Effect of Soil Overburden Pressure on Penetration of Fine Metal Probes[1]

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ABSTRACT

The interactive effect of overburden pressure and root confinement on root elongation in a fine-structured loam soil has been examined using fine-metal probes to simulate a plant root. Substantial increases in probe resistance with simulated overburden pressure were found only at high soil bulk densities and high ratios of probe to soil volumes. These findings suggest that for low root to soil volumes (root density) and the maximum soil density used, 1.63 g cm^{-3}, the elongation rate of plant roots at a depth of 150 cm would be only 4% less than in the surface layer. For root densities in excess of 0.01 and the same bulk density and depth of overburden, the model predicts a 30% reduction in elongation rate.

Additional Key Words for Indexing: **root growth, overburden, root simulation, penetrometer.**

PLANT roots are often found in soil layers which, because of their particle size distribution and lack of sufficient aggregation, have pore sizes less than the diameter of the root tip. Under these conditions roots elongate by deforming the surrounding soil.

Local compaction of sandy loams adjacent to root channels caused by displacement and rotation of the grains was first observed by Barley (1954). Greacen et al. (1968a) used X-ray photography to illustrate the increase in soil density near the soil-root interface of elongating pea roots. Although most soils are deformable, some pans have been found that behave essentially as rigid materials (Lutz, 1952). Root penetration in these latter soils is possible only if the pore sizes exceed the size of the plant roots (Wiersum, 1957). While shear failure with local compaction has been suggested (Barley and Greacen, 1967) as the most common way in which growing plant roots deform ordinary, unsaturated soils, the effects of discontinuities such as shrinkage cracks and old root channels on root proliferation cannot be overlooked. It is generally agreed that roots explore these soil cavities.

In this study we limit our interest to fine-structured soils in which root elongation requires compression of the soil surrounding the plant root. Specifically we consider the case in which the mobility of the soil particles is restricted either by the weight of overlying soil or by neighboring roots. Our objective is to determine the interactive effect of overburden pressure and root confinement on the resistance of the soil to local deformation during root elongation. Fine-metal probes are used to simulate the plant root.

MATERIALS AND METHODS

The soil material was taken from the surface horizon of a Dickinson loam and contained 51% sand, 33% silt, and 16% clay. Air-dry soil, less than 2 mm in diameter, was brought to a water content by weight of approximately 19% with a fine mist. The weights of moist soil required to produce cores with a desired density were compressed from both ends into lucite cylinders 7.76 cm long and 3.78 cm or 7.47 cm in diameter. The cores in their containing cylinders were allowed to wet on porous ceramic plates with the base of the cores under a 0.5-cm head of water for 48 hr. They were then drained to equilibrium at a suction of 0.3 bar. After removal from the ceramic plates, the cores were stored in plastic bags in a dark place for 7 days to remove any residual gradient in soil-water potential.

Density Determinations

Gamma-ray attenuation was used to measure the variations in density of the prepared soil cores. The gamma-ray apparatus consisted of a 251 mc Cs^{137} source, a detecting and analyzing system, and a mechanism for positioning the source and detector with respect to the soil samples. The arrangement of the source, detector, and positioning device has been described by Kirkham et al. (1967). Each core encased in its lucite cylinder was placed on a stationary horizontal stand between the source and detector. The gamma beam traversed the core vertically and ten 1-min counts were made at each centimeter increment down the core. Variations in density were calculated assuming a constant water content. As expected, the variations in soil density increased with decreasing mean soil density and

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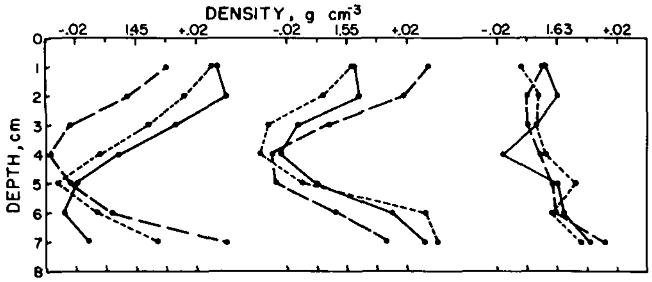

Fig. 1—Variation in bulk density within nine cylindrical soil cores 3.78 cm in diameter with mean densities of 1.45, 1.55, and 1.63 g cm^{-3}.

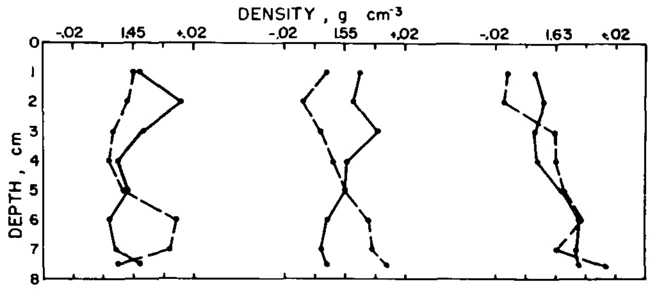

Fig. 2—Variation in bulk density within six cylindrical soil cores 7.47 cm in diameter with mean densities of 1.45, 1.55, and 1.63 g cm^{-3}.

decreasing core diameter, with the ends of the core more dense than the center (see Fig. 1 and 2).

Overburden Pressure Apparatus

At a depth, z, below the surface of a homogeneous soil mass, the vertical normal stress, σ_1, is

$$\sigma_1 = \gamma z$$

where γ is the effective unit weight of the overlying soil mass. The horizontal stress, σ_3, at depth, z, is equal to

$$\sigma_3 = K_o \gamma z$$

where K_o is the coefficient of earth pressure at rest.

The apparatus constructed to meet the above stress conditions is shown in Fig. 3. Pressure was applied to the basal surface of the soil core by means of a flexible rubber membrane. By regulating the pressure in the cell, a range of overburden pressures could be simulated. The apparatus was constructed to accommodate soil cores 3.78 cm and 7.47 cm in diameter. Lucite split-rings (acrylic plastic) were used to maintain, before and during probe penetration, the necessary condition of zero horizontal strain at the soil-ring interface. The rings were clamped to the soil core by tightening a fine-threaded screw to give an estimated average contact pressure of 10 g cm^{-2} between each lucite ring and the core. This contact pressure of 10 g cm^{-2}, while sufficient to prevent slippage of the lucite rings under their own weight, has an insignificant effect on the probe resistance.

Since the contact pressure could not be measured directly, it was estimated as follows. The force, F_f, required to overcome friction between the soil core and a confining ring is given by:

$$F_f = \tan \psi \; \sigma_n \; 2\pi rh + C_a \; 2\pi rh$$

where r is the radius of the soil core, h is the height of the lucite ring, σ_n is the average contact pressure between the core and the ring, $\tan \psi$ is the coefficient of soil lucite friction (0.41), and C_a is soil-lucite adhesion (4.2 g cm^{-2}). The force, F_f, was computed for a contact pressure of 10 g cm-2 and the fine-threaded screw adjusted until the lucite ring would barely slide down the core under a weight, F_f.

Had the soil core been confined within a continuous tube, the internal soil stresses produced by applying a compressive force to the ends of the core would have varied through the soil core because of soil-tube friction. If soil-lucite adhesion, C_a, is ignored, the normal compressive stress on an axial plane at a distance, x, from the loaded end of a confined soil core of diameter, d, is given by:

$$\sigma(x) = \sigma_o \exp(-4K_o \tan \psi \; x/d)$$

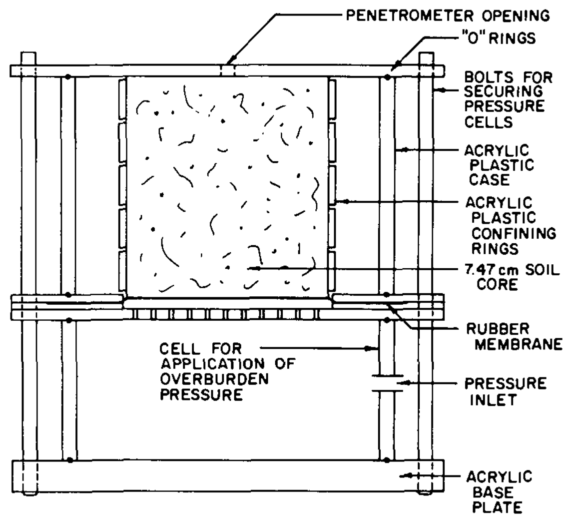

Fig. 3—Apparatus for simulating overburden pressure.

where σ_o is the normal compressive stress at the soil surface and K_o is the measured coefficient of earth pressure at rest for the soil. From triaxial tests with zero lateral strain, this coefficient of earth pressure at rest was found to be 0.5. For a ring of height, $2x$, the minimum normal compressive stress occurs at height, x, of the ring and may be computed from the preceding expression. In this study ring heights of 1 cm and 1.78 cm were used for the small and large soil cores, respectively, and the ratio $\sigma(x)/\sigma_o$ was approximately 0.9.

Penetration Measurements

Steel probes with diameters of 0.242, 0.376, and 0.514 cm were driven into radially confined soil cores 3.78 cm and 7.47 cm in diameter. With these core and probe diameters, the ratio of the core cross section to probe cross section could be varied from 53 to 953. A separate core was used for each measurement of probe resistance with penetration at the core axis. The probes were similar to those described by Barley et al. (1965) and allowed point resistance to be measured separately from the wall friction. The included angle of the point was 60°. The value of the point resistance, q, per unit cross section of the probe was taken as the average force per unit area after the probe had penetrated a depth of not less than five times the probe diameter. Variations in point resistance below this depth were slight.

Penetration rates ranging from 0.1 cm hr^{-1} to 13.1 cm hr^{-1} have no noticeable effect on point resistance (Fig. 4). A penetration rate of 5.0 cm hr^{-1} was used throughout the study.

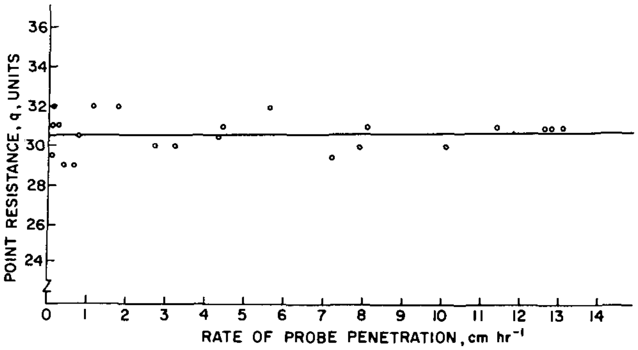

Fig. 4—Point resistance q as a function of rate of probe penetration in confined cores; $\rho = 1.45$ g cm^{-3}, suction 0.3 bar, radius of probe = 2.42 mm.

RESULTS AND DISCUSSION

The effect that externally applied soil stresses have on the point resistance encountered by a metal probe in our study might be likened to the effect that soil overburden pressures have on the mechanical pressure encountered by a growing root tip. Unfortunately the simulation is not entirely adequate, because the effect of the physical differences between rigid probes and deformable plant roots cannot be disregarded. The ability of a plant root to adapt its shape, that is, to alter its relative radial to axial growth rates, to suit its environment is well known. Abdalla et al. (1969) interpret observed increases in root thickness with increasing confining pressure as a stress relief mechanism for the elongating root tip. They argue that when axial elongation of the root tip is inhibited by the confining pressure, continued radial growth of the meristematic region eventually reduces the stress at the root tip to a level at which axial growth is again possible. Also, Greacen et al. (1968a) have shown that the soil density distribution in the vicinity of a blunt probe differs markedly from the density distribution in the vicinity of a plant root. These physical differences undoubtedly limit the quantitative value of our probe simulation study of root elongation.

Nevertheless, for short-term experiments on root elongation, Taylor and Gardner (1963), Barley et al. (1965), Eavis and Payne (1968), and Taylor and Ratliff (1969) have shown that (when a single plant species and soil type are used) probe resistance correlates well with the rate of root elongation.

The interactive effect of overburden pressure and root density on the growth rate of plant roots can be evaluated from the probe results if the following assumptions hold. First, a unique relationship exists between probe resistance and the rate of root elongation and, second, the confined probe effectively simulates a growing root tip in the presence of neighboring plant roots. This latter assumption implies that root density may be expressed as the ratio of the cross-sectional area of the probe to the cross-sectional area of the soil core.

Experimental evidence (Eavis and Payne, 1968; Taylor and Ratliff, 1969) indicates that the first assumption is acceptable for seedling roots when a single plant species is used. For mature plants suitable experimental data on root growth is limited. However, rhizotrons or root growth laboratories (Rogers and Head, 1963; Taylor, 1969) should greatly facilitate the study of root growth during extended periods of plant growth.

The validity of the second assumption is more difficult to assess. Experimental studies to determine root growth pressures or elongation rates for a range of root densities are difficult to design and evaluate because of the confounding effects of genetic and environmental factors.

Models other than our confined-probe model might be used for estimating the effect that neighboring roots have on the resistance of soil to root penetration. For example, Greacen et al. (1968b) used a multiple-probe system. This model predicted an initial decrease in resistance to root penetration with increasing root density and a subsequent increase, a result which conflicts with the predictions of our model. Limited work with a multiprobe system in which the central test probe is inserted following entry of surrounding probes showed that the basal pressures on the probe for the confined probe model and this multiprobe system were not significantly different over the range of root density used in this study. The tests were conducted on Dickinson loam at a bulk density of 1.45 g cm^{-3} and at 0.3-bar suction. This finding suggests that the gross differences in probe pressure for the confined probe and multiprobe methods of root density simulation reported by Greacen et al. (1968b) might have resulted from their use of a concurrent penetration of the soil by all probes in the multiprobe system. The significant reduction in probe pressure for their multiprobe system is consistent with the prediction of group pile theory (Nishida, 1961). Nevertheless, reductions in probe pressure from multiprobe systems resulting from tensile fracturing of the soil between neighboring probes cannot be discounted. This fracturing, which is more likely to occur in some soils than in others, would also explain the differences between our observations and those reported by Greacen et al. (1968b). While we recognize several inadequacies in our method of root simulation, we feel that our model results improve our understanding of the effects of soil overburden pressure on root growth.

For Dickinson loam an increase in applied pressure or increase in the ratio of probe-core cross section (a^2/D^2) increased the probe resistance at all three bulk densities (Table 1). However, significant increases were obtained only at high a^2/D^2 values and at high soil densities. To show how the interaction of overburden pressure with root density might affect root growth, we have applied these results to the relationships between penetrometer resistance and root elongation rates for peanut seedlings (*Arachis hypogaea* L. 'Virginia Bunch') reported by Taylor and Ratliff (1969). They found that the relationships between penetrometer resistance and root elongation rate could be expressed as

$$Y = 2.694 - 0.084x + 0.0007x^2$$

where x is the penetrometer resistance in bars and Y is the rate of elongation in mm hr^{-1}. In their experiments Taylor and Ratliff used a polished steel probe with a conical tip similar to that used in our study.

The relationship between overburden pressure, root den-

Table 1—Point resistance, q(kg cm^{-2}), for Dickinson loam at 0.3-bar suction

a^2/D^2*	Depth, cm	Bulk density, g cm^{-3} 1.45	1.55	1.63
0.00104	0	10.51	14.40	19.01
	50	10.57	14.54	19.27
	100	10.65	14.68	19.54
	150	10.76	14.84	19.84
	200	10.88	15.11	20.16
0.00253	0	10.61	14.57	19.34
	50	10.71	14.72	19.61
	100	10.82	14.90	19.84
	150	10.96	15.20	20.26
	200	11.13	15.51	20.83
0.00473	0	11.01	15.41	20.55
	50	11.32	15.91	21.18
	100	11.64	16.47	21.88
	150	11.97	17.10	22.76
	200	12.36	17.78	23.79
0.00989	0	12.01	16.55	22.20
	50	13.04	17.70	23.85
	100	13.97	19.26	25.73
	150	14.85	20.50	27.55
	200	15.67	21.85	29.50
0.01849	0	12.91	17.84	24.27
	50	14.04	19.10	26.20
	100	15.11	21.05	28.42
	150	16.13	22.72	30.53
	200	17.03		

* a^2/D^2 is the ratio of probe-core cross-sectional area.

sity, and root elongation rate shown in Fig. 5 were obtained from Table 1 and the preceding equation.

The results indicate that for low root densities < 0.004 overburden pressure will have a significant effect on root elongation rates only at soil densities higher than those used in this study. At our maximum density of 1.63 g cm^{-3} the root elongation rate at a depth of 150 cm is only 4% less than in the surface layer. For root densities in excess of 0.01, predicted reductions in root elongation rates range from approximately 10% at a bulk density of 1.45 g cm^{-3} to 30% at a bulk density of 1.63 g cm^{-3}.

Similar predictions for cotton roots (*Gossypium hirsutum* L. 'Empire') result from data given by Taylor and Ratliff (1969). While the estimated decrease in root elongation rate due to overburden pressure probably does not exceed 30%, this decrease could still have a significant effect on root distribution patterns.

In field soils, however, the effect due to increasing overburden pressure may often be masked by factors such as changes in soil resistance due to soil layering.

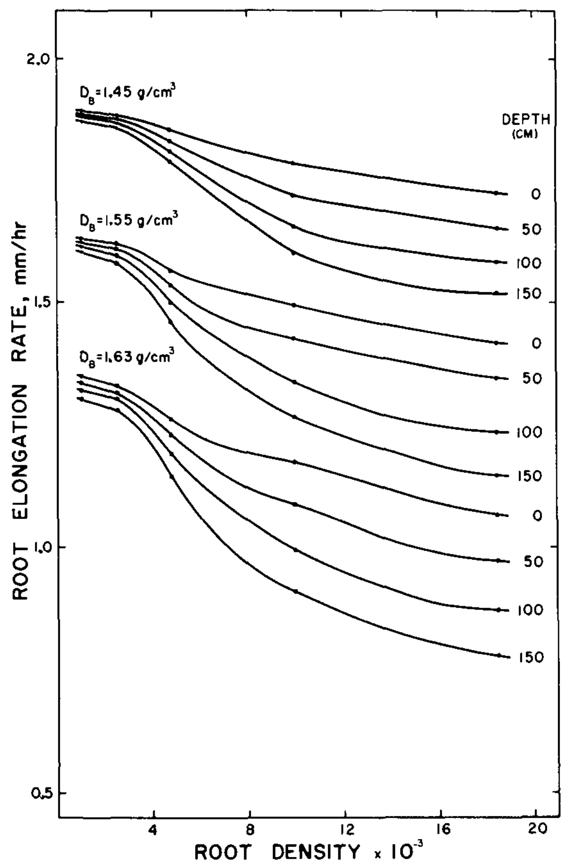

Fig. 5—Effect of root density and depth of soil overburden on the predicted elongation rates of peanut roots.

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