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Soil compaction around a small penetrating cylindrical body and its consequences

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Abstract

Penetrometer probes as well as roots and earthworms push soil particles (grains or small aggregates) radially during penetration and/or thickening due to growth. By this, the adjacent soil within a concentric layer is compacted. The degree of compaction depends on soil texture and soil physical properties that are influenced by soil moisture status. In the present study an estimate of the mean but constant increase of the initial bulk density and of the outer radius of this concentrically compacted zone, which are interdependent, is given. For instance, an increase from 1.2 g/cm^3 to 1.6 g/cm^3 yields a compacted zone of radius 0.5 mm when a body of radius 0.25 mm penetrates into a soil. This estimation is less laborious, but also less exact than that of Dexter (1987: Comparison of soil around roots. Plant Soil, 97: 401–406). This study shows that the distance between adjacent penetrations, when measuring resistance to penetration, should be $\geqslant 10$ times the probe radius. It is moreover supposed that the compaction produced by roots and earthworms makes it easier for them to anchor within (loose) soil. However, it possibly diminishes infiltration and exchange of soil solution.

Key words: Soil compaction, consequences

1. Introduction

The effect of root or earthworm penetration into the soil on the adjacent soil is often compared with the penetration of fine probes. Farrell and Greacen (1966) have divided the affected soil into four separate zones (I–IV) in which compaction to minimum pore volume, plastic deformation without and with relaxation, and elastic deformation occur. All such comparisons take the well known difference between the penetration of an inflexible needle probe and the flexible root (e.g., Groenevelt et al., 1984) or earthworm into consideration. Both root and earthworm are able to search for regions of minimal soil resistance (e.g., Dexter, 1986a, 1986b; Lee, 1985). In contrast to blunt or sharp probes which push soil particles away during continuous penetration, roots and earthworms push the adjacent soil

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away by radial growth (root) (e.g., Richards and Greacen, 1986) or thickening of the corpus (earthworm) (Lee, 1985).

To get an idea of the stress exerted by a tube or a radially growing root within the different zones mentioned above, and of the radius of the affected soil around the penetrating subject, Farrell and Greacen (1966), Greacen et al. (1968), and Misra et al. (1986a, 1986b) among others have calculated for some given conditions the stress distribution around a probe. This is identical to that of a radially growing root. Emphasis was placed on the distribution of stress, strain, and strength, rather than bulk density within those zones as it is affected by internal friction, cohesion, and soil-metal-friction. To the author's knowledge, only Dexter (1987), Graff and Hartge (1974), Greacen et al. (1968), and Seymour (1978) have given information on the bulk density and its distribution around a penetrating body. Dexter (1987) conscientiously but labouriously analyzed the changes in pore volume around a root, which corresponds to changes in bulk density. The object of this study is to show how a rapid but rough estimate of the mean but, in contrast to Dexter (1987), constant increase in bulk density and the distance to which this constant increase occur can be made, and to discuss some consequences of the increase.

2. Estimation

Consider a homogeneous soil, e.g. a soil aggregate, of given bulk density without any macropores (as pathways for roots or earthworms) and a cylindrical body of given diameter penetrating into this soil. The degree of compaction around this body, measured as an overall increase in bulk density, and the distance to which this increase occurs, depend only on the diameter of the body under the conditions given. The volume of the soil cylinder of body diameter (r) and of unit length (l) is compressed into the surrounding soil by the body along unit length. By this a hollow cylinder of soil is affected (Fig. 1). The inner radius r of the hollow cylinder corresponds to the radius of the body, and the outer radius r_c depends

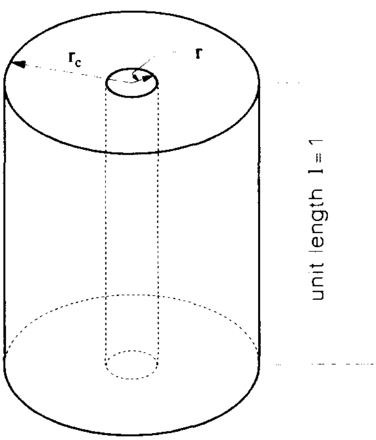

Fig. 1. Sketch of affected hollow cylinder (r = inner radius = outer radius of the affecting body, r_c = outer radius).

on the initial bulk density and the possibility of rearranging soil particles within this region. Rearrangement depends on cohesion and internal friction, which are affected by the existing soil moisture status. The overall increased bulk density ρ_{b_c} is estimated by Eq. (1) assuming a given outer radius r_c of the hollow cylinder

$$\rho_{b_c} = \frac{\rho_b \cdot V_G}{V_V} = \frac{\rho_b \cdot \pi \cdot l \cdot r_c^2}{\pi \cdot l \cdot (r_c^2 - r^2)} = \frac{\rho_b \cdot r_c^2}{r_c^2 - r^2} \quad (1)$$

Rearranging Eq. (1) and assuming an increased bulk density ρ_{b_c}, the outer radius r_c of the hollow cylinder is estimated by Eq. (2)

$$r_c = \sqrt{\frac{\rho_{b_c} \cdot r^2}{\rho_{b_c} - \rho_b}} \quad (2)$$

In Eqs. (1) + (2) ρ_b = bulk density ⟨g/cm^3⟩ of the unaffected soil, ρ_{b_c} = bulk density of the compressed soil ⟨g/cm^3⟩, V_G = volume of the suggested complete soil cylinder before compression, V_V = volume of the (compressed) hollow soil cylinder, l = unit length of cylinder, r = radius of compressing body = inner radius of hollow cylinder, r_c = radius of complete cylinder = outer radius of hollow cylinder $\neq$ thickness of compressed layer.

The penetration path within a soil aggregate when using a needle probe of 0.5 mm diameter clearly shows an affected thin layer of about 50 μm on SEM images (Fig. 2) (Becher, 1991a). If no more soil around the body is affected (r_c = 0.3 mm), a soil volume per unit length of 0.196 mm^3 would be compressed into a volume V_V of 0.086 mm^3

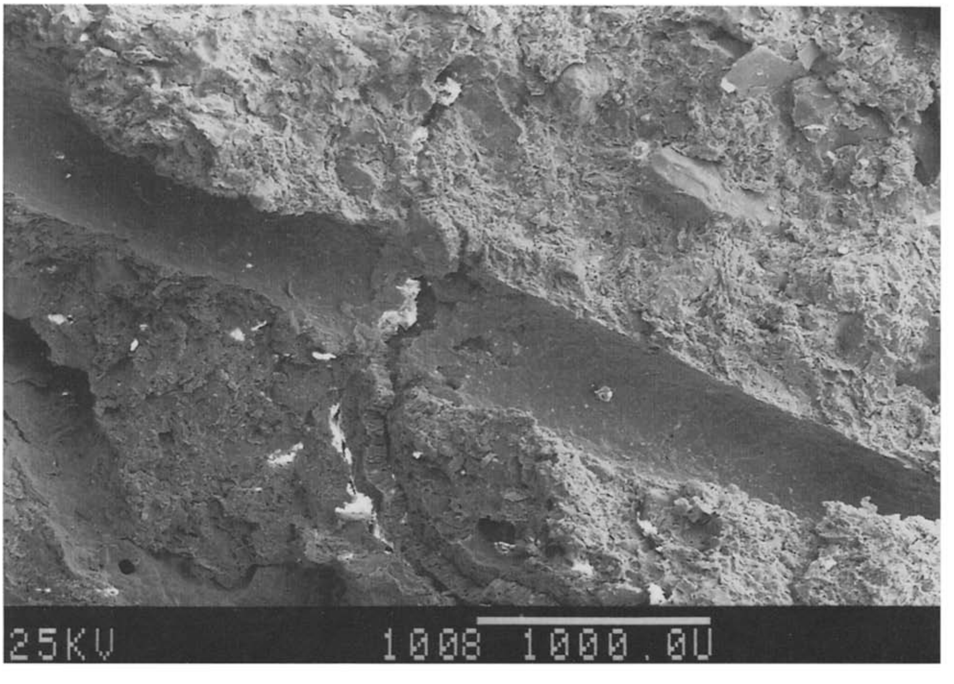

Fig. 2. SEM of the pathway of a 0.5 mm-probe showing the very thin layer compacted to minimum pore volume.

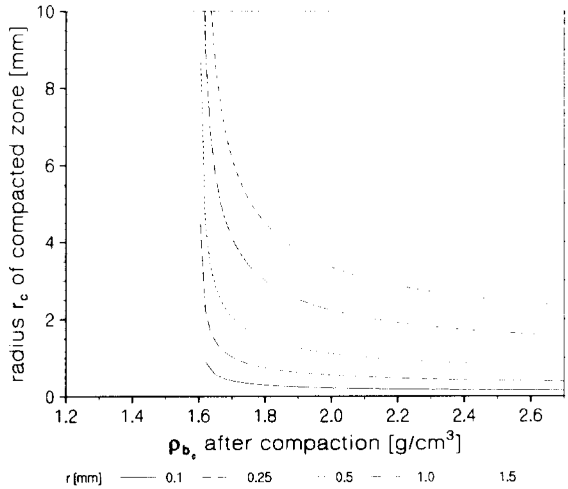

Fig. 3. Influence of body radius r on the affected radius r_c for an initial bulk density $\rho_b = 1.6$ g/cm^3.

(= hollow cylinder), or a total volume V_G per unit length of 0.283 mm^3 would be compressed to that V_V. Assuming a bulk density of a soil aggregate of 1.8 g/cm^3 (e.g. Becher, 1991b), this yields a bulk density value of 5.89 g/cm^3 within the very thin compacted layer. Because the soil may be compacted only to a maximum ρ_{b_c} of 2.0–2.2 g/cm^3, such a high bulk density is impossible. Therefore, the soil around the body must be affected to a much larger distance. Using these two values of bulk density we obtain r_c values of 0.79 mm and 0.59 mm, yielding thicknesses of the compacted layer of at least 0.54 mm and 0.34 mm. Only 0.05 mm of this layer could be observed as compacted on SEM images, and may possibly have a somewhat greater bulk density. This indicates that zones II and III of Farrell and Greacen (1966) are not detectable on this and similar SEM images.

As pointed out by Dexter (1987), Graff and Hartge (1974), and Greacen et al. (1968), there should not be an abrupt change of bulk density at the outer boundary of zone III, but rather a gradual change or tailing off of the bulk density to the unaffected zone IV. Disregarding the high bulk density in zone I and its thinness, the estimated bulk density within zones II + III is a total average valid for the estimated or assumed radius r_c. The real boundary thus should not lie far outside of r_c, depending on the cohesion and internal friction of the soil considered.

Using different body radii r and an initial $\rho_b = 1.6$ g/cm^3, it is possible to calculate r_c for different ρ_{b_c} (Fig. 3). Fig. 4 presents the relations for a constant body radius $r = 0.25$ mm and variable initial ρ_b values. The estimated ρ_{b_c} for variable r_c are given in Fig. 5 when using different body radii r and two initial values of ρ_b. These three figures, and similar figures when using other values for the parameters, result in only one figure with two curves (Fig. 6) when using dimensionless bulk density BD and radius R according to Eqs. (3) and (4), respectively,

$$BD = \frac{r_n^2}{r_n^2 - 1} \qquad (3)$$

$$R=\sqrt{\frac{\rho_n}{\rho_n-1}} \tag{4}$$

with $n=(r+\Delta r)/r$ and $\rho_n=(\rho_b+\Delta\rho_b)/\rho_b$. Derivation of Eqs. (3) and (4) are given in the Appendix. Fig. 6 shows that small increases in bulk density due to penetration only occur if the radius of the affected region (zones I–III) is at least three times the body radius. On the other hand, considerable increases occur if the radius is $\leqslant 1.5$ times the body radius. Stating an increased dimensionless bulk density ρ_n of 1.3, the soil around the probe is

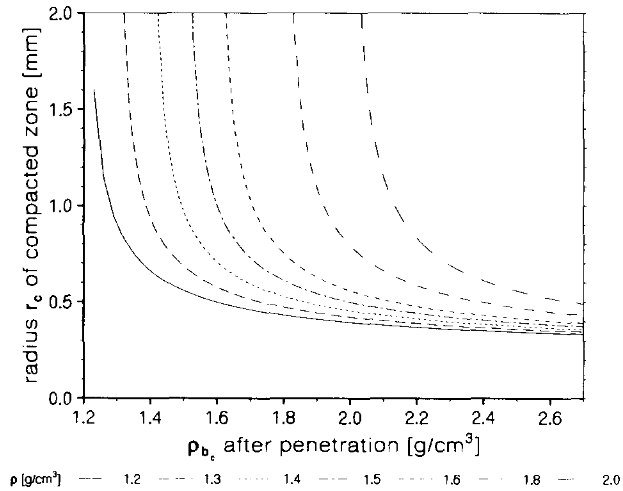

Fig. 4. Influence of initial bulk density ρ_b on the affected radius r_c for a body radius $r=0.25$ mm.

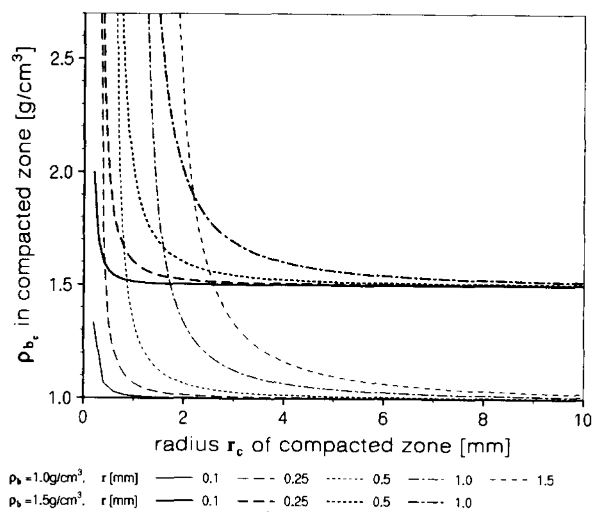

Fig. 5. Influence of affected radius r_c on ρ_{b_c} for different body radii r and $\rho_b=1.0$ and 1.5 g/cm³.

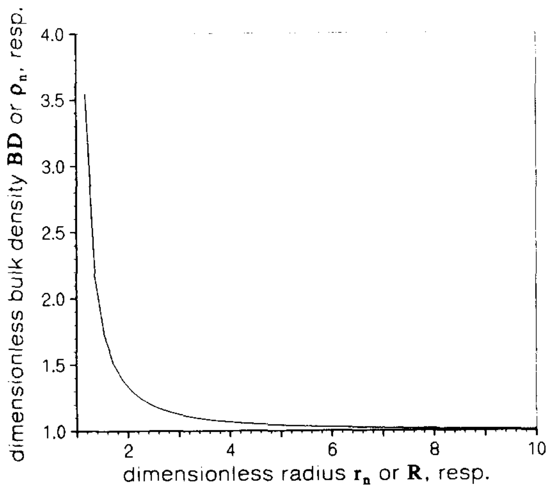

Fig. 6. Relationship between dimensionless radius r_n (or R) and dimensionless bulk density BD (or ρ_n).

compressed within the dimensionless radius R of about 2.1 that is more than two times the body radius. It must be emphasised, however, that BD or ρ_n values > 1.5 are only valid for very loose mineral soils, and values of > 3.0 for peaty soils or soils from similar substrates. In general, a large radius r_c of the compacted zone corresponds to a small increase in mean bulk density ρ_{b_c} due to compaction by a penetrating body.

3. Consequences

The rearrangement of soil particles during penetration of a body depends on the soil moisture status. Under moist to wet conditions, the compressed zone (= zone I–III of Farrell and Greacen (1966)) must therefore be thin but dense, because water films are relatively thick and the forces generated by menisci are small. Moreover, homogenization of material in zone I occurs as demonstrated earlier by Figs. 1 and 2 in Hartge and Becher (1971) and as indicated by the very thin layer along the penetration path (Fig. 2). With decreasing water content, water films also decrease, and the forces of the menisci therefore increase. Thus the mobility of soil particles is reduced, resulting in a thicker but less compressed zone. This yields the very thin (smeared) layer in Fig. 2 and no visible rearrangement, in contrast to Hartge and Becher (1971). To avoid errors during measurements of penetration resistance on small soil samples, e.g. aggregates (Becher, 1992), measurements must be carried out further apart when increasing soil moisture suction. If this is not done, soil compaction and even tensile failure cracks would produce erroneous values of penetration resistance (Bengough, 1990; Bengough and Mullins, 1990). Using a 0.5 mm probe on aggregates with a bulk density ρ_b of 1.7 g/cm^3 and producing an expected mean compressed bulk density $\rho_{b_c} = 1.9$ g/cm^3, the threshold distance is $2 \cdot r_c = 2 \cdot 0.77 = 1.54$ mm. This distance is appropriate for evaluation of the strength distribution within soil aggregates of even 20 mm diameter by measurements of resistance to penetration. At decreased water content, however, a mean compressed bulk density $\rho_{b_c} = 1.8$ g/cm^3 due to less rearrangement of particles, causes a r_c value of 1.06 mm. This yields a threshold distance of 2.12 mm. As pointed out above, there must be a tailing off of the bulk density within zone III until the initial bulk density is reached at r_c. The minimum distance between adjacent penetrations can therefore be set to 2.5 mm for this probe without affecting the result of penetration measurements. This distance is about 2.5–3 times greater than r_c and 10 times the probe radius, and was used for soil aggregates of 15–20 mm size (Becher, 1993). For larger aggregates (> 20 mm) the distance was set to 5.0 mm, which is on the safe side under all conditions.

As mentioned above, radial growth of roots or the thickening of the corpus of earthworms compresses the surrounding soil (Richards and Greacen, 1986). This results in a rearrangement of fine soil particles as well as in an increase in bulk density (Blevins et al., 1970). The increased bulk density must yield a decrease in the amount of large pores within the compressed soil layer. Thus, the root itself destroys the possible pathways for exploring the soil around the root channel. On the other hand, the compaction of soil by the radial growth of roots, e.g. within loose soil, makes it easier for the plant to anchor in this soil. This compaction by roots growing horizontally near the surface leads to the well known phenomenon that the upper parts of those roots appear more and more at the soil surface, the older they become (e.g. Hartge and Horn, 1991). Similarly, the compacted soil around an earthworm burrow provides a good grip allowing the earthworm to move relatively rapidly up or down a burrow. On the other hand, destruction of the large pores by compacting (and smearing) could result in a diminished infiltration of water entering the burrow from the top, which endangers the earthworm itself within its burrow. Some earthworm species like *Lumbricus terr.*, use mainly the same burrow during their lifetime, although they continue to grow (i.e. thickening of the corpus itself) (Joschko et al., 1991). These earthworm species therefore compact the surrounding soil during their movement as shown by Joschko et al. (1991), otherwise they could not pass through the burrow without eating earth. Thus, in both cases (channel and burrow) the compacted wall strongly reduces the exchange of soil solution between the macropore and the interior of the aggregate because the interconnecting pathways across the wall are narrowed, interrupted, or destroyed. This diminishes the possibility of sorption or desorption of soil pollutants, depending on the degree of water saturation, and concentrates macropore flow on these pores.

The increased bulk density within the wall was indirectly evaluated by radiation techniques (Greacen et al., 1968; Joschko et al., 1991), but further studies using very fine needle probes should give more information on the bulk density distribution along and within those walls and the adjacent soil.

4. Conclusion

The study has shown that a cylindrical body like a probe, a root, or an earthworm species penetrating into or increasing in diameter within the soil, compacts the adjacent soil. This compaction depends on the initial conditions of the soil as well as on the radius of the body and affects the conditions for the living subjects themselves. In addition, it prescribes the distance between adjacent penetrations when evaluating strength distributions within small soil samples like aggregates (Becher, 1993).

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Appendix

The dimensionless forms of Eqs. (1) and (2) are obtained as follows when setting $\rho_{b_c} = \rho_b + \Delta\rho_b$, $r_c = r + \Delta r$, $\rho_n = (BD=)\ (\rho_b + \Delta\rho_b)/\rho_b$ and $r_n = (R=)\ (r+\Delta r)/r$:

A.

$$\rho_{b_c} = \frac{\rho_b \cdot r_c^2}{r_c^2 - r^2} = (1) \tag{A1}$$

$$\rho_b + \Delta\rho_b = \rho_b \cdot \left(\frac{(r+\Delta r)^2}{(r+\Delta r)^2 - r^2}\right) \tag{A2}$$

$$\frac{\rho_b + \Delta\rho_b}{\rho_b} = \frac{\frac{1}{r^2}\cdot(r+\Delta r)^2}{\frac{1}{r^2}\cdot((r+\Delta r)^2 - r^2)} = \frac{\left(\frac{r+\Delta r}{r}\right)^2}{\left(\frac{r+\Delta r}{r}\right)^2 - 1} \tag{A3}$$

$$BD = \frac{r_n^2}{r_n^2 - 1} = (3) \tag{A4}$$

B.

$$r_c = \sqrt{\frac{\rho_{b_c} \cdot r^2}{\rho_{b_c} - \rho_b}} = (2) \tag{A5}$$

$$r + \Delta r = r \cdot \sqrt{\frac{\rho_b + \Delta\rho_b}{(\rho_b + \Delta\rho_b)\rho_b}} \tag{A6}$$

$$\frac{r+\Delta r}{r} = \sqrt{\frac{\frac{1}{\rho_b}\cdot(\rho_b + \Delta\rho_b)}{\frac{1}{\rho_b}\cdot((\rho + \Delta\rho_b) - \rho_b)}} = \sqrt{\frac{\frac{\rho_b + \Delta\rho_b}{\rho_b}}{\frac{\rho_b + \Delta\rho_b}{\rho_b} - 1}} \tag{A7}$$

$$R = \sqrt{\frac{\rho_n}{\rho_n - 1}} = (4) \tag{A8}$$