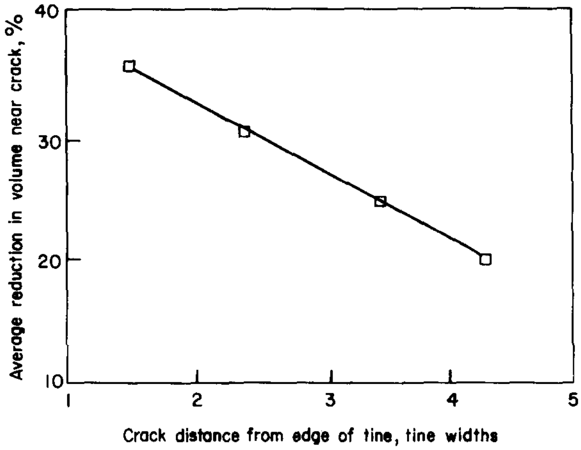

Fig. 14. Influence of crack distance from tine on percentage volume reduction near crack, tine below critical depth

The distribution of macropores after tining, *Fig. 15*, shows considerable disturbance at depth well beyond and below the major failure planes. Disturbance is greatest near the failure plane, where the macropore loss is complete, gradually decreasing as the limits of disturbed area are approached. Above critical depth considerable soil reworking, with a complete loss of root channels, occurred within a distance of approximately 10 mm of the failure plane. Little disturbance occurred beyond this region.

Hydraulic conductivity values confirmed the decrease in disturbance with distance from the failure planes. Spoor and Fry[11] recorded a marked fall in hydraulic conductivity with a decrease in the number and size of discrete root channels. Where the root channel walls were stabilized with hardened iron salts, much smaller changes in size and number were observed.

(ii) *Coarse structured or massive fine textured soils.* Attempts to monitor, through soil density change, the limits and degree of disturbance in fine textured soils without discrete macropores and at relatively high degrees of saturation (85–100%) proved unsuccessful due to the small changes involved. Hydraulic conductivity measurements were more sensitive and showed hydraulic conductivity reductions beneath and immediately adjacent to the tine at its working depth, see Spoor and Fry.[11] The actual soil disturbance, however, was limited to a maximum thickness of approximately 10 mm from the failure plane, being in the form of a reworked or smeared zone. Once this zone was broken off from the samples, the hydraulic conductivity approached that of the undisturbed soil. Field observations on many sites revealed reorientation of the clay plates to a similar thickness at the failure planes themselves, at shallower depths in the profile.

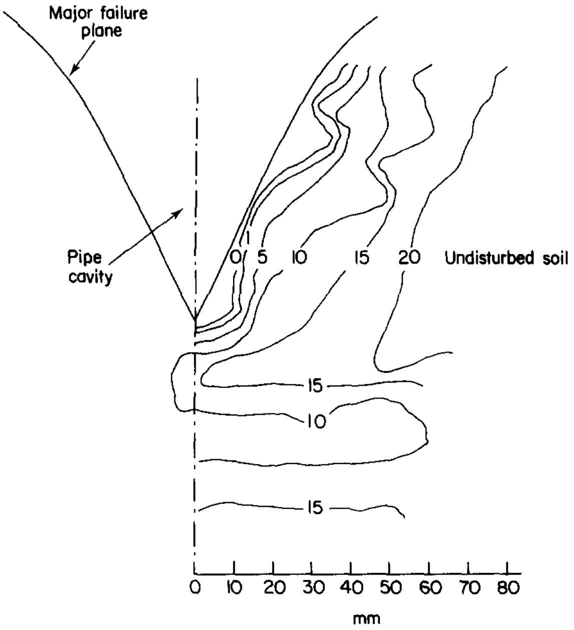

Fig. 15. Distribution of macropores per unit of plan area at working depth, tine below critical depth (sample area 0·004 m²)

4. Discussion

The results suggest that when tines are working above the critical depth for the prevailing conditions, the soil failure planes define the limits of soil disturbance, apart from some soil reworking at the failure plane interface. The thickness of this local reworking in the field varied between 0 and 10 mm, and tended to increase as soil shear strength decreased.

Soil within the major failure planes, regardless of tine position relative to critical depth, was always found in a loosened state. In field tests, top soil was frequently found at depth in this area. Depending upon the soil conditions, when tines are working below critical depth, unfilled cavities may be left between the failure planes at depth. Cavities were more prevalent on highly cohesive soil and absent under loose friable conditions.

With tines operating below critical depth soil disturbance occurs near working depth beyond the major failure planes. The resulting change in state or density and its extent in this area is dependent upon soil conditions. Under fairly homogeneous dense, unsaturated soil conditions, in the absence of discrete macropores and cracks, no compaction was monitored. As the bulk density of the soil decreased, however, some compaction occurred and the depth of the compacted zone above working depth increased with decreasing initial soil density. Compaction in this area is more pronounced in soils containing relatively large discrete cracks. Under these conditions, providing there is adequate strain available (½ tine width), soil tends to move laterally, mainly by mass flow, into the crack region. The greater the strain available from wider tines, the greater the likely extent of lateral movement. Continued increase in tine width will in the limit shift critical depth to below working depth, changing the nature of the disturbance. Crack infill tends to be less at working depth than at higher levels in the profile, unless strains are large and cracks close to the tine.

In soils containing discrete macropores, such as old root channels, significant pore deformation can occur beyond the failure planes when tines are working below critical depth. In relatively low shear strength, almost saturated soils the compressive normal stress needed to collapse these root channels is likely to be much greater than the lateral compressive stresses developed by the tine. In addition, little deformation occurred within the strongly stabilized pores. This would suggest that shear failure is the major factor causing channel size reduction or collapse. At high degrees of saturation and relatively low shear strength significant channel collapse through shear is, therefore, probable, with minimal or zero net compaction. The risk of channel collapse will be less at lower moisture contents when shear strengths increase.

Where compaction occurs at depth beyond the failure planes it tends to be more uniform within the disturbed zone in homogeneous soils than in those containing discrete cracks and pores. In the latter the compaction or disturbance effect tends to decrease with increasing distance from the tine side.

Reducing vertical confining stress locally with appropriately positioned shallower leading tines (see Spoor and Godwin[1] and Spoor and Fry[11]) may allow the failure plane position at depth to be extended laterally, increasing the vertical component of movement and so reducing compaction near tine working depth. Loosening the complete soil surface has an equivalent effect to reducing tine working depth and hence the critical depth position can be moved downwards.

Soil deformation beneath the tine base will be dependent upon the soil bearing capacity and the magnitude of the loading and contact pressures at the soil/tine interface.

5. Soil deformation mechanisms and controlling factors

5.1. *Deformation mechanisms*

The experimental results suggest that two forms of soil deformation occur simultaneously.

(a) An intermittent form, relatively close to the tine, where soil is brought to complete failure and slips towards the soil surface along well defined failure planes—upward failure.

(b) A continuous, more general form of disturbance, more closely associated with horizontal planes, where the failure state may not be reached—lateral deformation.

5.1.1. *Upward failure*

Glass-sided tank studies by Hettiaratchi and Reece[13] and Tanner,[14] examining soil deformation ahead of tines in vertical elevation, clearly show the regular generation of curved failure planes extending from the tine base to the soil surface. The forward extent of these failure planes ahead of the tines decreases rapidly at depth with increasing working depth until they approach, in the limit, the soil wedges on the tine face. The side failure planes observed on excavation are the final result of this failure ahead of the tine as the tine moves forward.

5.1.2. *Lateral failure*

Fig. 16, taken from Godwin and Spoor,[9] shows the trajectory of soil particles when forced to move in a horizontal plane ahead of a vertical tine—pure lateral deformation. The extent of the movement is considerable, deformation occurring along many planes, with the soil moving towards undisturbed soil ahead and to the sides of the tine. This type of movement may cause either compaction or loosening depending upon soil compactability, confining stress and particle trajectory. Within compactable soils, compaction must occur with initial strains in situations where no upward component of movement exists, such as in *Fig. 16*. Compaction need not occur if the soil is free to move upwards. Other situations may arise where, although compaction does occur initially, the final net density change may still be zero. In these cases the forward limit of the disturbed zone continuously advances as the tine moves forward, and hence compaction caused by soil movement towards the undisturbed soil may be alleviated almost immediately as the "undisturbed" soil itself is moved away.

The limit of soil disturbance to the side of the tine will, for a given potential strain, be dependent upon soil compactability and the shear stress/strain relationship for the particular soil. Providing the vertical component of movement is sufficiently greater than the lateral component no compaction will occur. With increasing sideways movement an even greater upward component will be required if compaction is not to occur.

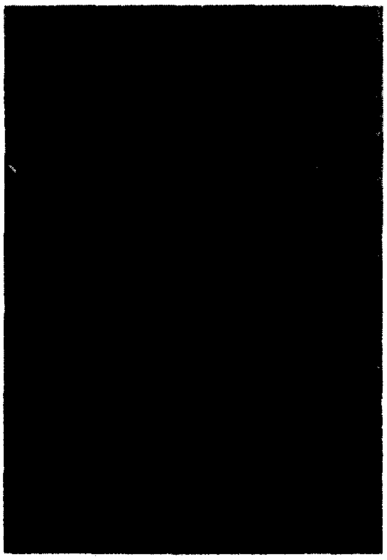

Fig. 16. Lateral soil deformation in front of vertical tine (after Godwin and Spoor[9])

5.1.3. *Soil deformation process*

The soil deformation process at depth can be summarized as follows. Soil deforms continually ahead of the tine in a form of lateral deformation, although not necessarily solely in a horizontal plane. Larger compressive stresses and strains are generated close to the tine and these increase until the boundary conditions for upward failure are satisfied. Upward failure then occurs with the failure planes, either at the limit or within the area already strained in a lateral manner. These failure planes are more likely to be at the limit of lateral deformation when tines are working above critical depth, and well within the disturbance limits when below critical depth. After upward failure the stress level immediately ahead of the tine will fall, lateral deformation will continue, with stress and strain levels building up for the next upward failure.

The examination of films associated with the glass-sided tank studies of Tanner[14] confirms considerable soil disturbance ahead of the tine at depth, with the upward intermittent failure planes developing within the disturbed area. The extent of the disturbed zone ahead of the failure plane increased with increasing working depth, decreasing soil density, and also as the failure plane approached the tine face.

5.2. *Controlling factors*

Upward failure will continue from the tine working depth so long as the boundary stress and strain conditions are met. The greater the working depth and the more compressible the soil, the greater the upward strain required for complete failure. Below a certain working depth tines with a limited lift height on the leading edge may be unable to generate sufficient vertical strain for failure. This has been shown to be the case with mole ploughs, see Godwin, Spoor and Leeds-Harrison,[2] where below a certain working depth upward failure ceases and stable mole channel formation becomes possible.

Whether a net increase in density occurs in the disturbed zone beyond the main failure planes is dependent upon the relative values of the upward and sideways components of movement. For compaction to be avoided the vertical component of movement must always exceed the lateral component, and the greater the latter, the greater the difference between the two must be. For a given soil condition at depth, the greater the vertical confining stress the smaller the vertical component of movement is likely to be, and hence the greater the risk of lateral compaction occurring. Vertical confining stresses increase with increasing working depth, larger tine rake angles, and with increasing shear strength in the upper soil layers. In the limit, with very high vertical confining stresses relative to horizontal ones, disturbance similar to that shown in *Fig. 16* can be expected.

In heterogeneous soils containing larger air-filled voids there is a tendency for the pores to close irreversibly due to combined shear and compression if they are in the line of the sideways trajectory; thus, local compaction is generated. In some cases the net overall density change may still be zero if a vertical component of movement exists, with some new voids being created to replace the old ones. From the point of view of hydraulic conductivity, however, the new voids may be less efficient water carriers than the original pores; this would certainly be the case where continuous discrete root channels are closed or misaligned.

6. Conclusions

Two forms of soil disturbance generated simultaneously by narrow tines have been identified: upward failure and lateral deformation. In upward failure, soil shear occurs along a few well defined failure planes, with the soil within the planes being subjected to a net loosening effect—brittle failure. Lateral deformation takes the form of shear along many planes with or without density change, the soil in most cases not being brought to complete failure.

The effects of upward failure tend to dominate, with tines working above critical depth and little soil disturbance occurs beyond the failure planes. Once below critical depth lateral deformation effects become more significant, until at greater working depths they dominate. Considerable soil deformation now occurs beyond the failure planes. There is, therefore, no abrupt change in the type of failure with increasing depth, as is often assumed for ease of analysis in many force prediction models. The critical depth represents the depth below which lateral deformation beyond the failure planes becomes significant.

Lateral deformation within single grained, weakly structured or structureless soils takes the form of movement along almost an infinite number of planes. Soil loosening or compaction may result from this disturbance, the result being dependent upon soil packing, compressibility and the potential for upward soil movement. As vertical confining stresses increase relative to lateral ones, through increasing depth and higher surface soil shear strengths, the chances of compaction increase; unsaturated low density soils being the most susceptible. In saturated conditions little net compaction is likely, but in soils containing discrete macropores these pores could disappear through shearing action. This latter effect is most likely when soil shear strength and pore stability are low.

In coarser structured soils and those containing shrinkage cracks the structural and shrinkage pores or fissures tend to be the main sites for lateral deformation effects. These pores form planes of weakness for shear failure and can be readily reduced in size with either partial or complete closure, depending upon the strains available and the uniformity and size of the fissures.

Local soil reworking with compaction or smear may occur in low shear strength soils at the failure plane interfaces, this is usually very limited in extent.

The reduction of vertical confining stresses, either generally or locally, on the soil at depth, tends to increase the vertical component of soil movement, reducing the risks of compaction.

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REFERENCES

[1] **Spoor, G.; Godwin, R. J.** *An experimental investigation into deep loosening of soil by rigid tines.* J. agric. Engng Res., 1978 **23** 243–258

[2] **Godwin, R. J.; Spoor, G.; Leeds-Harrison, P.** *An experimental investigation into the force mechanics and resulting soil disturbance of mole ploughs.* J. agric. Engng Res., 1981 **26** 477–497

[3] **Naarding, W. H.** *Trench versus trenchless drainage techniques.* Proc. Int. Drainage Workshop, Wageningen, The Netherlands (Ed. J. Wesseling). Publ. I.L.R.I., 1979 543–560

[4] **Olesen, S. E.** *Trenchless drainage experiments in Denmark.* Proc. Int. Drainage Workshop, Wageningen, The Netherlands (Ed. J. Wesseling). Publ. I.L.R.I., 1979 527–535

[5] **Eggelsman, R.** *Comparisons between trenchless and trenching sub-drainage.* Proc. Int. Drainage Workshop, Wageningen, The Netherlands (Ed. J. Wesseling). Publ. I.L.R.I., 1979 536–542

[6] **Kostritsyn, A. K.** *Cutting of a cohesive medium with knives and cones.* Silsoe, Bedford: N.I.A.E. Transl. 58, 1956

[7] **Zelenin, A. N.** *Fizicheski osmovie teorii rezaniya gruntov* (Basic physics of the theory of soil cutting). Moscow, Leningrad: Akademia Nauk S.S.S.R. (Silsoe, Bedford: N.I.A.E. Transl., unnumbered), 1950

[8] **O'Callaghan, J. R.; Farrelly, K. M.** *Cleavage of soil by tined implements.* J. agric. Engng Res., 1964 **9** (3) 259–270

[9] **Godwin, R. J.; Spoor, G.** *Soil failure with narrow tines.* J. agric. Engng Res., 1977 **22** (3) 213–228

[10] **Roscoe, K. H.; Schofield, A. N.; Wroth, C. P.** *On yielding soils.* Géotechnique, 1958 **8** 22–53

[11] **Spoor, G.; Fry, R. K.** *Field performance of trenchless drainage tines and implications for drainage system efficiency.* J. agric. Engng Res., 1983 **28** (to appear)

[12] **Fry, R. K.; Spoor, G.** *Electrical analogue studies of the influence of soil compaction and smear in the vicinity of a pipe drain on drain performance.* J. agric. Engng Res., 1983 **28** 207–216

[13] **Hettiaratchi, D. R. P.; Reece, A. R.** *Boundary wedges in two-dimensional passive soil failure.* Géotechnique, 1975 **25** (2) 197–220

[14] **Tanner, D. W.** *Further work on the relationship between rake angle and the performance of simple cultivation implements.* J. agric. Engng Res., 1960 **5** (3)

[15] **Robson, J. D.; George, H.; Heaven, F. W.** Soils in Lincolnshire 1. Sheet TF 16 (Woodhall Spa). *Soil Survey Record No. 22.* Harpenden, 1974 71–74