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Quantifying the Effect of Substrate Compaction on Root Development in Cover Systems

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Abstract

Vegetation is understandably an integral component of the cover systems used on most tailings and waste rock disposal facilities. The soil in these covers is usually placed and spread using earthmoving equipment such as trucks, scrapers, dozers and front-end loaders. Trafficking of this equipment can easily result in a high degree of compaction of the cover soil, which may compromise the ability of roots to develop laterals or penetrate to adequate depth. Poor root development may curtail the vegetation survival and growth, and thus reduce the effectiveness of the cover system.

Soil was collected from the stockpile of a candidate cover soil at a tailings storage site in Western Australia. The soil was compacted according to the relevant Australian Standard in 50 cm long, 10 cm diameter PVC growth columns. Three compaction configurations were used, namely high, low and stratified, in a replicated root penetration experiment. Pre-germinated seeds of Acacia celastrifolia were planted into each column and grown in a temperature regulated glasshouse facility. At 40 days and 60 days after detection of first growth, soil was extruded from the cylinders and the root architecture defined using a WinRHIZO scanner and software.

The paper illustrates that the (limited) available literature on the effect of compaction density on root development is simplistic and can be unnecessarily restrictive if adhered to blindly. The importance of working within a framework that contextualizes the degree of compaction, such as is used in engineering earthworks, is shown to be a key factor in interpreting the results of this type of study.

1 Introduction

Many mining operations will face the prospect at closure of having to place an engineered cover system over vast areas. Almost all tailings storage facilities (TSFs) and waste rock dumps will require some form of engineered cover, and many of these facilities cover areas of the order of hundreds of hectares. Engineered covers should consist primarily of either selected and stored stockpiled natural soil, or appropriate waste rock (regolith) material that has pedogenic potential. These materials may sometimes include small quantities of rock. This means that required earthwork volumes will typically be of the order of 500,000 m^3 or more. To transport, place and spread this volume of material, large earthmoving equipment will invariably be required.

In most soils used for construction of a cover system, it will be impossible to place and spread the soil without causing a relatively high degree of compaction. Even if the soil is placed in relatively thick layers (0.5 m thick), the upper 30 cm or so will still experience high compaction stresses merely as a consequence of the transferred load of the earthmoving equipment (Scott, 1975).

2 Compaction due to surface loading

2.1 What is compaction?

In very general terms, compaction is an increase in density of a soil due to the expulsion of air, as a result of the application of energy. Compaction cannot occur in a fully saturated soil, as the water would in this case absorb all the applied energy and no change in volume (increase in density) would occur. Engineered compaction is the key to improving the strength and stiffness (resistance to settlement) of many soils used in civil engineering earthworks. The goal of engineered compaction is usually to achieve the maximum possible density for a given input of energy (determined by type of compaction equipment used). A key relationship used in this process is illustrated in Figure 1.

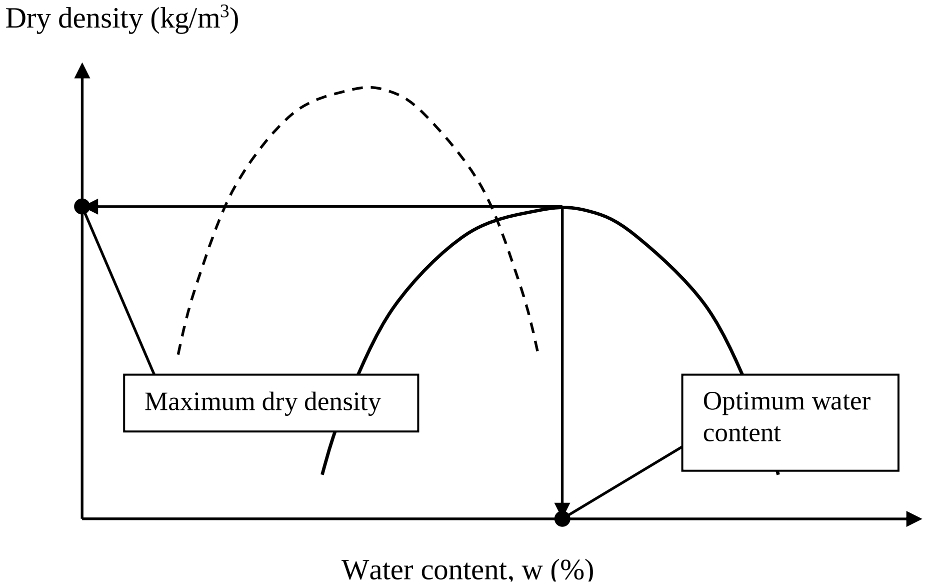

Figure 1 Illustration of the relationship between water content and dry density for soil subjected to a compaction test

The axes in this figure are the gravimetric water content, w (M_w / M_s), where M_w is the mass of water and M_s is the mass of soil, and the dry density, ρ_d, not to be confused with the bulk unit weight, ρ_b, ($\rho_d = \rho_b / (1 + w)$). The dry density is the density of a given volume of soil with all the pore water removed. The solid line parabola on this figure represents a typical relationship between w and ρ_d for a soil, with this relationship being obtained using a standard testing procedure (e.g. AS1289). As shown, increases in water content result in a greater achievable dry density up to a point, beyond which further increases in water content result in decreasing dry densities. The value of water content at which the maximum dry density is achieved is known as the optimum water content. It is important to realize that (for a given compaction energy), if a soil is compacted at a water content that is either less than or more than the optimum water content (known as the ‘dry’ side and ‘wet’ side respectively), it is not possible to achieve the maximum dry density. During engineering compaction projects significant attention is therefore paid to preparing the soil at (or very close to) the optimum water content to ensure the desired densities are achieved.

The dashed parabola in Figure 1 represents a w- ρ_d relationship for the same soil as before, but resulting from the application of a higher energy input than before (e.g. by using significantly heavier earthmoving equipment). In this case, a higher maximum dry density is achieved, but at a lower optimum water content. The two curves illustrated in Figure 1 represent target conditions for a particular soil, for two different levels of energy input. In civil engineering parlance these two curves could be thought of as representing the Standard, or Proctor curve (the solid line parabola) and the Modified AASHTO (American Association of State Highway and Transportation Officials) compaction curve (dashed line parabola), where the difference in input energy is of the order of a factor of four. The Standard compaction curve is typically used to provide target values of water content and dry density for applications such as compacted clay liners and covers. The Standard curve was used to provide target densities for the root penetration study reported later in this paper.

There is a great deal of literature dealing with engineered compaction and how best to achieve optimum results for various soil types. In contrast, when considering the construction of an engineered cover system, such as a store-and-release cover, the opposite goal may be paramount, i.e. the prevention of compaction by earthmoving equipment to a density that compromises the cover performance, for example by preventing root penetration and thus vegetation establishment. There are some heuristics that indicate that root penetration is not possible in a soil having a bulk density greater than a particular value. However, it is our assertion that guidelines such as these need to be formulated in terms of a more generic framework and we suggest expressing the root penetration resistance density (RPRD), for particular plant growth forms, as a percentage of the Standard compaction maximum dry density. For example, we foresee conclusions such as, 'for soil type S and plant species P, resistance to root penetration occurs at 93% of the Standard compaction maximum dry density'. There are clearly too many combinations of soil and plant types that might be used in cover systems to make it feasible to test all the possible combinations, but establishing cutoff values for a few combinations is a necessary first step.

Before describing the experimental programme that considered a particular soil/plant combination, it is necessary to consider why compaction is important, and how surface loads (earthmoving equipment) can be related to changes in density with depth below surface.

2.2 Why is it important when considering cover systems?

There is extensive reporting in the literature of compaction (often referred to as densification) having a negative impact on plant development, e.g. Siegel-Issam et al. (2005) describe how compaction caused by intensive forest management practices reduced tree growth rates substantially. The effects of compaction on soil properties can be physical, chemical or biological. The most obvious impact is an increase in soil strength and a consequent reduction in the amount of friable substrate available to plant roots. The increased resistance to root penetration limits root exploration of the regolith, and can significantly alter root architecture (Harrison et al., 1994; Henderson, 1989; Rokich et al., 2001). Reduced root penetration limits the ability of plants to access water stored at depth in the profile, a particularly valuable resource in Western Australian systems, leading to reduced seedling establishment in rehabilitation areas (Rokich et al., 2001). Furthermore, compaction can decrease soil fertility by reducing the store and supply of nutrients and water (Hamza and Anderson, 2005), while reduced oxygen diffusion through the soil profile can result in de-nitrification (Renault and Stengel, 1994) and decreased micro-organism activity (Hamza and Anderson, 2005).

It has been suggested that the main effect of compaction beyond a critical density is the reduction in large pores (defined as > 30 μm), resulting in decreased values of the soil hydraulic conductivity and surface infiltration rates, reduced soil arthropod and earthworm activity, and altered water retention characteristics (Hakansson et al., 1988). It is also accepted that a soil profile will take a long time to recover naturally from compaction beyond a critical density, if it occurs at all. For example Blake et al. (1976) reported the persistence of increased density in the absence of ploughing. Although it has been suggested (Soane and van Ouwerkerk, 1980) that problems associated with a high degree of compaction are particularly severe where highly mechanized agriculture is practiced in high rainfall areas (presumably because the soil is closer to the optimum water content shown in Figure 1 more often than in dry climates), the problem is one that can be expected to occur in any cover system construction, irrespective of the prevailing climate. This is because the type of equipment likely to be used in construction of these covers will often be significantly heavier than that used in agriculture, from where the vast majority of the literature on over-compaction originates, and thus lower optimum water contents might be relevant.

Although the literature emanating from the agricultural sciences may not always be directly applicable to mining cover systems (as mentioned above), it is a rich source of information and worth considering in some detail.

2.3 Relationship between equipment type and changes in density below ground surface

It is clearly an increment in applied stress that will cause a change in volume (densification) of soil below an applied surface load. It is intuitive to expect the magnitude of the stress increase to decrease with depth below the applied surface load, as can be illustrated by reference to an idealized situation indicated in Figure 2 as the solid line. This shows the increment in vertical stress with depth, below the centerline of a circular surface load, expressed as a fraction of the applied surface load. This solution is described in many standard soil mechanic texts (Scott, 1975), and although it represents an idealized condition of a homogeneous, isotropic, elastic medium, it provides a useful point of reference. At the ground surface, directly below the applied load, q (in kPa), the increase in vertical stress is equal to q. Below the surface it decreases rapidly with depth. For a typical surface contact area of about 900 cm^2 (radius of loaded circle equal to 17 cm), which is based on a tire width of 30 cm, the increase in vertical stress is 50% of the applied surface stress at a depth of about 22 cm below surface, i.e. a relatively thin layer of soil is subject to large stress increases.

However, before going any further, it is important to emphasize the highly idealized condition illustrated in Figure 2. Firstly, it represents conditions below a circular loaded surface area. Truck and other equipment typically have rectangular contact areas. Similar solutions to that illustrated in Figure 2 exist for these conditions, and an example of this is shown for a low pressure dozer track (with dimensions of 3.2 x 0.57 m). It can be seen that the depth at which significant loads are transferred to the soil increases, with the 50% point now occurring at about 60 cm depth. In the case of the low pressure dozer considered here, the contact stress was of the order of 82 kPa, so a significant increase in stress is transferred through the soil profile, e.g. even at a depth of 1 m, the vertical stress would increase by about 24 kPa. Considering the information provided later in this paper (dealing with the effect of load magnitude in addition to ground contact stress), it can be seen that the use of heavy machinery, even when equipped with larger treads, can still be problematical.

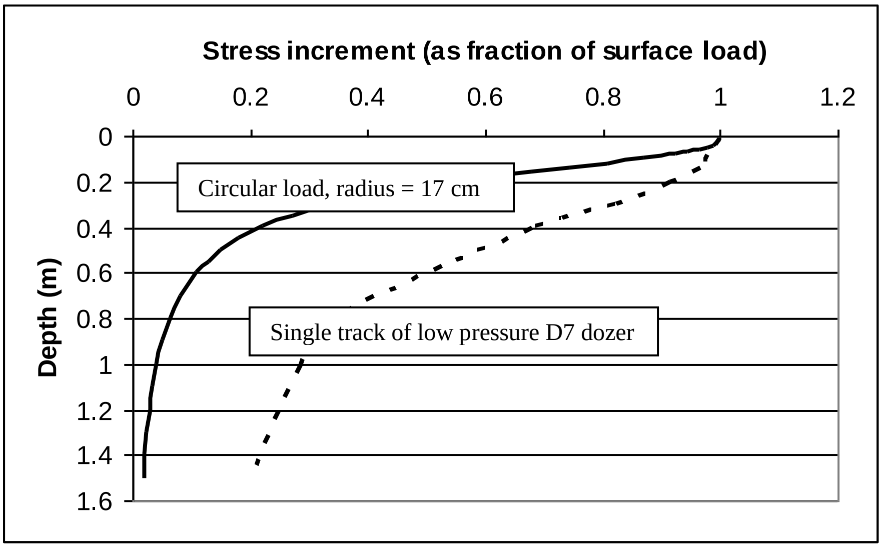

Figure 2 **Theoretical increase in vertical stress with depth below centerline of loaded area, expressed as a fraction of applied surface load**

The general conclusions described above are consistent with many field studies reported in the literature. As an example, Dumbeck (1984, as quoted in Hakannson et al., 1988) found increases in density to depth of 1 m with only 100 kPa ground pressure, but where the total load (in kN) was high. Corcoran and Gove (1985) also describe how the effect of tracked vehicles may be worse than thought, probably due to the large surface contact area discussed above, an effect that is exacerbated by uneven pressure distribution between two parallel tracks, the longer duration of loading that results under a tracked load, vibrations that are transmitted through the tracks, as well as the additional loads applied during turning and slewing. The suggested limits that have been set in countries such as Germany (40 kN) and Sweden (60 kN) on individual wheel loads (Hakansson, 1988) to avoid compaction deeper than 40 cm, may be completely irrelevant when conventional mining earthmoving equipment is used during construction of a cover system, even if the equipment is supposedly low contact pressure equipment.

In the current study we have set out to test the relationship between standard engineering compaction curves and the capacity for plants roots to penetrate compacted soil at two contrasting densities on the curve (Figure 1). This was achieved by growing seedlings of a fast growing, short-lived tree species in columns of an appropriate soil material under different levels of compaction and assessing the rooting dynamics under the different treatments.

3 Methods and materials

3.1 Soil characteristics

The soil used in this study represented material designated for use as a growing medium on covered tailings storage facilities. It was air-dried for three weeks in a drying room at approximately 35°C. After drying, it was sieved to less than 6 mm in size, mainly to remove gravel and wood debris. Index tests on the soil produced the values summarized in Table 1.

Table 1 Index test properties of soil used in column tests

Soil Property	Value
Specific gravity	2.61
Liquid limit	53%
Plasticity index	27%
Maximum standard dry density	1840 kg/m^3
Optimum water content	12.4%

The maximum dry density and corresponding optimum water content were obtained using the test discussed in Section 2.1.

3.2 Preparation of soil columns

The soil was packed into 10 cm diameter, 50 cm long PVC columns. Packing was achieved using a Standard compaction hammer. The bottom end of each column was sealed with a PVC cap which had been drilled with six holes of 0.5 cm diameter to provide base drainage. Three different density configurations were used, representing a high degree of compaction (H), low degree of compaction (L) and a composite profile (C). All columns were packed in three layers of equal thickness. Details were:

- H columns were compacted to a uniform dry density of 1650 kg/m^3 (99% of standard maximum value), at a water content of 13.9%.
- L columns were compacted to a uniform dry density of 1548 kg/m^3 (93% of standard maximum value), at a water content of 8.6%.
- C columns were compacted in three layers, with the upper layer being at the same density and water content as the L columns, as the two lower layers being at the same density and water content as the H columns. This was done to evaluate the effect of a density change on the development of rooting depth.

Each configuration (H, L and C) had eight replications, with four of each being dismantled 40 days after first detection of growth, and the other four being dismantled 60 days after detection of first growth.

Acacia celastrifolia, a local native legume, was chosen for use in the study because of its rapid growth habit and large root system. Seeds were sterilized in dilute hypochlorite solution and pre-germinated on 1.5% water agar plates in a controlled temperature room. An adequate amount (1.0 g) of a proprietary thrive fertilizer providing a full range of macro and micro nutrients was added to each layer prior to compacting it into the designated column to encourage plant growth. An 8 cm layer of gravel was placed at the bottom of each column to assist in column drainage. Soil was then compacted into the columns according to one of the three designations listed above. A thin (3 cm) thick layer of potting mix was spread over the surface of the compacted soil column to provide a bedding layer.

As soon as the seeds had germinated, they were planted into the prepared soil columns by drilling three equi-spaced holes to a depth of 1.5 cm into the bedding layer. The columns were placed in an air-conditioned glasshouse, with the column arrangement following a completely randomized block design to ensure factors such as sunlight, wind drafts and position had no influence on the test results.

The start of the growth period was subjectively determined by visual inspection, with day zero being taken as when shoots could be seen to emerge from the growth medium. The columns were watered approximately two to three times per week, depending on the degree of drying that occurred between measurements. The watering schedule for the study was chosen to maintain the columns at 50% of the total porosity.

3.3 Harvesting of plants, and measurement of root and shoot responses

Harvesting occurred at 40 days and 60 days after the first evidence of growth was detected. The above-surface material (referred to as 'shoots') was cut off and bagged for analysis, the base of the columns cut off and the soil cylinders extruded and bagged. Each of the cylinders was divided into six intervals, with measurements of root depth and length being made from the bottom of the germination layer. The roots were hand-washed until free of all soil and then stored in brown paper bags overnight, before carrying out further measurements.

The roots and shoots were analyzed using a WinRHIZO pattern recognition system, with a resolution of 150 dpi. After scanning, the roots were dried for 24 hours in a 70°C oven, to determine their moisture contents. The data are summarized in Table 2, which shows root depth, length and biomass, leaf surface area, shoot biomass, and root-to-shoot ratio. The percentage of the total root mass present in the six depth intervals is shown in Figure 3.

Table 2 Results from harvesting of plants at 40 days and 60 days after detection of first growth. Values are means with standard error in brackets

	Results at 40 days			Results at 60 days		
Configuration	**H**	**L**	**C**	**H**	**L**	**C**
Average root depth (cm)	9 (4)	178 (4)	11 (1)	13 (0)	39 (0)	15 (1)
Total root length (cm)	283 (135)	312 (94)	417 (79)	1376 (48)	2679 (263)	2689 (233)
Leaf surface area (cm^2)	46 (24)	25 (6)	34 (7)	154 (19)	366 (24)	341 (21)
Dry root biomass (mg)	59 (15)	67 (18)	48 (3)	358 (91)	753 (132)	827 (183)
Shoot biomass (fresh), (mg)	112 (44)	117 (33)	121 (11)	1190 (255)	3174 (453)	3518 (237)
Root-to-shoot-ratio	0.53	0.57	0.4	0.3	0.24	0.24

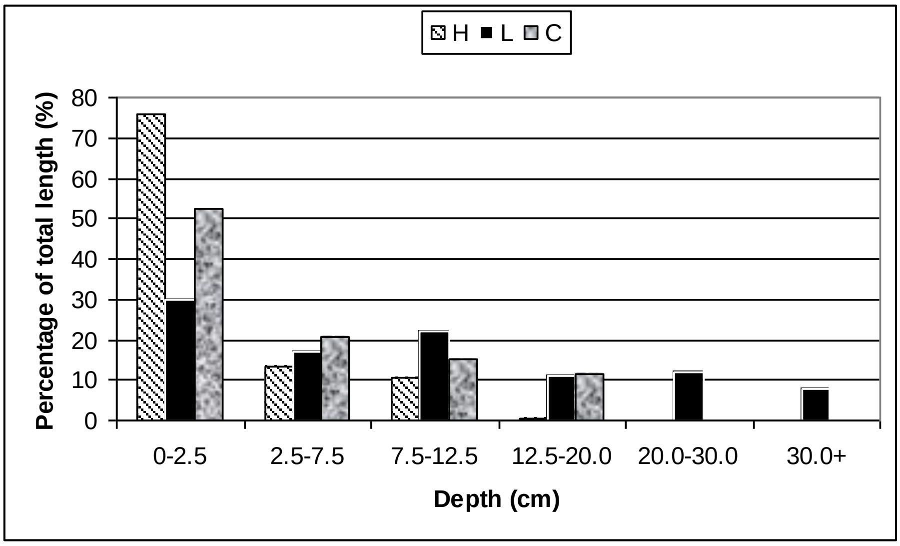

Figure 3 Percentage of total root length occurring within different depth intervals for high density (H), low density (L) and composite (C) compaction profiles. Results were obtained after 60 days of growth

There are clearly major differences between the three configurations, and it is worth comparing the differences between the high (H) and low (L) compaction density profiles to start with. Considering both Figure 3 and Table 2, it can be seen that the low density profile produces a much greater total root length than the H profile (about twice as much), with the difference being more pronounced after 60 days than after 40 days of growth. The average root depth is three times greater for the L profile, and as can be seen in Figure 3, the roots proliferated throughout the profile, unlike the H profile, where they did not penetrate below about 20 cm depth, and barely reached beyond 12.5 cm. The leaf surface area, root biomass and shoot biomass are also approximately twice as great in the L profile results at 60 days, with the root-to-shoot ratio accordingly being relatively similar. There is a very high concentration of root development within the upper 2.5 cm of the H profile, being almost 80% of the total root length. Therefore, although the H profile did sustain vegetation establishment, and the vegetation appeared healthy at the time of harvest, the very shallow rooting system would render any mature vegetation susceptible to drought, uprooting by winds and to exposure by erosion processes in the short term. Access to subsoil water and nutrient stores by shallow rooted vegetation will also be limited.

4 Results in comparison with previously reported data

The ability of the vegetation to establish as well as it did in the H profile is somewhat contradictory to accepted wisdom (generally originating from agricultural sources), where a bulk density of 1700 kg/m^3 is often considered an upper limit for vegetation establishment, whereas the H profile had a bulk density of 2068 kg/m^3. In fact, even the L profile had a bulk density of 1780 kg/m^3, so it comfortably exceeds the 1700 kg/m^3 limit, but exhibited excellent root development, with relatively uniform spread of roots with depth. The composite (stratified) profile (C), with the low density layer overlying the high density layers produced, as might be expected, a response that is generally somewhere between the other two profiles. There was a greater concentration of roots in the upper 2.5 cm than in the L profile, but also a greater distribution with depth than in the H profile (see Figure 3). In some ways, it slightly outperformed the L profile, producing larger root and shoot biomass, although the differences are relatively small. The positive conclusion that might be drawn from this result is that a heavily compacted profile might reasonably be treated by ripping and disturbance to a relatively shallow depth (say 15 cm), which is a commonly used technique. Remembering that much of the commonly used earthmoving equipment produces a density profile that decreases rapidly with depth, it might be that the issue is relatively easily addressed. Of course, it remains to conduct experiments with a range of combinations of soil and vegetation type, as the results presented in this paper may represent an isolated case: for example the vegetation chosen may be much more resilient than the norm. Extrapolation to other circumstances is thus inadvisable, but the results are certainly promising in that they indicate current rules of thumb may be unnecessarily restrictive.

5 Conclusions

The potential effect of inadvertently compacting soil in a cover system to such a high density that vegetation cannot become established should not be overlooked. The results reviewed in this paper indicate that even earthmoving equipment that is regarded as inducing low ground pressures can actually induce significant increases in density. In addition, when the loaded area is large, such as with dozer tracks, the increase in density can occur to depths of 1 m or more. However, the commonly accepted limits of allowable bulk density (such as an upper limit of 1700 kg/m^3 bulk density) may be unnecessarily restrictive, and indeed misleading.

In this paper experiments were conducted on columns of a soil compacted to produce different density profiles. A single type of plant, *Acacia celastrifolia*, was grown in these columns and the root morphology mapped after 40 days and 60 days of growth. The results indicate that growth was achieved in densities in excess of even 2000 kg/m^3 bulk density, although better results were achieved at a lower density.

An important factor discussed in the paper is the use of a standard method of comparing density profiles. The procedure adopted in this paper was the use of the standard compaction curve as the reference framework, which is a logical approach as all earthmoving quality control uses this same procedure in controlling earthworks placement and compaction. It is suggested that this framework be adopted for future work to provide a rational means of comparing data from different studies.

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