Chapter 1

Introduction

Deep profile mixing of certain soil types may result in improved crop yields. In the Lower Macquarie Valley of New South Wales, deep mouldboard ploughing to 0.5 m of a red–brown earth produced spectacular yield responses (300 %) in irrigated cotton (Harrison *et al.* 1984) in the first season. The reasons for this response are thought to be the effects of soil decompaction and mixing of subsoil material with the topsoil which promotes cracking and reduces crusting (Harrison *et al.* 1984).

Despite the success achieved on this particular soil, little is known about the soil conditions that favour deep profile mixing as a means of increasing crop production. In particular, the effect of the amount of subsoil on soil resistance to compaction degradation should be investigated before the method can be generally advocated.

The physical factors which determine the capacity of a soil to support root growth relate to the adequacy of soil pore space for unrestricted root penetration and for the store and rapid movement of water and oxygen. Compaction reduces the proportion of transmission pores and is detrimental to the extent that it increases mechanical impedance to root extension and reduces the flow of water and oxygen toward roots. Deleterious compaction occurs where heavy agricultural machinery is used.

In order to investigate some of the factors relevant to profile mixing, a field trial was established by the New South Wales Department of Agriculture at the Trangie Research Centre in 1984. Tillage treatments applied to replicated plots of 0.3 ha included deep mouldboard tillage and conventional disc tillage with and without application of gypsum (5 t ha^{-1}) . A complementary laboratory project was initiated a year later with the broad aim of establishing detailed relationships between those physical properties thought to be important in determining the success or failure of deep profile mixing. The combined information from these two research projects would be used to formulate recommendations for management of tillage on similar soils in the Lower Macquarie Valley. Distribution of soil types in the Valley is under investigation in a third research project, the results of which will facilitate dissemination of information for tillage management.

A laboratory study was needed so as to accurately describe the relationships between soil compactness, soil horizon mixing and the physical factors that determine soil fertility. Accurate quantitative relationships for the purpose of modelling soil physical fertility are difficult to establish in the field because of the lack of control over environmental conditions. However, a wide range of conditions of soil water content, compaction and soil horizon mixing can be made in a controlled laboratory environment. The quantitative results of the laboratory study must then be checked against the behaviour of soil in the field.

The results of the laboratory investigation of the mechanical and physical properties of the Trangie red–brown earth soil are reported in this thesis. Properties of both top and subsoil, as well as various mixtures of these horizons were investigated. The aims of this study were to:

- establish criteria for the optimal amount of soil horizon mixing to be performed by deep mouldboard tillage,
- develop criteria for the management of compacted irrigated red– brown earth soils based on those physical factors which are thought to be critical for unrestricted root growth,
- develop a model for soil management for red–brown earths that incorporates the above criteria.

To fulfil these aims I have characterised the effects of:

- soil horizon mixing on particle size distribution and plasticity index, both routinely measured soil properties related to physical behaviour (Chapter 2),
- compressive stress, soil water content and soil horizon mixing on soil compaction (Chapter 3),
- soil compactness, water content, horizon mixing and gypsum application on soil penetration resistance (Chapter 4),
- soil compactness and soil horizon mixing on water retention and saturated hydraulic conductivity (Chapter 5),
- soil compactness, water content and horizon mixing on soil oxygen supply (Chapter 6),
- soil compaction and soil horizon mixing on soil physical fertility in Chapter 7 using the penetration, water and oxygen constraints to root growth established in Chapters 4–6, and the consistency and compaction behaviour determined in Chapters 2 and 3.

The results of this investigation were obtained in the laboratory and, as such, need to be applied rather cautiously to field conditions. Wherever possible, field verification of laboratory derived information was carried out and the results were generally found to correspond. Under these circumstances, reasonable confidence can be attached to the applicability of the recommendations for management of field tillage.

Chapter 2

Soil Properties

Abstract

The morphology, particle size distribution and clay mineralogy of the Trangie red–brown earth soil identify it with red–brown earth soils which are prone to structural degradation when they are used for irrigated cultivation. Drop cone penetrometer measurements of the plastic and liquid limits as a function of soil horizon mixing show that soil horizon mixing increases the liquid limit and thereby increases the plasticity index. The plasticity index is directly related to the tillage energy required to produce a seedbed and consequently it may not be desirable for it to be increased. The level of soil horizon mixing attributable to deep mouldboard ploughing does not substantially increase the plasticity index of the soil and hence the energy required in tillage operations. The plasticity index is closely correlated with the geometric mean particle diameter of the soil horizon mixtures. In applying tillage which mixes soil horizons a desirable level of mixing, on the basis of minimising the energy required for seedbed preparation, could be determined to be that which did not substantially increase the plasticity index.

2.1 Introduction

Crop yields on red–brown earth soils in the Lower Macquarie Valley have declined steadily since irrigated cultivation began in 1967 (McKenzie *et al.* 1984). This yield decline can be attributed to reduced physical fertility resulting from the deterioration of soil structure. The susceptibility of red–brown earths to physical degradation is related to their morphological, chemical and textural properties.

Deep mouldboard ploughing modifies the particle size distribution of the topsoil. This may influence soil behaviour in relation to the growth of plants. Field studies on Block 4A at Trangie Research Centre have sought to establish a relationship between deep mouldboard tillage and crop response (McKenzie *et al.* 1984). To complement the field study, a laboratory investigation of the properties of top and subsoil as well as mixtures of these horizons was undertaken. The aims of this chapter are, to present morphological and chemical data for the red–brown earth from Trangie block 4A and to investigate the effect of soil horizon mixing on particle size distribution and the resulting soil consistency behaviour.

2.2 Literature Review

The susceptibility of red–brown earths to physical degradation is often related to their morphological, chemical and textural properties. This literature review presents information on these properties relevant to the management of these soils. Particular attention has been given to the relevance of soil consistency to management and methods of soil consistency assessment.

2.2.1 Distribution

The red–brown earth from Trangie block 4A is typical of the Trangie alluvium which dominates the older floodplain of the Macquarie River. Also, morphologically similar red–brown earths (Northcote 1981) are widely distributed in Australia (Figure 2.1). Improvements to the management of this soil may have economic benefits.

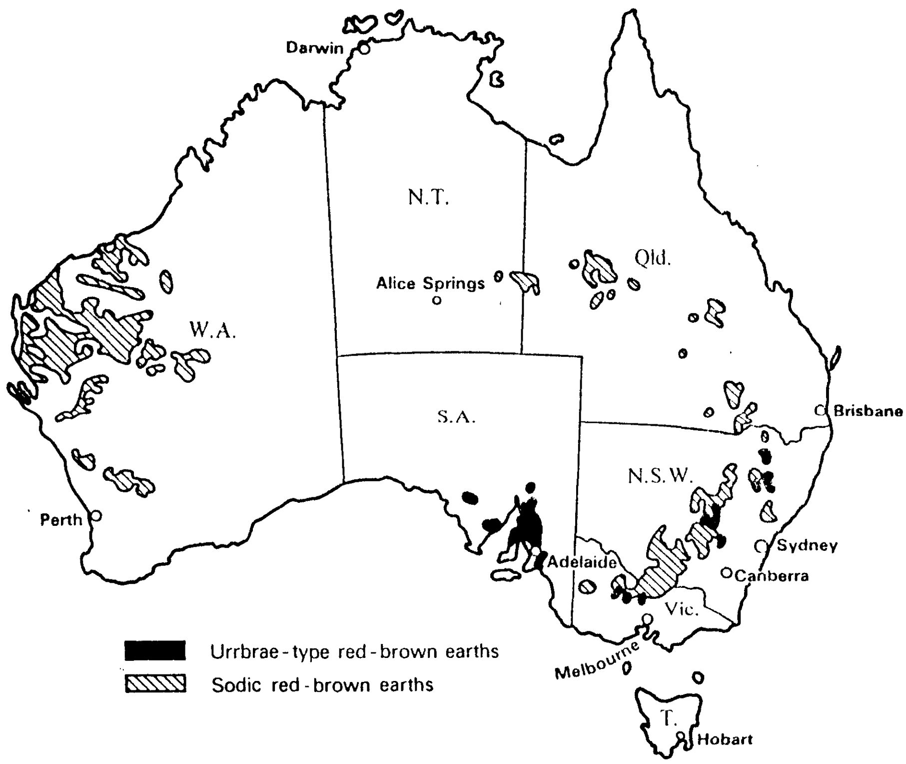

Figure 2.1: The distribution of Urrbrae–type and sodic–type red–brown earths (from Northcote 1981)

2.2.2 Morphology

Two distinct types of red–brown earths have been recognised (Northcote 1981). The Urrbrae–type described by Prescott (1931) was the original definitive example in the Australian Great Soil Group Classification. Subsequently, the more widely distributed sodic type red–brown earth has been described (Stace *et al.* 1968) in which the subsoil is sodic, i.e. it has an exchangeable sodium percentage greater than 6. The sodic type has come to epitomise red–brown earths. This is because it dominates in the dry (250 – 500 mm average annual rainfall) riverine plains of south–eastern Australia, where irrigation developments have required detailed soil studies (Northcote 1981). These soils are often prone to physical degradation when cultivated and irrigated.

The characteristic feature of red–brown earths is a clear texture and colour contrast between the A and B horizon (Prescott 1931). The texture contrast arises from the high fine sand and silt contents in the A horizon in contrast to the high clay content in the B horizon. The dull brown A horizon, darkened by organic matter, contrasts with the brighter coloured B horizon, made red by iron oxides. Morphologically, the sodic type differs from the Urrbrae–type by the presence of a bleached subsurface A_2 horizon, in addition to having a sodic subsoil. The bleached A_2 indicates a subsoil which remains fully friable only over a limited water content range (Northcote 1981). Northcote (1981) designated the Shepparton fine sandy loam as representative of the sodic type red–brown earth. A full profile description of this soil is provided by Stace *et al.* (1968).

2.2.3 Distribution

Because red–brown earths predominate in areas developed for irrigation in south–eastern Australia they have become one of the most economically important irrigated soils. Figure 2.2 shows the extent of irrigated red–brown earths in south–eastern Australia.

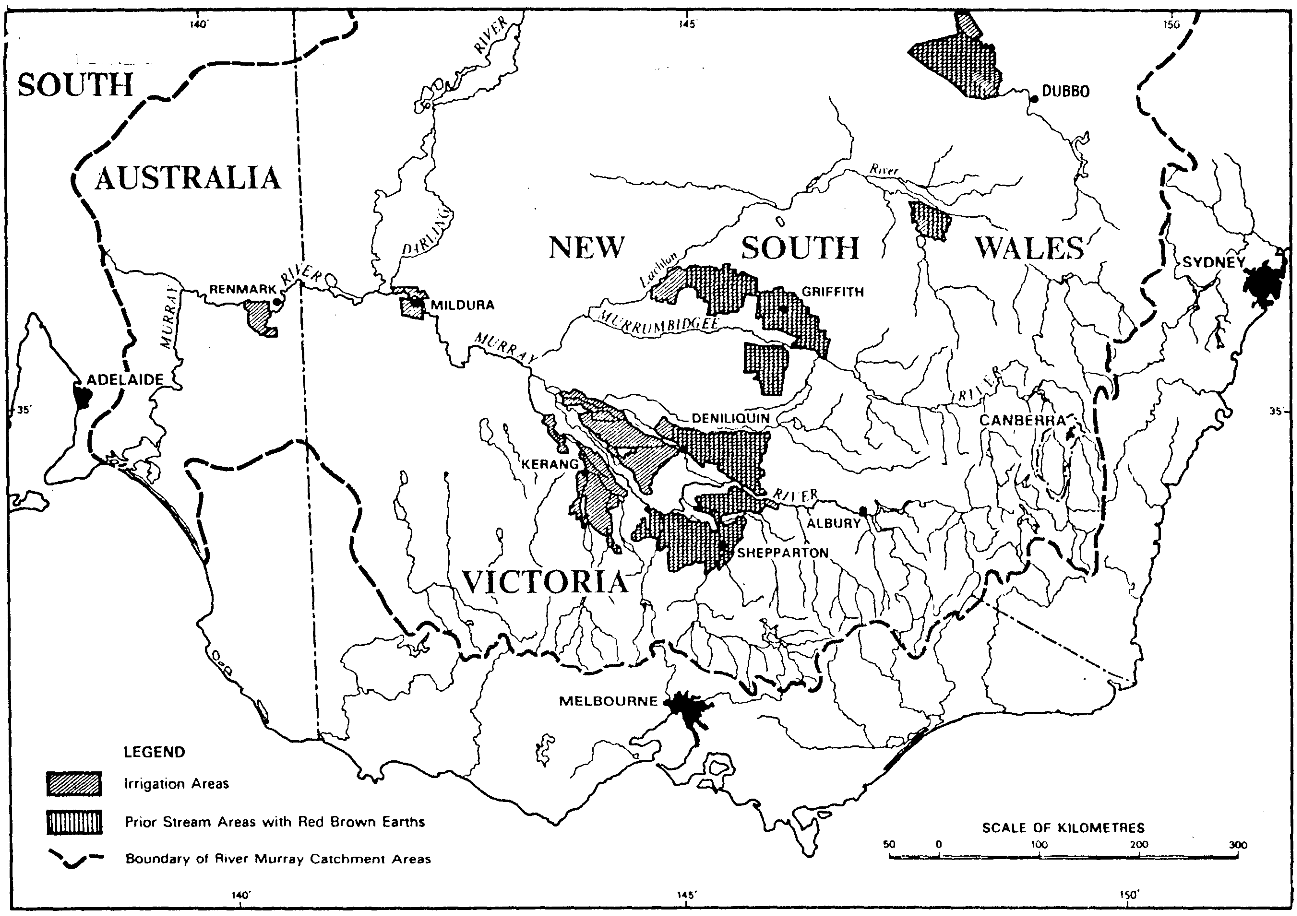

Figure 2.2: Irrigation areas in south-eastern Australia showing the extent of red–brown earths (Cockroft and Martin 1981).

2.2.4 Chemical Properties

The chemical properties of red–brown earths were reviewed by Williams (1981). The cation exchange capacity varies greatly, but is usually low to moderate because of the predominance of kaolinite and illite in the clay fraction. Calcium and magnesium are the dominant cations throughout the profiles with magnesium content increasing with depth. The presence of high ratios of magnesium to calcium and the high levels of exchangeable sodium in the B horizon of some soils promotes rapid swelling or dispersion of the clay leading to low permeability and waterlogging problems for water of low electrolyte concentration.

The organic matter content is an important factor affecting the overall fertility of red–brown earths. In the untilled state, organic matter levels are adequate to maintain suitable structure. However, organic matter is rapidly depleted under continuous cropping resulting in soil structural deterioration and physical infertility (Williams 1981).

2.2.5 Mechanical Properties

The A horizons of red–brown earths have high proportions of fine sand and silt. Clay domains are oriented around these particles to form a fine soil fabric (Dalrymple and Jim 1984). Particles are bonded into aggregates by organic matter and clay domain bridging. If shearing forces are applied when the soil is wet (such as during cultivation or raindrop impact) the interparticle bonding between clay particles may be broken, thus rendering them susceptible to extra dispersion (Emerson 1983). The destruction of organic matter bonding between clay domains and quartz particles by mechanical forces leads to the slaking of soil aggregates, so that the domain surfaces are exposed for dispersion. Dispersion of clay particles near the soil surface may lead to the formation of a thin surface crust which reduces infiltration and impedes seedling emergence.

The dominant clay minerals in red–brown earths are illite and kaolinite and these minerals disperse relatively easily (Emerson 1983). Thus, particle size distribution, clay mineralogy and low organic matter content of red–brown earth topsoils make them sensitive to structural breakdown when cultivated.

Red–brown earth subsoils have higher clay contents than the topsoils. The higher clay and lower organic matter content make subsoil clay more easily dispersed by mechanical disruption (Rengasamy *et al.* 1984b). Subsoils high in clay are generally deficient in macropores. Consequently swelling of subsoil clay minerals may cause a drainage problem in the profile (Rengasamy *et al.* 1984a).

2.2.6 Soil Consistency

Maintenance of favourable aggregate structure requires that tillage be carried out at the correct soil consistency state. The soil consistency states described by Archer (1975) are (1) hard, (2) friable, (3) plastic and (4) liquid, in increasing order of soil water content. The boundaries between these states occur at the water contents corresponding to the (1–2) shrinkage limit; (2–3) plastic limit; (3–4) liquid limit. Soil response to deformation changes from decompaction when the soil is dry or friable to compaction when the soil is relatively wet and plastic. Resistance to smearing and compaction are both high in the friable state, while implement draught is low (Archer 1975). The plastic limit represents the upper water content at which soil can be cultivated without causing structural damage. Tension failure can occur at water contents greater than the lower plastic limit without damage to structure. Fragmentation at low water contents can form dust.

Plasticity index is a fundamental soil physical property dependant on soil texture and is calculated as the difference between the liquid and plastic limits. It is a measure of dry soil strength and can be used to predict the amount of energy required to produce a seedbed. Campbell (1976a) found plasticity index, for a wide range of soil textures, to be the principal property affecting clod number and resistance to crushing. Greacen and Sands (1980) stated that plasticity index is a measure of the frictional forces between soil particles and could be used to predict the resistance of soil to compaction.

Initially the liquid and plastic limits were arbitrarily chosen by Atterberg in 1911 and empirically determined. The standard engineering technique was developed by

Casagrande (1932, cited by Archer 1975). However, the standard technique for plastic limit measurement is subjective and prone to operator error (Campbell 1976b).

Campbell (1975, 1976b) described an improved plastic and liquid limit measurement technique using a drop cone penetrometer. Campbell determined the plastic limit as the minimum of a penetration vs water content curve developed from dropping a cone of standard mass and dimensions from a standard height into packed soil over a range of water contents. The liquid limit was determined as the water content at which the cone penetrated a certain distance.

According to Campbell (1976b), the plastic limit is measured more reliably with a drop cone penetrometer than the Casagrande method. The minimum of a water content–cone penetration curve was numerically less than but closely correlated with the Casagrande plastic limit (PL) for a wide range of soils. This drop cone penetrometer plastic limit (DCPL) was more reproducible when carried out by different operators and required less time to measure than the Casagrande method.

The nature of the DCPL measurement suggests that it represents a change in soil behaviour. The presence of a minimum on the cone penetration– water content curve at this point indicates a change in soil physical state from friable to plastic (Towner 1973; Campbell 1976b). Campbell *et al.* (1980) found that the DCPL corresponded better with the optimal water content for soil compaction than the PL. The DCPL may thus be a better indicator of soil consistency in the field than the PL, and was investigated further in this study.

2.2.7 Soil Horizon Mixing

Mixing red–brown earth B horizon with the A horizon has been used to ameliorate soil physical problems. Mixing in slots enriched with gypsum has been used in Northern Victoria to ameliorate a water infiltration problem (Jayarwardane and Blackwell 1985). Deep mouldboard ploughing has been used in the Lower Macquarie Valley to mix subsoil with topsoil with beneficial effects on cotton yield (Harrison *et al.* 1984). The response in the Lower Macquarie Valley was attributed to bringing smectitic clays to the surface, which, when treated with gypsum, become self–mulching (Rengasamy *et al.* 1984a) and ameliorate the surface sealing problem.

The yield increase after deep mouldboard ploughing in the Lower Macquarie Valley does not persist for more than two or three seasons. At the property where this technique was first used deep mouldboard ploughing is repeated after every crop. Deep mouldboard ploughing changes soil texture, and hence consistency. Therefore we would expect there to be a durable effect of deep mouldboard tillage on soil physical fertility. The possible effects of deep mouldboard tillage are,

- a change in the clay content and mineralogy of the topsoil leading to self–mulching behaviour,
- change in particle size distribution and therefore consistency and strength behaviour,
- soil decompaction.

The first two effects would be expected to be more permanent than the third.

2.3 Materials and Methods

2.3.1 Sample Collection

Soil samples for the laboratory study were collected in May 1985 from the deep mouldboard tillage trial (Block 4A) at the Trangie Agricultural Research Centre. Fifty kilograms of soil was sampled from the horizons indicated with each of the following tillage treatments: control (disk ploughed to 180 mm) – A_1, A_2 and B_1 horizons; deep mouldboard ploughed to 500 mm – plough layer and B_1 horizons; control + gypsum (5 t ha^{-1}) – A_1, A_2 and B_1 horizons; deep mouldboard + gypsum (5 t ha^{-1}) – plough layer and B_1 horizons.

The lower boundary of the A_1 and A_2 horizons was wavy, hence the depth of the soil horizon samples varied for different plots.

Samples were taken from each of the three replicates on the tillage trial. Sampling was carried out in pits 1.5 m deep located 10 meters in from the tail drain end of each treatment irrigation bay.

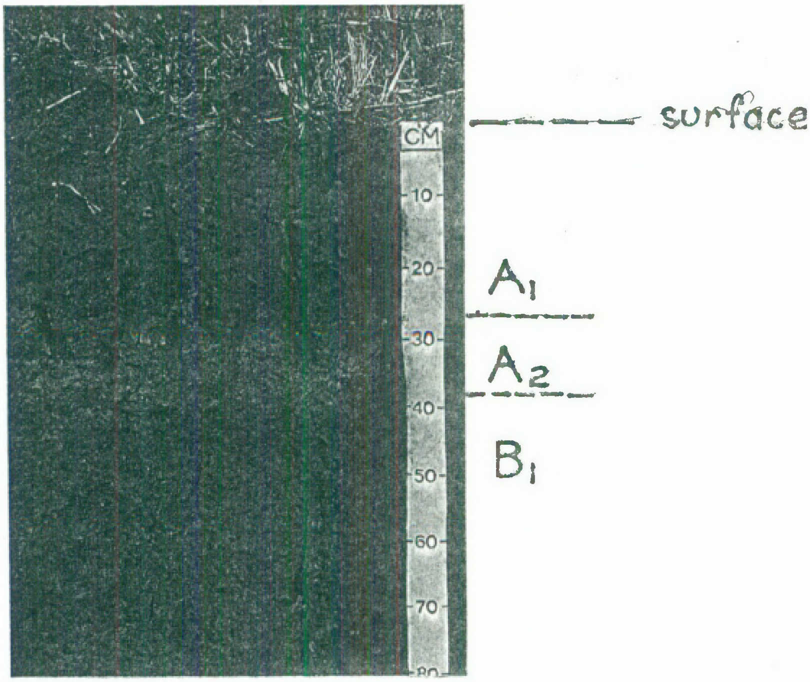

Figure 2.3: Trangie red–brown earth soil profile – Control treatment.

2.3.2 Sample Preparation

Soil samples were hand textured (Northcote 1979), air dried and lightly ground to pass through a 2 mm mesh sieve. Artificial mixtures of A and B horizon soil were used to measure the effect of subsoil mixing on soil physical behaviour. The A_1 and A_2 horizon samples from the conventionally tilled treatment replicates were combined, mixed and sub–sampled to produce the A horizon component of the soil horizon mix. The mass ratios of A and B horizon soil in the resulting mixes was:

- 100 A 0 B
- 91 A 9 B
- 75 A 25 B
- 50 A 50 B
- 25 A 75 B
- 0 A 100 B

The air dried quantities of A and B horizon soil were mixed in a cement mixer. The 75 A 25 B can be approximately related to the maximum level of subsoil mixing produced by deep mouldboard tillage on this soil, with the boundary between the A_2 and B horizon at 350–400 mm (Figure 2.3) and deep tillage to 400–500 mm.

A preliminary study of the particle size distribution of mouldboard treatment and non–mouldboard treatment samples did not reveal significant differences in texture. This is because the soil horizons were not uniformly mixed by the mouldboard treatment where the samples were taken from at the end of the plots. Consequently, the main study deals with the proporties of the artificial mixtures of A and B horizon soil rather than the mouldboard treatment.

2.3.3 Particle Size Distribution

Soil particle size distribution was measured by the pipette method (Day 1966). Ten gram soil samples were dispersed in 20 ml of dispersant (40.9 g l^{-1} sodium hexametaphosphate, 9.1 g l^{-1} sodium carbonate) by a 6 minute pulse from a Branson B-12 ultrasonic dispersing probe set on maximum power (100 watts) then made up to 1 l with distilled water. Clay ($\leq$0.002 mm), silt (0.002$\leq$0.02 mm), fine sand (0.02$\leq$0.2 mm) and coarse sand (0.2$\leq$2.0 mm) contents were measured. Geometric mean particle diameter (d_g) and geometric standard deviation (σ_g) were calculated according to Shirazi and Boersma (1984) from,

$$d_g = \exp a$$
$$\sigma_g = \exp b$$
$$where$$
$$a = \sum m_i \ln d_i$$
$$b = [\sum m_i(\ln d_i)^2 - a^2]^{\frac{1}{2}}$$

where m_i is the mass fraction of textural class i, and d_i is the arithmetic mean diameter of class i. The international particle size classification is used (Marshall and Holmes 1981, p4). The summation was taken over the four texture classes coarse sand, fine sand, silt and clay where d_{clay} = 0.001 mm, d_{silt} = 0.011 mm, $d_{finesand}$ = 0.116 mm and $d_{coarsesand}$ = 1.106 mm.

The mineralogy of the clay fraction was examined by X–ray diffraction, using copper radiation and magnesium–saturated samples solvated with ethylene glycol and heat treated at 80, 325 and 550^{o}C (Bullock and Loveland 1974).

2.3.4 Soil Consistency Limits

The drop cone method (Campbell 1976b) and the standard Casagrande technique (Sowers 1966) were used to measure consistency limits of the soil mixtures. For the drop cone determination, soil samples were mixed with water to give ten different water contents from air dry soil to a water content at which the soil was liquid. Most of the water contents were in the middle of the range to give good definition to the minimum of the cone penetration–water content curve. Soil was moulded, stored in a sealed container overnight and remoulded before testing.

Moist soil was packed into a rigid metal cup 55 mm in diameter and 45 mm deep using a teaspoon. The smearing compaction ensured the soil was packed evenly to a minimum volume. The penetration of the sample by a free falling 30° cone of mass 80 g was determined for a 5 second release time. The measurement was replicated five times. The water content of the soil immediately around and below the test penetrations was measured. The mean and standard deviation of five penetrations for a given sample were plotted against the mean water content. The water content at the minimum of the penetration depth verses water content curve was taken as the drop cone penetrometer plastic limit ($DCPL$) (Campbell 1976b) and the water content at which the free–falling cone penetrates 20 mm after 5 seconds was taken as the drop cone penetrometer liquid limit ($DCLL$) (Campbell 1975).

The Casagrande technique for plastic and liquid limit measurement was done according to Sowers (1966). The plasticity index was determined as the difference between the liquid limit and the plastic limit.

2.4 Results and Discussion

2.4.1 Morphology

The experimental soil is classified as a red–brown earth (Stace *et al.* 1968) and as Dr2.33 in the Northcote classification (Northcote 1979). There was no evidence of a hard surface crust. The weakly structured A horizon set hard as it dried out. The B_1 horizon has a strong angular blocky structure grading to a weak angular blocky structure in the B_2 (Table 2.1). The roots of crop plants noticably followed channels made by previous roots and the interaggregate spaces in the B horizon. This root distribution implies that the compactness of the soil matrix restricted root penetration.

The A horizon of the Trangie soil is weakly structured (Table 2.1) and appears to be massive and compact (Figure 2.3). Water content fluctuation, higher clay content and shrinking and swelling behaviour in the B_1 horizon are possible factors in the development of structure in this horizon. The B_2 horizon is weakly structured

Table 2.1: Profile description of Trangie red–brown earth soil from Block 4A, Agricultural Research Centre, Trangie, N.S.W. (D. Hall, unpublished data)

Horizon	Depth(mm)	Description
A_1	0 to 200	Greyish-brown (7.5YR 4/4 moist); fine sandy loam weak subangular blocky; earthy; pH 6.5; clear and wavy to:
A_2	200 to 400	Light greyish–brown (7.5YR 4/6 moist; 7.5YR5/4 dry); fine sandy loam; weak subangular blocky; earthy; pH 7.0; sharp and wavy to:
B_1	400 to 1000	Red (2.5YR 4/6 moist); medium clay; strong angular blocky; smooth ped; pH 8.0; few calcium carbonate concretions; diffuse and wavy to:
B_2	below 1000	Reddish–brown (5.0YR 4/4 moist); medium clay; weak angular blocky; smooth ped; pH 9.0; few carbonate and manganiferous concretions

(Table 2.1) probably because soil water content does not fluctuate. Thus, the bottom of the B_1 horizon (1000 mm) is also the approximate limit of root penetration and water uptake. Remnant root systems of trees which had covered the area before the land was cleared for irrigation, extended into the B_1 and B_2 horizons and acted as preferred pathways for wheat roots. Thus management that creates a structure in the A_1, A_2 and B_1 horizons which offers low resistance to root penetration should increase root growth and,thus, potentially increase crop yield.

The Trangie red-brown earth has the morphological characteristics (Table 2.1) of weakly structured red-brown earth. This soil is similar to a large group of soils which are easily damaged by cultivation. Topsoil amelioration techniques developed for the Trangie soil should therefore be relevant to the improvement of other weakly structured red-brown earth soils. However, red-brown earth soils which exhibit other specific problems, i.e., a B horizon throttle to water movement, may need a different approach to the soil studied here.

2.4.2 Chemical Properties

The Trangie red-brown earth soil has a low cation exchange capacity (CEC) (Table 2.2). CEC was calculated as the sum of exchangeable calcium, potassium, magnesium and sodium.

Table 2.2: Chemical properties of red-brown earth soil from Block 4A, Agricultural Research Centre, Trangie, N.S.W..

Horizon	Depth	EC	OM	Ca	Mg	K	Na	CEC	pH
	(mm)	(dS m^{-1})	(%)		—cmol(p^+) kg^{-1}—				
A_1	0 to 200	0.18	1.8	6.1	1.2	1.4	0.08	8.8	6.0
A_2	200 to 400	0.17		6.5	1.6	1.3	0.12	9.5	6.9
B_1	400 to 1000	0.17		10.1	4.6	1.4	0.25	16.4	7.4

The low proportion of Na^+ on the exchange complex and the low electrical conductivity for both A and B horizons indicate that the soil is not sodic (Table 2.2), although the Northcote classification, Dr 2.33, groups this soil with the sodic type red-brown earths described in Stace *et al.* (1968). The higher proportion of Mg in the B horizon is not sufficient to cause structural instability (Williams 1981). The low CEC and low organic matter content throughout combine to indicate a soil which is prone to slaking when disturbed by cultivation (Williams 1981).

2.4.3 Mechanical Properties

Particle Size Distribution

The particle size fractions for the A horizon (100 A 0 B) and the B horizon (0 A 100 B) (Table 2.3) are similar to published data for a soil with the same Northcote classification (Stace *et al.* 1968). The Trangie soil is relatively high in fine sand and silt, reflecting its alluvial origin. The large fine sand and silt fraction, the low organic matter content and the predomoninance of illite and kaolinite produce a soil which is prone to structural breakdown when it is cultivated (Rengasamy *et al.* 1984b).

Table 2.3: Particle size distribution for Trangie Red–brown earth A and B horizons and mixtures of the two. CS is sand 0.2–2.0 mm, FS is sand 0.02–0.2 mm, S is silt 0.002–0.02 mm, C is clay < 0.002 mm, d_g is the geometric mean particle diameter and σ_d is the geometric standard deviation.

Horizon mass fraction	CS	FS	S	C	d_g (mm)	σ_d	Clay mineralogy		
	—(% mass)—						illite	kaolinite	interst*
100 A 0 B	12	47	21	20	0.041	9.513	+++	++	
91 A 9 B	11	46	21	22	0.036	9.879			
75 A 25 B	10	45	19	25	0.024	11.340			
50 A 50 B	8	43	18	30	0.021	9.951			
25 A 75 B	6	41	16	36	0.019	12.453			
0 A 100 B	4	39	15	41	0.013	10.538	++	+++	+

*Interstratified material

The high fine sand content relative to silt and clay in the Trangie soil (Table 2.3) gives the soil the capacity to pack to low void volumes once soil aggregation is destroyed. Thus, massive compact topsoils are liable to develop as a result of irrigated cultivation.

The B horizon has a higher clay content than the A horizon and contains interstratified clay minerals (Table 2.3). These properties, and the confinement of

Table 2.4: Consistency limits for soil horizon mixtures of Trangie red–brown earth using the Casagrande method and the drop cone penetrometer method.

horizon mass fraction	Casagrande test PL ($kg\ kg^{-1}$)	LL ($kg\ kg^{-1}$)	PI ($kg\ kg^{-1}$)	Drop cone test DCPL ($kg\ kg^{-1}$)	DCLL ($kg\ kg^{-1}$)	DCPI ($kg\ kg^{-1}$)
100 A 0 B	0.14	0.19	0.05	0.10	0.21	0.11
91 A 9 B	0.13	0.19	0.06	0.10	0.21	0.11
75 A 25 B	0.13	0.22	0.09	0.10	0.22	0.12
50 A 50 B	0.14	0.24	0.10	0.11	0.26	0.15
25 A 75 B	0.13	0.31	0.18	0.12	0.33	0.24
0 A 100 B	0.16	0.37	0.21	0.14	0.36	0.22

subsoil clay, produce a subsoil which shrinks and swells slightly rather than slaking as does the A horizon when wetted. Thus, this contributes to the B_1 horizon having a better structure than the A horizon does not (Table 2.1).

Soil Consistency

The plastic limit measured with a drop cone penetrometer (DCPL) was consistently lower than the casagrande plastic limit (PL) (Table 2.4). This finding is supported by Campbell (1976b). The liquid limit (LL for the Casagrande and DCLL for the drop cone method) was similar for both methods. PI and DCPI in Table 2.4 are the plasticity index measured by the Casagrande method and the drop cone penetrometer method respectively.

2.4.4 Soil Horizon Mixing

Soil horizon mixing will introduce interstratified clay minerals into the topsoil. Harrison *et al.* (1984) considered that the beneficial effect of deep mouldboard tillage was in the shrink/swell ability achieved by bringing these clays to the surface. When brought to the surface, the very low concentration of interstratified clay in the Trangie B_1 horizon had no noticeable effect on cracking behaviour on the mouldboarded treatments on Trangie Block 4A. Hence, it is unlikely that the subsoil clay brought to the surface by deep mouldboard ploughing contributed shrink/swell ability to the soil surface in this case.

The liquid limit increases with soil horizon mixing while the plastic limit remains relatively constant until the mixture is made up of mostly B horizon soil (Table 2.4). This results in an increase in the plasticity index. The increase in plastic and liquid limits is related to the increase in clay and decrease in sand contents with soil horizon mixing.

Plasticity index (DCPI), as a measure of dry soil strength, indicates the energy required to cause tensile failure in dry soil during tillage (Archer 1975). Thus, it appears that only a slight increase in the energy required for soil breakup occurred up to a mixing ratio of 75 A and 25 B horizon soil (Figure 2.4). This is the maximum level of mixing attainable using deep mouldboard tillage with an A horizon depth of 300–400 mm and deep mouldboard ploughing to 400–500 mm. Consequently, subsoil mixing by deep mouldboard ploughing should not substantially increase dry soil strength.

The DCPI is related to the cohesive forces between soil particles, which increases as mean particle size decreases. As the geometric mean particle diameter (d_g) decreases to 0.02 mm (silt size range) DCPI increases rapidly to a maximum value (Figure 2.4). d_g decreases as the proportion of B horizon in the mix increases and, consequently, the two highest values of DCPI in Figure 2.4 correspond to the 25 A 75 B and the B horizon soil (0 A 100 B). Both these mixtures have clay contents greater than 35 %. Gupta and Larson (1982) reasoned that for clay contents greater than 33 % the packing behaviour of the soil matrix was determined by the clay rather than sand and silt fractions. Thus, the soil horizon mixtures represent points in continuum of change in soil consistency behaviour between that of the A and that of the B horizon, which is moderated by mean particle diameter. There was no relationship between DCPI and the geometric standard deviation (σ_g).

Soil plasticity is also affected by organic matter, clay mineralogy and exchangeable cation species (Archer 1975). Thus, measurement of DCPI rather than interpretation of particle size distribution data should be used to determine the maximum desirable level of soil horizon mixing on the basis of the energy required to break

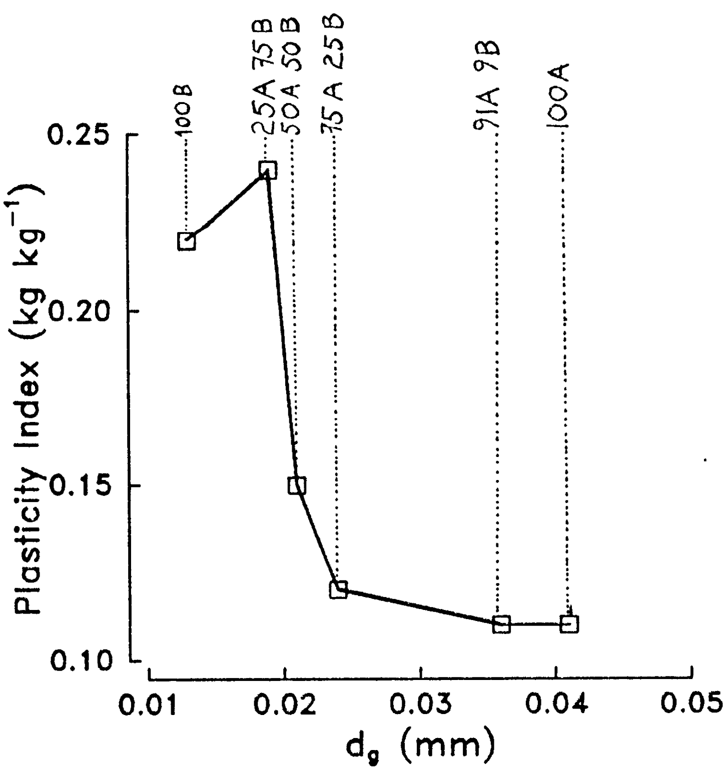

Figure 2.4: Plasticity index, measured with a drop cone penetrometer, versus geometric mean particle diameter (d_g) for Trangie red–brown earth soil horizon mixtures.

up the soil during tillage.

2.5 Conclusions

- The Trangie red–brown earth has morphological and textural properties which indicate susceptibility to structural degradation when conventional seedbed preparation techniques are used.

- These physically unstable red–brown earths occur widely on the riverine plains of south–eastern Australia in lower rainfall areas ($<$500 mm annual average rainfall) and are of considerable economic importance.

- The high fine sand and silt content and the low organic matter content combine to produce a topsoil with a weak structure that will compact to low void ratios.

- The plastic limit measured with a drop cone penetrometer is lower than that measured with the standard Casagrande technique. This suggests that plastic deformation behaviour begins at water contents less than the standard plastic limit. Thus, the drop cone penetrometer plastic limit is a safer upper water content limit for tillage and traffic to minimise compaction.

- Soil horizon mixing produces a finer particle size distribution by increasing the clay content of the topsoil.

- Soil horizon mixing increases the soil plasticity range, by increasing the liquid limit — but not as a linear proportion.

- A desirable level of subsoil mixing could be determined on the basis of plasticity index measured with a drop cone penetrometer, assuming that the subsoil contains clay minerals which will create a self mulching topsoil and that a desirable level of mixing is one which does not greatly increase soil plasticity.

Chapter 3

Soil Compaction

Abstract

The purpose of Chapter 3 is to describe the effects of soil water content and soil horizon mixing on soil compaction behaviour under uniaxial compression. Soil horizon mixing increases soil resistance to compaction while increasing soil water content reduces soil resistance to compaction. Although, dry soil was compacted by slight vibration during core preparation, preparing soil cores at the plastic limit water content generally produces higher void ratios at the start of a compression test than wetter or drier soil cores.

Soil compressive strength at the plastic limit water content is dependant upon the plasticity index. This relationship may be used to predict soil compaction at the maximum water content recommended for tillage. A multiple regression relationship between void ratio, uniaxial stress and soil water content is developed for use in the compaction management models in Chapter 7.

3.1 Introduction

Smith (1984) emphasises the need for theory relating physical changes wrought by tillage management techniques to the resultant crop response. Papers presented at a symposium on root zone management (Muirhead and Humphreys 1984) describe several tillage management techniques for irrigated red brown earths; however, none of them develop the criteria by which rational tillage decisions can be made. The theory required to accomplish this is outlined by Greacen and Sands (1980) and Greacen (1983), and is based, in part, upon the ability to predict soil mechanical strength as a function of soil compactness and water content.

The aim of the research reported in this Chapter is to investigate compaction behaviour for a range of mixtures of A and B horizon material from a red–brown earth sampled in the Lower Macquarie Valley. The components of the investigation were:

- measurement of soil compaction in response to applied stress and soil water content,
- determination of the effect of soil horizon mixing on the resistance of soil to compaction,
- determination of the relation between soil compaction behaviour and plasticity index,
- formulate a compaction model which may be used for predicting void ratio from compressive stresses attributed to traffic.

3.2 Literature Review

There are several methods for characterising soil compaction behaviour. Compression tests are reviewed and the theoretical background to interpretation of these tests is developed. The effects of soil water and texture on soil compaction and the relationship between soil plasticity and compaction are reviewed.

3.2.1 Compression Tests

Laboratory compression tests involve measurement of soil volume reduction under either static or dynamic loading. It is arguable which method of loading is more representative of compaction beneath wheels. In the field, the stress under a surface wheel load can be characterised by isotropic stress increase (Smith 1985). In the laboratory, compaction of an initially loose soil under a pneumatic tyre can be simulated by applying an isotropic stress pulse (Stafford and Mattos 1981). However, Koolen (1974) maintained that compression of soil in a rigid cylinder by a piston advancing at a constant rate is a more accurate representation of compaction processes in agriculture than hydrostatic compaction by an isotropic stress, which causes equal compaction in all directions. Koolen calls the former a uniaxial compression test because the mean path of soil particles is along the axis along which the major principle stress acts.

The use of a constant compression rate in a uniaxial test removes the effect of stress duration on soil compaction. Dexter and Tanner (1974) found that stress duration affected soil compaction. They measured equilibration times of 2×10^3 s (for volume equilibrium under static isotropic stress) and quote a stress duration of 2×10^{-2} s for compaction under a tractor drawn tillage implement and a figure of 10^4 s for stresses applied by growing plant roots. Thus, soil volume will not equilibrate with the stress applied by traffic during the duration of the stress. Similarly, soil volume does not equilibrate with the stress at failure measured in a uniaxial test. The uniaxial test is thus considered to be a better approximation of traffic compaction than static load tests of long duration.

The effect of stress duration on soil compaction is influenced by soil water content. Stafford and Mattos (1981) found that compaction increased with pulse duration at water contents drier than the plastic limit but was independant of pulse duration when the soil was wetter than the plastic limit. Soil in the plastic consistency range compressed rapidly to final volume determined by soil water content within the duration of stress pulse, i.e. the soil compressed until only water filled pores remained. Soil drier than the plastic limit compressed less rapidly, hence the dependance of compaction on the duration of the stress pulse.

Stafford and Mattos (1981) also found that compaction under tractor tyres increased with reduced tractor speed for a wide range of soil water contents. The tractor speed effect was larger at lower soil bulk densities. Stress duration is therefore likely to be an important factor in the compaction of loosened soil, such as at sowing, when the soil is drier than the plastic limit.

The tractor speed effect on compaction was attributed by Stafford and Mattos (1981) to shear strain (induced compaction due to wheelslip) , which is less at higher rates. It is not possible to simulate this effect with the uniaxial compression test and this test will underestimate compaction of surface soil in contact with a moving wheel, that is sheared as well as compacted.

The rate of strain used is an important consideration in a uniaxial test. Stafford and Tanner (1983) found that soil cohesion increased exponentially with increasing deformation rate. Compressive strength increases with compression rate up to a critical speed (2 to 4 m s^{-1}) and may be three times higher than at lower speeds (Koolen and Kuipers 1983, p73). Compression speed should be low enough to allow rapid dissapation of air pressure resulting from compression of soil air, yet rapid enough to allow the test to be completed in a reasonable time. Koolen (1974) used a compression speed of 10 mm min^{-1} and obtained uniform compaction in soil cores. The choice of piston speed was based on time constraints and sample size.

The dimensions of the soil sample influence the uniformity of the compaction process and the accuracy of strain measurements. External stress required for compaction to a certain pore space, and the rate dependency of this stress are greater for larger soil bodies (Koolen and Kuipers 1983, p32). Friction between the soil and the cylinder wall reduces the uniformity of the stress field in the core and hence the uniformity of compaction. Koolen (1974) found that sample aspect ratios (diameter/height) ranging from 1.7 (at the start of a test) to 3.0 (at the end of a test) produced uniform compaction and permitted the height of the core to be measured with acceptable accuracy.

The validity of the uniaxial compression test to describe agricultural compaction has been established. The results of uniaxial compression tests can be used to predict field compaction by agricultural machinery provided that the limitations of the technique are borne in mind. The main limitation to use of uniaxial compression tests is that compaction by traffic depends on stress duration and shear caused by wheelslip, particularly in the case of loose friable soil close to wheels. Consequently a uniaxial test may underestimate the compaction of soil in this condition. Koolen and Kuipers (1983) suggest that soil immediately beneath a moving wheel would be 25 % more compact than predicted by the uniaxial compression test.

3.2.2 Compaction Theory

A description of the mechanical behaviour of agricultural soil using Critical State Soil Mechanics Theory (CSSM) is given by Hettiaratchi and O'Callaghan (1980). CSSM uses spherical stress (equal in all directions) and deviatoric stress (shear stress) to describe the packing state of saturated clay soils. Void ratio or specific volume can be used as parameters of soil packing state.

For the case of one dimensional compression, initially uncompacted soil, when loaded mainly by vertical forces such as those induced by the passage of rolling wheels, compacts along a *virgin compression line*. In this stress state deviatoric stress is a constant ratio of spherical stress (Hettiaratchi and O'Callaghan 1980) and compaction can be described by variation in the logarithm of spherical pressure (Blackwell and Soane 1981; Smith 1985).

In one dimensional compression the principle stress, σ_1, on a cubic soil element will be vertically oriented and the soil will distort with negligible horizontal strain. These conditions occur at depth in the soil where the element has adequate lateral constraint. Koolen and Vaandrager (1984) showed that one dimensional compaction could be simulated by a uniaxial compression test using measurements of void ratio and σ_1 instead of spherical pressure (P) since P is a function of σ_1 for uniaxial compression.

In the uniaxial test, lateral stress (σ_3) is a constant ratio of the principle stress (σ_1) determined by the internal friction angle. Koolen and Vaandrager (1984) showed that σ_3/σ_1 varied with the amount of shear stress from unity (isotropic compression) to 0.11 at the critical state. For the uniaxial compression test σ_3/σ_1 is about 0.5 and this can be regarded as the upper limit of σ_3/σ_1 for one dimensional agricultural compaction since, in practice, there will be some lateral strain on a soil element. In the field, a soil volume element under a wheel will broaden as well as flatten (i.e. $\sigma_3/\sigma_1 < 0.5$). This broadening increases compaction at a given σ_1 value by as much as 25% (Koolen and Kuipers 1983, p42).

3.2.3 Effects of Soil Water

Soil pore space may be occupied by both water and gas. The pore water pressure, which is negative, can be likened to an external isotropic stress (Terzaghi 1943). Thus, the effective stress, σ, acting on an unsaturated soil element, is equal to the external stress plus the stress contributed by negative pore water pressure (Equation 3.1),

$$\sigma = \overline{\sigma} - \chi u_w \tag{3.1}$$

where $\overline{\sigma}$ is the applied normal stress and u_w is the pore water pressure, and χ is the wetted area per unit gross area of partly saturated soil. χ describes the area over which pore water pressure acts and may be approximated by relative saturation of the soil (Hettiaratchi and O'Callahgan 1980). Because u_w is negative soil drying is equivalent to an increase in the stress state by an amount χu_w.

The concept of effective stress can be used to extend critical state soil mechanics to describe the compaction of unsaturated soil (Hettiaratchi and O'Callahgan 1980; Leeson and Campbell 1983). Soil stress state increases as the soil dries. Leeson and Campbell (1983) found that the gradient of the virgin compression line increased and its intercept decreased as the water content and degree of soil saturation increased. Towner and Childs (1972) showed that effective stress was a curvilinear function of degree of saturation. Larson *et al.* (1980) used a linear approximation of this function, which they determined statistically, to describe the change in the intercept of the virgin compression line with changing soil water content.

The effect of decreasing soil water content on the magnitude of the slope of the virgin compression line, the compression index, is not accounted for by the theory applied to saturated soil behaviour. Verpraskas (1984) found that changes in effective stress did not account for changes in soil strength for dispersed soil materials. He attributed this to dispersed silt particles moving to contact points between sand particles as the soil dried. This rearrangement would increase the frictional resistance among sand grains on drying independant of any change in effective stress. If this hypothesis were proved correct it would explain the change in slope of the virgin compression line for unsaturated soils since the compression index is a measure of the frictional resistance between soil particles.

3.2.4 Soil Texture

For a duplex soil, such as a red–brown earth, deep mouldboard ploughing increases the clay content of the plough layer. Larson *et al.* (1980) found that an increase in clay content between soils of the same taxonomic soil order produced an increase in the slope of the compression curve or compression index. Above a clay content of 33% the compression index was virtually constant. This was attributed to the soil matrix becoming dominated by clay with coarser materials embedded in it.

The maximum packing density attainable under compression depends on the area of contact between soil particles. Bodman and Constantin (1965) found that a mixture of fine sand and silt allowed for maximum area of contact between soil particles and maximum packing density. The Trangie red–brown earth has a well sorted particle size range and is thus capable of packing to high packing densities.

The optimal particle size distribution for dense packing is where finer particles can fit between larger particles to form very small pores. Gupta and Larson (1979) used a random packing model to delineate susceptibility to surface sealing and pan formation in soils of similar texture. Mixing a clay subsoil with a coarser sandy loam topsoil may increase the maximum packing density attainable until the coarser voids are filled by clay particles and a clay dominated matrix is formed.

3.3 Materials and Methods

Uniaxial compression tests give a reasonable indication of the vertical stresses in the soil beneath traffic. Vertical pressure is the main cause of compaction in soil which is beneath the surface and is laterally confined. The slope of the void ratio versus log vertical pressure curve, the compression index, is expected to be constant for a particular soil. Increasing the relative saturation of soil by increasing the water content reduces soil compressive strength. Consequently, measurements of void ratio as a function of vertical pressure and soil water content are made for the Trangie A and B horizons and soil horizon mixtures. Preparation of the soil horizon mixtures is described in Chapter 2, Section 3.

3.3.1 Water Content Equilibration

Five kilogram soil samples were spread 2 cm deep on a flat surface. Water was added to soil mixtures in a fine spray and mixed with the soil by hand. Soil was pushed through a 2 mm sieve to reduce large aggregates, sealed in plastic bags, and left to equilibrate in a uniform temperature environment (20 ± 1^o C). The sieving treatment remoulded the soil, consequently, the strength properties being studied relate to soil remoulded by tillage and not uncultivated soil. Water contents ranged from near air dry to above the plastic limit.

3.3.2 Uniaxial Compression Test

Soil equilibrated at a particular water content was dumped into an aluminum cylinder. Cores 175 mm long and 73.6 ± 0.5 mm diameter were compressed on a base which inserted into the bottom of the core. The sample aspect ratio (height:diameter) was effectively halved by having an active piston at either end of the sample.

Soil cores were compressed with a uniaxial compression testing instrument (JJ Lloyd M5K, Figure 3.1). A piston with tapered sides and a diameter 1 mm less than the internal diameter of the core containing cylinder was attached by means of a drill chuck to the crosshead of the compression tester. The position of the piston was zeroed at the surface of the soil core. The initial height of soil in the core was recorded and then the piston advanced at a constant rate of 10 mm per minute until a maximum load of 4 kN registered on the compression tester via the 5 kN load cell attached to the piston through the crosshead. Peak values of load (kN) on the piston and distance moved by the piston (mm), at the peak load, registered digitally on the compression tester and as continuous output to a flat-bed plotter.

Axial strain was measured from the continuous plot of axial stress vs strain on the flat-bed plotter for the following seven values of axial stress, 0.1, 0.3, 0.6, 1.0, 2.0, 3.0, 4.0 kN. Axial load in kN was converted to pressure in kPa by dividing by

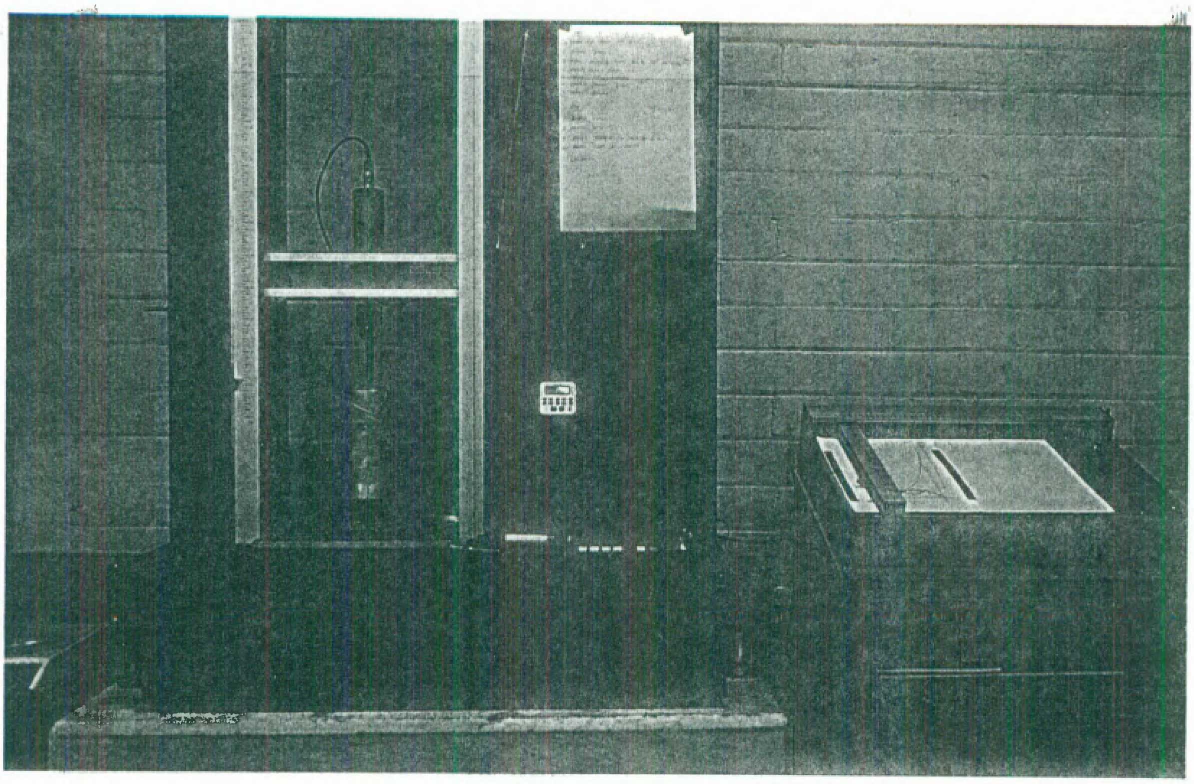

Figure 3.1: Uniaxial compression test on a soil core with the Model M5k materials testing instrument made by J.J. Lloyd, England. Stress is recorded by a flat bed plotter and a digital display for continuous strain increase.

the piston cross-sectional area of 4.254×10^{-3} m^2.

Implicit in the measurements is the assumption that the method simulates the compactive effect of a very slow moving vehicle in the field (Section 3.2.1). Koolen (1974) provides justification for this assumption. Furthermore, the difficulty of performing these tests in the field supports use of the laboratory method used here, provided the limitations of the data are not overlooked.

3.3.3 Core Dimension Effects

The effect of core height on the shape of the compression curve was investigated. Uncompressed sample heights of 175, 150, 125, 100, 75, 50 and 25 mm and diameter 73.6 mm were used to give aspect ratios 0.42, 0.50, 0.58, 0.71, 1.0, 1.43, 3.33 respectively. The measurements were done for both A (fine sandy clay loam) and B horizon soil (medium clay) to determine the effect of texture in combination with aspect ratio. Aspect ratio had no significant effect on the compression curves for this soil.

3.3.4 Virgin Compression Lines

The slope of the least squares regression line of void ratio (n) on $\ln \frac{\sigma_1}{\sigma_0}$ was used as the compression coefficient. The model fitted by least squares regression was

$$n = A.\ln\left(\frac{\sigma_1}{\sigma_0}\right) + n_0 \tag{3.2}$$

where A is the compression coefficient, n is the void ratio (m^3 m^{-3}), σ_1 is the axial pressure applied through the compressing piston and σ_0 is an arbitrary starting pressure of 1 kPa. n_0 is the void ratio at an initial unit pressure of 1 kPa.

Void ratio is used as an index of soil compaction rather than bulk density. Void ratio (m^3 m^{-3}) is dimensionally simpler than bulk density (kg m^{-3}) and is a consistant index of soil pore space for soils with different particle densities. Also, though some workers have analysed compression test data in terms of bulk density and pressure (Larson *et al.* 1980; Saini *et al.* 1984), the relationship between void ratio and pressure conforms more closely with theoretical compaction curves (Leeson and Campbell 1983). The preparation of soil horizon mixtures was described in Chapter 2, Section 3.

3.4 Results

3.4.1 Virgin Compression Lines

There is a general trend for virgin compression lines (n vs $\ln\frac{\sigma_1}{\sigma_0}$) for the soil mixtures to be shifted towards the origin as soil water content is increased (Figures 3.2–3.7). Consequently, the initial void ratio determined from Equation 3.2 (n_0) decreased as soil water content increased. Some precompaction of the dried samples occurred as a result of core preparation (Figures 3.2, 3.5, 3.6, 3.7). Dry powdery soil is less resistant to compaction by slight vibration than soil at water contents approaching the DCPL (Section 2.3.4). Initial void ratios tended to be a maximum at water contents close to the plastic limit (DCPL), particularly as the proportion of B horizon material increased, and lower at water contents wetter than the DCPL (Figure 3.2, to 3.7).

Virgin compression lines at the DCPL fit the loglinear regression model Equation 3.2 ($r^2 > 99\%$). At higher water contents the relationship deviated from the log linear relationship as normal pressure exceeded 500 kPa (Figures 3.2 to 3.7). Virgin compression lines are best described by the loglinear model (Equation 3.2) when the soil is at the DCPL water content.

Mixing B horizon soil with the A horizon reduces soil compactness at any level of axial stress, at the DCPL water content. Increased B horizon material in the soil mix results in a higher initial void ratio (Figure 3.8). B horizon soil is more compactable than the 25 A 75 B horizon mix but still less compactable than the A horizon at the DCPL.

3.4.2 Compression Index

The slope of the log linear part of the virgin compression curve, the normal consolidation line, is used as a compression index (Soehne 1958; Larson *et al.* 1980;

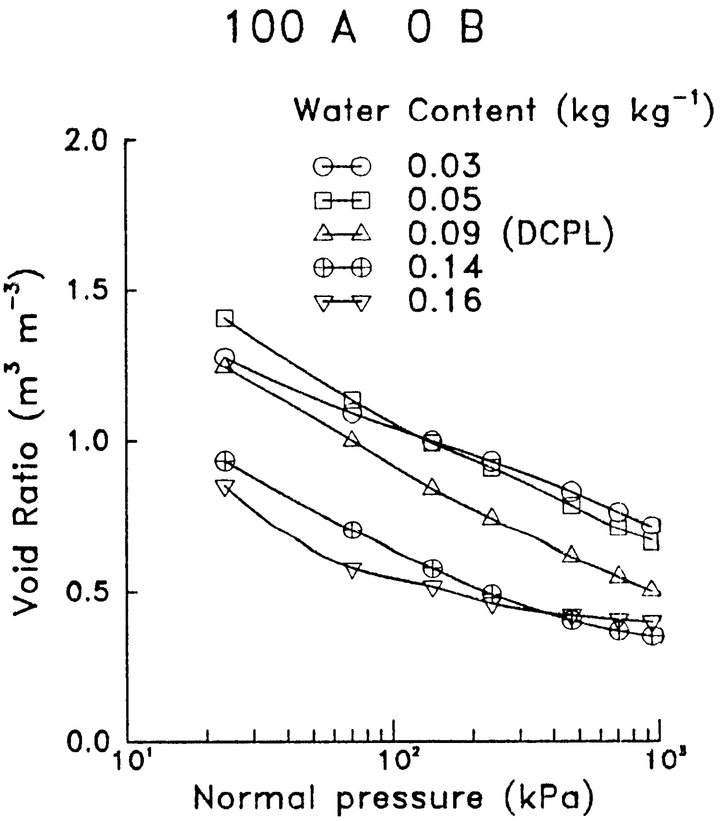

Figure 3.2: Virgin compression curves for the 100 A 0 B Trangie red-brown earth soil horizon mix. DCPL is the drop cone penetrometer plastic limit. Normal pressure is the pressure applied by a piston advancing at a constant rate.

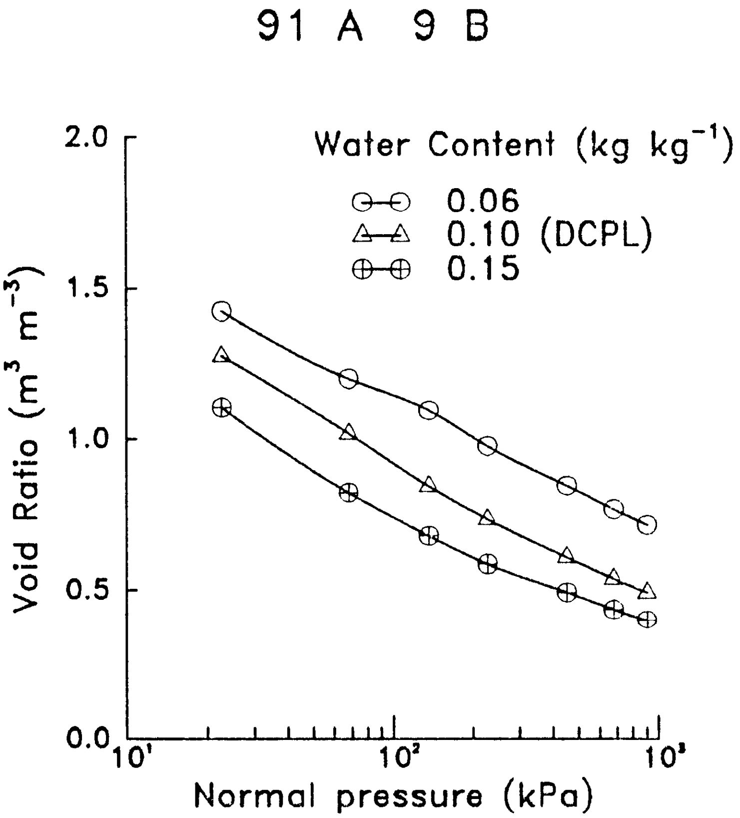

Figure 3.3: Virgin compression curves for the 91 A 9 B Trangie red-brown earth soil horizon mix. DCPL is the drop cone penetrometer plastic limit. Normal pressure is the pressure applied by a piston advancing at a constant rate.

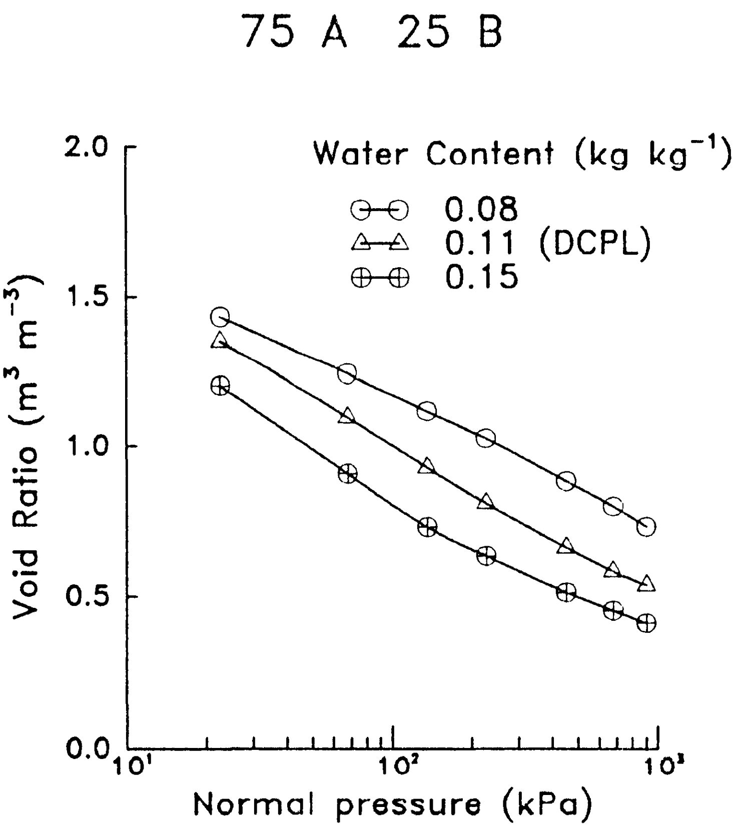

Figure 3.4: Virgin compression curves for the 75 A 25 B Trangie red-brown earth soil horizon mix. DCPL is the drop cone penetrometer plastic limit. Normal pressure is the pressure applied by a piston advancing at a constant rate.

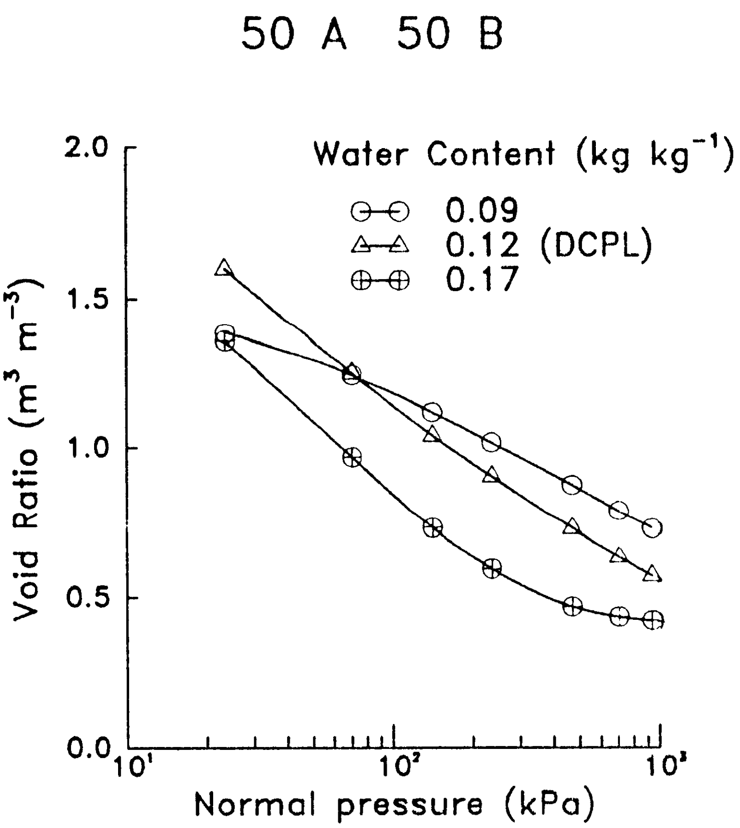

Figure 3.5: Virgin compression curves for the 50 A 50 B Trangie red-brown earth soil horizon mix. DCPL is the drop cone penetrometer plastic limit. Normal pressure is the pressure applied by a piston advancing at a constant rate.

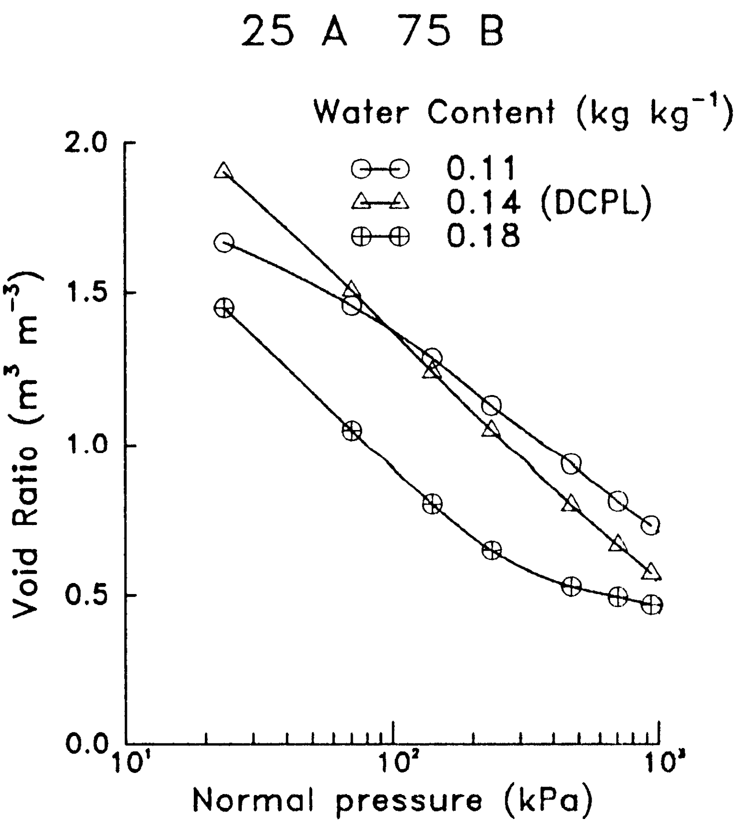

Figure 3.6: Virgin compression curves for the 25 A 75 B Trangie red-brown earth soil horizon mix. DCPL is the drop cone penetrometer plastic limit. Normal pressure is the pressure applied by a piston advancing at a constant rate.

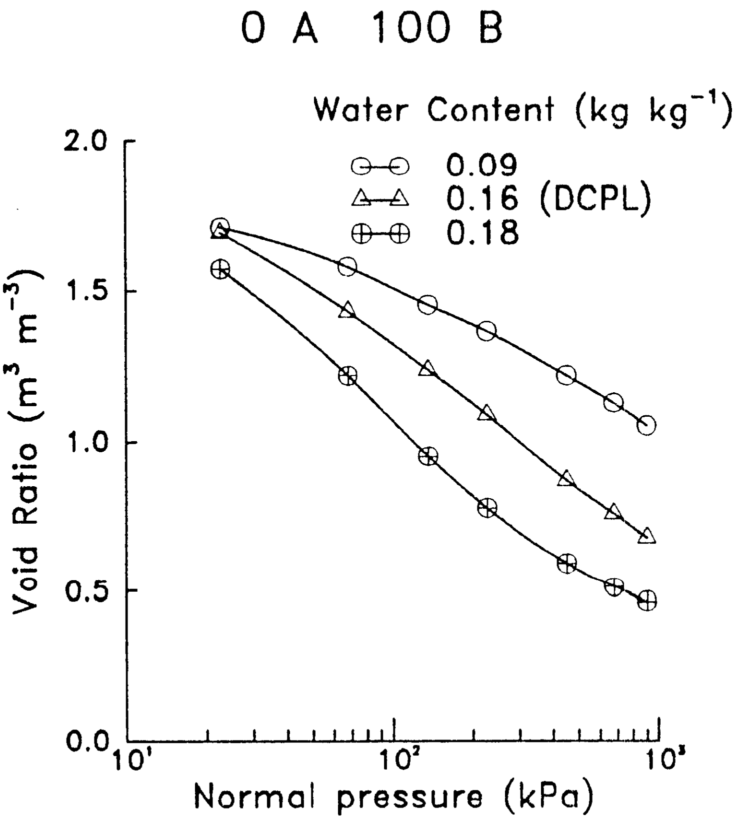

Figure 3.7: Virgin compression curves for the 0 A 100 B Trangie red-brown earth soil horizon mix. DCPL is the drop cone penetrometer plastic limit.

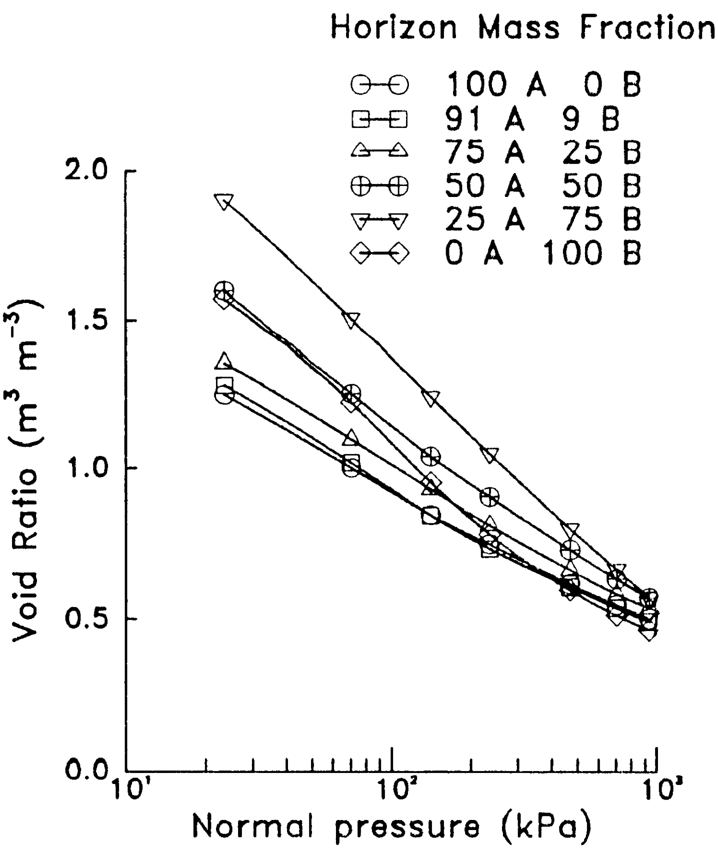

Figure 3.8: Virgin compression lines for each soil horizon mix at the drop cone plastic limit water content (DCPL). Normal pressure is the pressure applied to the soil by a piston advancing at a constant rate.

Saini *et al.* 1984), and is reputedly characteristic of a soil independent of water content (Equation 3.2).

In this study the slope of the virgin compression lines varied with water content, being most negative at the DCPL water content (Figure 3.9). A good fit of the log linear model (Equation 3.2) and a high negative value of A at the DCPL identify normal consolidation. The compression index (C), characteristic of a soil, was determined from Figure 3.9 as the compression coefficient at the DCPL water content (i.e. $C = A_{DCPL}$).

3.4.3 Soil Horizon Mixing

The compression index (C) decreased steadily from -0.5 to -0.8 with increased soil horizon mixing up until the 25 A 75 B soil mixture and then increased to -0.7 for the B horizon (0 A 100 B) (Figure 3.9). Compressibility is said to increase as C becomes more negative. The compression index C and the intercept, n_0, are related to the plasticity index (DCPI) by linear regression (Equations 3.3 and 3.4). C and n_0 had different variances for each mix, depending on the goodness of fit of the loglinear model (Equation 3.2) to the compression curve. Consequently, the values of C and n_0 for each mix were weighted by the inverse of their respective variances in the regression on DCPI.

$$C = -0.280 - 1.89 \times DCPI \tag{3.3}$$

$$n_0 = 3.74 + 0.809 \times \ln DCPI \tag{3.4}$$

Equations 3.3 and 3.4 accounted for 95 % of variation in the data. The data and the models are shown in Figure 3.10.

3.4.4 Compaction Model

At any water content, soil compressive strength depends on the air–filled void volume, i.e. more pressure is needed to compress soil as the volume of voids is reduced,

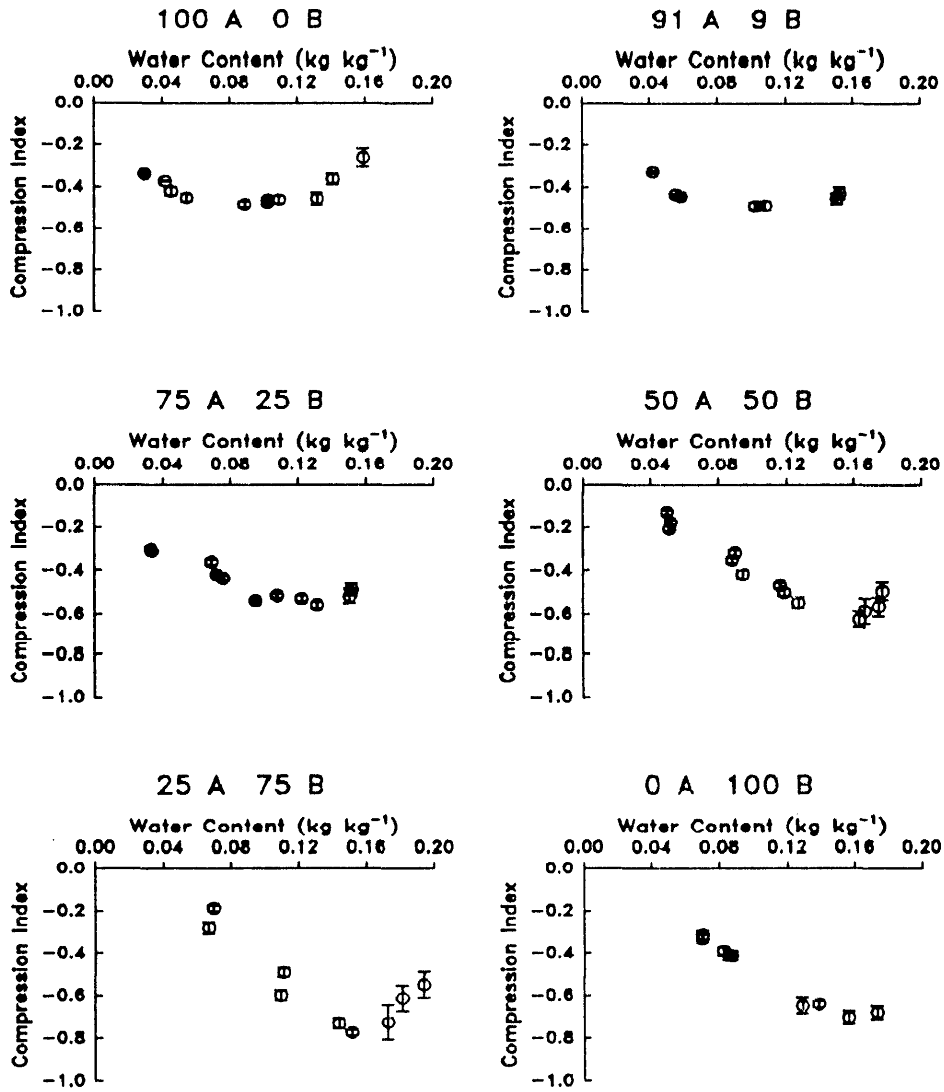

Figure 3.9: Compression coefficient A from the model $n = A \ln \frac{\sigma_1}{\sigma_0} + n_0$ plotted against gravimetric water content (θ_g) for each of the soil horizon mixtures of Trangie red–brown earth used in the study.

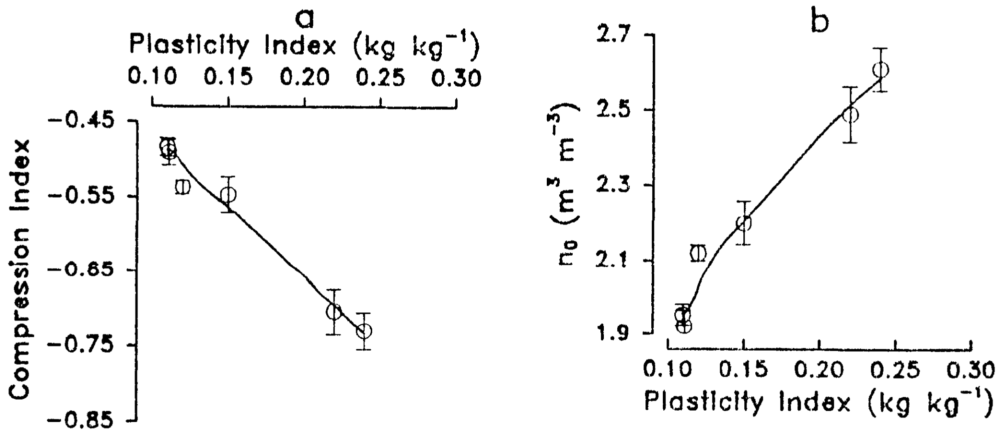

Figure 3.10: (a) Compression index (C) vs plasticity index calculated from the consistency limits measured with a drop cone penetrometer (DCPI); (b) void ratio at a pressure of 1 kPa, n_0, vs DCPI. The error bars represent one standard error deviation.

while at any particular degree of compaction (void ratio) compressive strength varies with the water filled void volume, i.e. virgin compression lines in Figures 3.2 to 3.7 shift towards the origin as soil water content increases. So, for uniaxial compression, void volume will depend on compressive stress and soil water content.

There was no single polynomial regression relationship between void ratio and uniaxial stress and water content which would fit the data for all the soil horizon mixtures. This problem may be caused by the fact that different soil mixtures at the same void ratio have different compressive strengths owing to variation in the volume of water retained and hence the air volume that can be reduced by compaction. A simple relationship between compaction and compressive stress is needed which reflects the log linear virgin compression relationship and incorporates the effect of water content on compressive strength. This was achieved by normalising void ratio according to the minimum void ratio attainable by compaction. Thus, the compaction parameter, n_{rel}, is defined as

$$n_{rel} = \frac{n - n_f}{n_f} \tag{3.5}$$

Table 3.1: Coefficients of the soil compaction model $n_{rel} = a + b\ln\sigma_1 + c\theta_g^{-1}$ (see Equation 3.6) derived for soil horizon mixtures of Trangie red brown earth.

Horizon mass fraction	coefficients			
	a	b	c	r^2
100 A 0 B	3.38±0.31	-0.976±0.053	0.368±0.008	95.9
91 A 9 B	2.46±0.32	-0.893±0.654	0.436±0.011	97.6
75 A 25 B	2.72±0.28	-0.883±0.048	0.426±0.007	97.6
50 A 50 B	1.99±0.17	-0.594±0.028	0.351±0.007	97.2
25 A 75 B	2.07±0.18	-0.739±0.029	0.491±0.013	96.1
0 A 100 B	2.03±0.25	-0.788±0.040	0.562±0.012	97.6

where n is void ratio (m^3 m^{-3}) and n_f is minimum attainable void ratio, i.e. the volume of water divided by the volume of solid, the water ratio. n_{rel} is equivalent to the volume of air filled voids divided by the volume of water and is inversely related to the gravimetric water content (θ_g), and an exponential function of normal stress (σ_1).

$$n_{rel} = a + b\ln\sigma_1 + c\theta_g^{-1} \tag{3.6}$$

The coefficients a, b, and c in Equation 3.6 were determined by least squares multiple regression for each soil horizon mix (Table 3.1).

Equation 3.6 can be solved for void ratio by substituting Equation 3.5 for n_{rel} as below,

$$n = n_f(a' + b\ln\sigma_1 + c\theta_g^{-1}) \tag{3.7}$$

,where $a' = a + 1$.

3.5 Discussion

3.5.1 Virgin Compression Lines

The initial and final stages of compression deviated from normal consolidation (Figures 3.2–3.7). At low pressure the shape of compression lines is affected by the initial

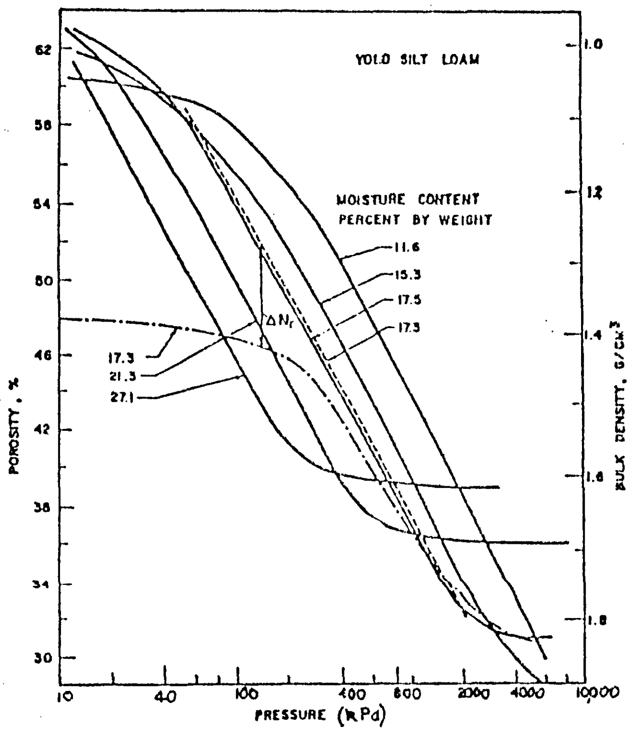

Figure 3.11: The relationship between porosity and compacting pressure for several soil moisture contents for precompacted and virgin soils (Soehne 1958).

packing condition, especially for dry soil where lightly tapping of the cores caused the soil to settle to a low void ratio (precompaction). At high pressures, and at water contents wetter than the DCPL, the compression lines deviate from the log linear form because water begins to carry the applied pressure causing consolidation, i.e. water flow from the core may not have been rapid enough to prevent water pressure building up ahead of the piston. Figure 3.11 illustrates the distortion of the virgin compression line by precompaction and high water content, as reported by Soehne (1958).

The compaction of soil under a tractor tyre also depends on the stress duration. Dexter and Tanner (1974) reported that the stress duration under a tractor tyre was about 0.5 s, depending on tractor speed. Stafford and Mattos (1981) found that 1 MPa pressure for 0.5 s was sufficient for soil bulk density to reach a final value which depended on the soil water content, where the soil was wetter than the

DCPL, i.e. most of the air–filled voids were removed and there was no consolidation. Thus in the field, as well as in the uniaxial compression test, soil water does not have time to equilibrate with the compressive stress. However, in the field the soil may rebound once the tractor tyre has passed, thus allowing soil to eqilibrate to a higher void ratio than that expected from the uniaxial test.

The virgin compression lines were non–linear for dry soil, if precompacted in preparation, and for wet soil where water movement retarded compaction at high stresses. There is evidence that field soil behaves in this way when compacted by traffic (Stafford and Mattos 1981). Stress duration would have to be simulated to accurately represent traffic compaction of soil in the compression test.

3.5.2 Soil Horizon Mixing

The DCPI is directly related to soil strength (Croney and Coleman 1954; Campbell 1975, 1976b). Data from Farrell and Greacen (1966) for three red–brown earth soils suggest linear relationships between compression behaviour and the plasticity index similar to that for soil horizon mixtures of the Trangie soil(Figure 3.10). The coefficients of the relationship between compression index and plasticity index for their soil are of the same order of magnitude as the coefficients in Equation 3.3. Differences arise from their using Atterberg consistency limits to determine plasticity index and isotropic stress to model compaction.

The compaction of cultivated Trangie red–brown earth soil can be predicted, and the susceptibility of different soil horizon mixtures to compaction damage assessed using Equations 3.3 and 3.4 and measurements of plasticity index with a drop cone penetrometer. This approach applies to the compaction of cultivated soil at the DCPL — the maximum water content at which soil should be tilled (Archer 1975). Field compaction also depends on soil structure and tractor speed (Stafford and Mattos 1981; Dexter and Tanner 1974), soil water content (Weaver and Jamison 1951), shear stress (Davis *et al.* 1973) and initial soil density (Stafford and Mattos 1981). However, the DCPI can be used to characterise soil strength at the upper water content recommended for cultivation. Thus, the DCPI is an indicator of soil strength that can be related to cultivation management and it may be used to compare different soils in their susceptability to structural damage by cultivation.

3.5.3 Compaction Model

Equation 3.6 applies equally well to the different textured soil horizon mixtures because void ratio is normalised to account for different water contents in different textured soils at the same void ratio. The stress component contributed by pore water at a particular void ratio depends on the surface area of water films in the soil. The surface area of water films is a function of the volume of water per unit volume of soil pores (Skopp 1985). This is accounted for in the parameter n_{rel} but not n. Larson *et al.* (1981) used relative saturation instead of n_{rel} in a soil compaction model that used bulk density as the soil packing parameter rather than void ratio. Although relative saturation is directly related to n_{rel}, the latter is a more rigorous quantity for inclusion in the void ratio prediction model.

The coefficients of Equation 3.6, presented in Table 3.1, can be used to predict compaction for any uniaxial stress and soil water content. However, Equation 3.6 needs to be calibrated against field measured compaction beneath wheels. The physical limits to root growth as a function of soil compactness are established in subsequent chapters.

3.6 Conclusions

- The compression index characteristic of a soil can be determined, using a uniaxial compression test, as the slope of the virgin compression line of soil at the plastic limit water content, measured with a drop cone penetrometer.

- Mixing B horizon with A horizon soil increases the slope and intercept of the virgin compression line at the DCPL. Thus, soil horizon mixing reduces the compactability of soil at a particular water content and compressive load.

- The slope and intercept of the virgin compression line can be estimated from measurements of plasticity index with a drop cone penetrometer. Thus comparative assessment of the effect of subsoil mixing on compaction can be made from measurements of plasticity index for mixtures of the A and B horizon.

- The relationship between vertical pressure (P), soil water content (θ_g) and void ratio (n) is expressed by $n = n_f(a' + b \ln \sigma_1 + c\theta_g^{-1})$ for initially loose and laterally confined soil. This model is used in Chapter 7 to predict soil compaction as a result of stresses attributed to traffic. This model needs to be tested against measured compaction under known wheel loads in the field if it is to be used to describe the compaction of soil in direct contact with wheels.

Chapter 4

Soil Penetration Resistance

Abstract

Soil penetration resistance directly affects root growth. Hence, a quantitative model of penetration resistance is needed to predict compaction conditions restrictive to root growth and to assess the soil horizon mixing effect of deep mouldboard tillage. Chapter 4 investigates soil penetration resistance as a function of soil compactness, water content, soil horizon mixing and gypsum application. Penetration resistance is measured with a cone penetrometer on disturbed soil cores and the results are compared with cone penetrometer measurements in the field.

Field penetration measurements indicate that compaction restricting root penetration occurs beneath the tilled layer of Trangie red–brown earth. The benefits of deep mouldboard tillage may result from a greater depth of loosened soil which does not mechanically impede root growth. The critical void ratio for high penetration resistance is 0.73 m^3 m^{-3} for the A horizon and 0.96 m^3 m^{-3} for the B horizon soil. Laboratory cone index measurements are not significantly different to cone index measured in the field. Consequently, the laboratory study of cone index as a function of void ratio, water content and soil horizon mixing is used to describe penetration resistance in the field. Cone index is a logarithmic function of void ratio, water content and an interaction term. Soil horizon mixing increases soil penetration resistance at constant water content and void ratio. This effect will counteract any beneficial effect of an increase in resistance to compaction attributed to soil

horizon mixing (Chapter 3).

Gypsum application (5 t ha^{-1}) does not affect the penetration resistance of the A horizon soil or a soil horizon mixture representative of deep mouldboard ploughing. Consequently the benefits derived from applying gypsum do not result from changes in the penetrability of the soil mass. It is possible that gypsum ameliorates a surface crusting problem on this soil and this aids water infiltration.

The differences between moulboard ploughed and non–mouldboard ploughed soil may result from differences in initial void ratio, and hence penetrability. However, both tillage treatments compact to similar void ratios in the field over two growing seasons. This indicates that processes other than traffic compaction are important. Soil settling after rapid wetting is one other process which may be compacting the topsoil.

4.1 Introduction

Soil physical properties that may restrict root growth include lack of plant available water, insufficient oxygen for root respiration and high soil penetration resistance. These factors interact in a complex manner. For example, penetration resistance is a function of soil water content and void volume, while oxygen diffusion may be markedly reduced at high water contents and low void volumes.

In order to characterise soil physical conditions likely to lead to restricted root growth, the interrelationships between water content, oxygen flux, soil strength and void ratio need to be established. These relationships may be investigated using field methods, but control of variables is more readily achieved in the laboratory. Accordingly, a study of the interaction between soil strength, water content and void ratio was undertaken using disturbed samples of Trangie red–brown earth soil. Natural soil horizons as well as artificial mixtures of A and B horizons were included in the study.

The detailed aims of this investigation were to

- verify that field and laboratory measured soil penetration resistance were similar and comparable,

- develop a predictive model of penetration resistance as a function of soil compactness and soil water content,
- evaluate the effect of soil horizon mixing and gypsum application on penetration resistance.

4.2 Literature Review

Strength is imparted to soil by cohesive forces between particles and by the frictional resistance caused when particles are forced to slide over one another. Deformation occurs when the applied stress exceeds the strength of the material and the soil fails by fracture or plastic flow. Several techniques are available for measuring soil resistance to deformation, each characterising a particular mechanical property, or combination of properties. O'Sullivan and Ball (1982) compared strength measurements with a cone penetrometer, a shear vane and a torsional shear box in the field. They found that measurement of soil strength was fastest with the cone penetrometer, however, the penetrometer registers a combination of soil compressive and shear strength. Cone index is an approximation of soil resistance to penetration. Cone index (MPa) is calculated from the axial force on a penetrating cone divided by the cone basal area. Measurement standards are given in ASAE R313.1 (1983).

The soil mechanics theory relevant to the cone penetrometer measurement, laboratory conditions affecting penetration resistance and interpretation of cone penetration resistance with regard to impedance to growing roots are reviewed.

4.2.1 Theory

Penetration resistance can be described by parameters of Critical State Soil Mechanics theory (*CSSM*). Cone index (*CI*) is a generally accepted measure of penetration resistance, defined as the pressure on a penetrating cone divided by the area of its base. Mulqueen *et al.* (1977) proposed that *CI* can be described by spherical stress P and deviatoric stress R. The stress state is a function of the pore volume parameter (void ratio). Theoretically *CSSM* theory can be extended to describe the *CI* behaviour of unsaturated soils of any texture.

Cone index values measured by Mulqueen *et al.* (1977) were not uniquely related to density and soil cohesion. As water content increased cone index values became less dependent on bulk density. A comparison was drawn with viscous materials where the resisting force on a body moving through the material depends on the viscosity and not the density. As the soil becomes drier, compression under and around the probe becomes more important and the penetration force is very dependent on soil density. At intermediate water contents, both compression and shear appeared to be important.

CSSM theory describes soil void ratio as an logarithmic function of soil stress state. Extension of *CSSM* theory to penetration resistance suggests that cone index is an exponential function of void ratio and water content.

4.2.2 Laboratory Conditions

Penetration Velocity

Soil impedance to a penetrating body depends on the penetration rate. The force required to produce the rapid failure in penetration tests may exceed the force required to keep the same penetrometer moving at rates of $\leq$0.035 mm min^{-1}, comparable to root growth rates. Waldron and Constantin (1970) determined a power law relating penetrometer resistance and velocity. It was used to illustrate that the observed discrepancies between root and penetrometer resistance may arise from velocity differences.

Several researchers (Cockroft *et al.* 1969; Bradford *et al.* 1971; Voorhees *et al.* 1975) have investigated penetration rates in relation to penetration resistance. Conclusions have varied: an increase in probe penetration rate can increase, decrease or not influence probe resistance. The lowest velocity reported is 0.167 mm min^{-1} (Barley *et al.* 1965). Penetration rates are frequently not reported, but in many procedures rates are several hundred times this value. On the other hand maximum root elongation rates are of the order of 0.1 cm hr^{-1} (0.0167 mm min^{-1}).

Sample Size

In shallow tests, where the depth of penetration is of the same order as the probe diameter, the mode of soil failure is partly upheaval of surface soil around the point of entry (Farrell and Greacen 1966). Cone index increases with depth of penetration to a steady maximum when depth of penetration is greater than three or four times the probe diameter (Mulqueen *et al.* 1977).

For penetration tests in confined soil cores penetration resistance increases to a maximum and then decreases (Mulqueen *et al.* 1977). Shear planes release stress through the soil surface at either end of a soil core. Failure planes are contained within the soil core when the penetrometer is at a distance from either end of the core 3 to 4 times the diameter of the penetrating cone (Whiteley and Dexter 1981a). Thus, the height of a soil core needs to be at least 6 times the diameter of the penetrating cone to attain a cone index characteristic of the soil mass.

Soil confinement in a rigid cylinder can add to soil penetration resistance. The diameter of a soil core should be at least 6 times the diameter of the penetrating cone to eliminate the effect of soil containment (Whiteley and Dexter 1981a).

4.2.3 Root Impedance Critera

Compaction effects on root growth may be a complex interaction between soil strength, water and nutrient availability, and aeration. Root elongation tends to vary inversely with resistance, and may stop when resistance exceeds the root growth pressures available to overcome it (Barley and Greacen 1967; Taylor *et al.* 1966; Camp and Lund 1968). Root elongation pressures are functions of cellular osmotic potential. They result from passive water movement from soil to plant cells, to equalise the chemical potential of water in respective phases of the growing root tip (Barley and Greacen 1967; Taylor and Ratliff 1969).

Roots must overcome the strength of the soil to penetrate pores of smaller diameters than themselves. Because compaction increases soil strength and decreases the number of macropores, the rate of root elongation and therefore root length is reduced. Typically elongation rate is reduced exponentially as soil strength (measured by a cone penetrometer) is increased, but there is a critical, ill-defined resistance P_c above which root penetration effectively ceases. Greacen *et al.* (1969) tabulated P_c values ranging between 800 to 5000 (mean 2500) kPa depending on species, soil type and penetrometer characteristics. Greacen *et al.* (1968) pointed out that root penetration in coarsely-structured soils cannot be predicted from values of strength measured with rigid probes, even when mechanical factors are limiting, as roots are able to explore planes of weakness. Nonetheless the penetrometer is one of the most practical instruments for assessing mechanical impedance of soils in the field.

Ball and O'Sullivan (1982) found that spring barley plant populations and grain yield were reduced in silt loam soils with cone resistances greater than 2500 kPa. Ehlers (1982) studied penetration resistance and root growth of oats in tilled and untilled loess soil. He found that the limiting penetration resistance for root growth was 3.6 MPa in the tilled Ap horizon but 4.6 — 5.1 MPa in the untilled Ap horizon and in the subsoil of both tillage treatments. The differences in the soil strength–root growth relationship were explained by the build up of a continuous pore system in untilled soil, created by earthworms and roots from preceding crops. These biopores occupy $\leq 1\%$ of the soil volume and act as preferred pathways of low resistance to growing roots.

Penetrometer pressures are generally higher than the pressures exerted by growing roots. Eavis and Payne (1969) compared the pressures exerted by pea roots entering soil cores with the pressures on a metal probe of similar shape and diameter. The penetrometer probe required a pressure of between 4 and 8 times larger than the roots. Whiteley *et al.* (1981) found a penetrometer had to exert a pressure 5.1 times greater than a root tip to penetrate the soil. They found penetrometer penetration pressure was independent of probe diameter in the 1–2 mm range in the soil used (Urrbrae fine sandy loam). Core confinement restricted radial root expansion and modified the penetration force of metal probes and plant roots. Whiteley *et al.* (1981) concluded that soil tensile failure facilitated penetration by roots, that root tips expand radially causing tensile failure ahead of the elongating root tip, facilitating penetration.

The motion of a penetrating root is not replicated by a metal probe. Waldron and Constantin (1970) found slow, small oscillations of a 2 mm diameter cylindrical penetrometer reduced soil resistance to slow penetration, probably by reducing the soil–metal coefficient of friction. These observations indicate that penetrometer penetration resistance is a comparative rather than absolute measure of the resistance encountered by growing roots.

4.2.4 Soil Factors

Stitt *et al.* (1982) examined the influence of 20 soil physical, chemical, and mineralogical properties on cone index for 50 tillage pan materials from the North Carolina coastal plain. They found water content, bulk density and the volume of pores with neck diameters between 74 and 136μm accounted for most of the variation in the observed cone index values. No simple relationship was found between texture and cone index and there was no evidence that cementing agents affected cone index values. Numerous investigations have shown that water content, bulk density, and texture influence cone index (Taylor and Gardner,1963; Barley *et al.* 1965; Camp and Gill 1969; Gerard 1965; Taylor *et al.* 1966). Soil strength has also been related to pore size distribution (Byrd and Cassel 1980; Gerard *et al.* 1966). It can be concluded that soil texture, water content, and void volume are the main factors affecting the cone index measurement.

Field versus Laboratory Results

Penetrometers are the customary diagnostic tool for gauging the resistance of soil to the penetration of plant roots. Their use can be separated into three broad categories

1. Field studies in which typically large (10-20 mm diameter) probes are driven downward from the soil surface for identifying root restricting horizons (Taylor 1974) and for studying soil compaction in relation to root growth and development.

2. Empirical investigations of relationships between penetrometer resistance and rates of root elongation (Eavis and Payne 1969; Mirreh and Ketcheson 1973;

Taylor and Ratliff 1969; Voorhees *et al.* 1975).

3. Studies of root penetration of surfaces (i.e. interfaces) in structured soil (Gardiner and Danielson 1964; Greacen *et al.* 1969; Dexter and Hewitt 1978)

It is necessary to know whether penetration resistance measured in the field is substantially different from that measured in the laboratory before laboratory measured cone index can be related to field conditions. A range of penetrometer sizes have been used by previous researchers. However, provided that effective soil particle size (aggregate size) is smaller than the penetrometer tip and that the included angle of the cone apex is constant, the pressure on the penetrometer tip should be independent of penetrometer size (Whiteley and Dexter 1981a). Thus, comparison between field and laboratory penetrometers of different diameters, with constant tip angle, may be valid provided the cone diameters greater than the diameters of the soil aggregates in both cases.

4.3 Materials and Methods

4.3.1 Field Study

Field penetrometer transects were made along the diagonal of each tillage trial plot at Trangie Agricultural Research Centre, Block 4A. Three penetrations with a Rimik recording cone penetrometer (Rimik Industries, Toowoomba) fitted with a 13 mm diameter, standard B cone (ASAE R313.1, 1983) were made every 20 m along the transects. Force on the penetrometer tip was recorded every 15 mm down to 300 mm depth. Soil water content was measured at 100 mm depth intervals. Data from a previous study of soil strength variation over an irrigation cycle (Barratt 1985) was used to develop a field model of cone index as a function of soil water content and void ratio.

4.3.2 Laboratory Study

Cores of Trangie red–brown earth A and B horizon and soil horizon mixtures (Chapter 2, Section 2.3.2) were compressed to different bulk densities and equilibrated to different water contents ranging from air dry to the plastic limit water content for penetration testing. Soil was brought to predetermined water contents in 4 kg subsamples. The subsample was spread to 2–3 cm depth on a plastic sheet and wetted with a fine spray. The wet soil was hand mixed and pushed through a 5 mm sieve to break up any large aggregates. Each subsample was stored in a sealed plastic bag. The subsamples for a given soil horizon mix were sealed in a large plastic bag and placed in an air–tight container to equilibrate at constant temperature for 4 weeks. The range of water contents prepared varied from air dry to above the plastic limit for each soil horizon mixture.

Soil cores were prepared using the method described in Chapter 3, Section 3.3.2. The soil core was then placed in the compression tester. The diameters of the compressing pistons at either end of the core were approximately 1 mm less than the diameter of the cylinder, to limit friction between the pistons and the cylinder wall. The side of the compressing piston at the base of the core was scored with a millimeter scale from which the starting height of the core could be calculated knowing the length of the cylinder and given that the top surface of the soil was flush with the top of the cylinder.

From the initial manufacture of a core at a measured bulk density, adjustment was made to the final height in the compaction process to attain cores at desired bulk densities using,

$$h_{f'} = h_f \times \frac{\rho_b}{\rho_{b'}} \tag{4.1}$$

$h_{f'}$ is the desired final compacted core height, $\rho_{b'}$ is the desired final bulk density, h_f is the measured final compacted core height, ρ_b is the measured dry bulk density corresponding to the measured core height.

Soil cores were compressed at an initial rate of 10 mm per minute. As the desired bulk density was approached the compaction rate was stepped down to 1 mm per minute to give more accurate adjustment of final core height. The core contained by the central 75 mm long cylinder was used in subsequent penetration resistance measurements. Extension cylinders either side of this central cylinder were used to ensure that the 75 mm cylinder used for the penetration test was completely filled with soil and therefore of standard dimensions. The ends of the core were levelled flush with the cylinder with a flat, sharp edged instrument.

Soil cores were subsampled for water content after the cone index measurement. Cores were split open and approximately 20 g of soil taken along the centre line with a sharp edged spatula. Samples were dried in a microwave oven (Hankin and Sawhney 1978) and water content expressed as a mass ratio.

Penetration tests were made at a penetration speed of 5 mm per minute using a stainless steel cone with a smooth ground surface, a diameter of 6.42 mm and tip angle of 30°. The penetrometer used was half the linear dimensions of the standard B size cone specified in ASAE R313.1 (1983). Reduction in cone size was neccessary to reduce the confining effect of the containing ring walls.

Penetration resistance (kN) and distance moved by the penetrating cone from the soil surface were registered digitally on the compression testing machine (JJ Lloyd Mk5) and graphically on a flatbed plotter. Maximum penetration resistance, and the distance penetrated to reach this maximum were recorded for each core. The maximum penetration resistance (kN) was converted into cone index (kPa) by dividing by the base area of the cone.

Gypsum was mixed with soil (100 A 0 B and 75 A 25 B) at a rate of 0.003 kg kg^{-1} in a cement mixer. This rate represented field application at 5 t ha^{-1} mixed evenly through the top 10 cm of the soil profile. The water content was adjusted to slightly wetter than the lower plastic limit by adding water to soil in the mixer with a fine spray. The soil was then left to equilibrate in a constant temperature environment (20 ± 1^{o} C) for two months to allow time for gypsum to react. A range of water contents down to air dry were obtained by slow drying of the moist soil for varying lengths of time. The soil was left in sealed bags in a constant temperature environment for one month for soil water content to equilibrate.

4.3.3 Data Analysis

Two part linear functions were fitted to the field data of Barratt (1985) and laboratory cone index data at discrete levels of compaction. A multiple linear regression model was fitted to model cone index as a continuous function of void ratio and water content. The effect of gypsum application was determined based on an F test of the pooled versus combined individual error terms when the model was fitted to pooled and treatment data.

4.4 Results and Discussion

4.4.1 Field Data

Cone penetrometer values in the mouldboarded plot are lower and rate of increase with depth less rapid than those in the control tilled plot with the soil at the same average water content (0.10 $\pm$0.02 kg kg^{-1}) (Figure 4.1). Laboratory data (Section 4.4.2) indicate that soil horizon mixing should increase cone index (Figure 4.3) unless there were differences in water content and/or compaction between plots.

Cone index increases rapidly below the tillage depth (180 mm) on the non-mouldboard ploughed treatment (Figure 4.1). There may have been a similar increase in cone index beneath the mouldboard tillage depth (400 mm), however the penetrometer used in the study had a maximum working depth of 300 mm. Figure 4.1 shows that a change in packing state occurs beneath the tilled layer. This may tend to restrict the vertical growth of roots and will be more restrictive on shallower tillage treatments, since deeper tillage will increase the depth range freely penetrable by roots.

The greater penetrability of the mouldboard ploughed plot may be due to mouldboard tillage producing a less compact plough layer than chisel or disc implements. Barratt (1985) measured a consistent, but not significant, bulk density reduction in mouldboarded compared with non–mouldboarded topsoil . His bulk density measurements were confined to the immediate vicinity of three neutron water meter

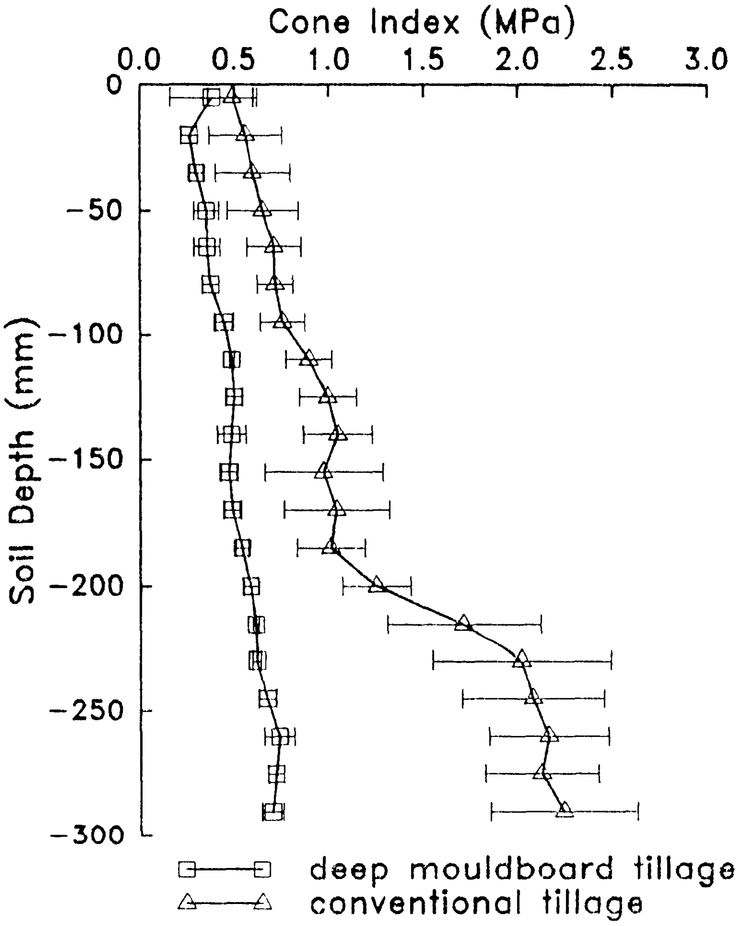

Figure 4.1: Average cone penetration resistance (cone index) as a function of depth for a deep mouldboard ploughed plot and a conventionally tilled plot on the Trangie Block 4A tillage trial, May 1985. The conventional tillage depth was 180 mm while the deep mouldboard ploughing depth was 400 mm. The water content is 0.10 kg kg^{-1} for both penetration curves.

access tubes inserted at the end of each plot. Bulk density and water content measurements directly related to penetrometer measurements are needed to conclusively determine the effect of mouldboard ploughing on penetration resistance in the field.

4.4.2 Laboratory Data

Cone index increased rapidly below a critical water content (Figure 4.2). The relationship between cone index and soil water content changed from linear to curvilinear below a certain void ratio. The data in Figure 4.2 was modelled with a two stage linear function which defined the critical water content as the point of inflection in the model. The critical water content for rapid CI increase (θ_c) for the field data is similar to θ_c for the A horizon laboratory data (Table 4.1).

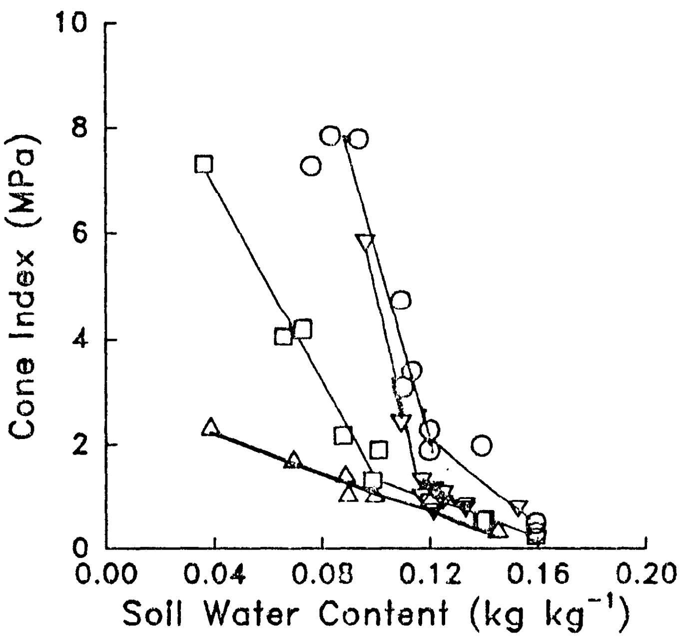

Figure 4.2: Laboratory cone index versus soil water content for the A horizon at three void ratios, △—△1.15 m^3 m^{-3}; □—□0.73 m^3 m^{-3}; ○—○0.55 m^3 m^{-3}; with field penetrometer data, ▽—▽0.66 m^3 m^{-3}.

Laboratory cone index measurements conformed with field measurements (Figure 4.2). θ_c for the field penetration data is not significantly different from θ_c for the laboratory data (Table 4.1).

Table 4.1: Values of θ_c (kg kg^{-1}) for field and laboratory data.

Soil	Study	Void ratio	θ_c	Standard deviation
A horizon	laboratory	0.55	0.12	0.01
		0.73	0.09	0.01
A horizon	field*	0.66	0.12	0.01
B horizon	laboratory	0.70	0.15	0.01
		0.96	0.16	0.01
		1.17	0.15	0.01

* Barratt (1985)

The change in strength behaviour as the soil is compacted may relate to pore size distribution changes. Transmission pores (>50 μm diameter, Greenland 1981) are the first pore size class to be reduced by compaction. Cone index has been found to increase rapidly once transmission pores are removed by compaction (Stitt *et al.* 1982). Thus, compaction causing a rapid increase in cone index as the soil dries may be related to the removal of transmission pores.

The void ratio, critical for rapid strength development as the soil dried, was 0.73 (m^3 m^{-3}) for the A horizon soil and 0.96 m^3 m^{-3} for the B horizon soil (Table 4.1). A two part linear relationship fitted the B horizon data at a void ratio of 1.17 m^3 m^{-3}, however root restricting penetration resistances do not develop.

4.4.3 Soil Horizon Mixing

Stepwise multiple linear regression was used to select a polynomial equation to fit the data. A logarithmic relationship between cone index and void ratio and water content gave the best fit to the data for each of the soil horizons and horizon mixtures:

$$\ln CI = a - b.n - c.\theta_g^2 + d.n.\theta_g^2 \quad (4.2)$$

where CI is cone index (MPa), θ_g is mass water content (kg kg^{-1}), n is void ratio (m^3 m^{-3}) and a, b, c and d are coefficients determined by regression (Table 4.2). A logarithmic relationship between cone index and void ratio is suggested by critical state soil mechanics theory (Section 4.2.1).

Table 4.2: Parameters of the cone index model $\ln CI = a - bn - c\theta_g^2 + dn\theta_g^2$ for each soil horizon mix. σ_a, σ_b, σ_c and σ_d are the standard deviations of the coefficients a, b, c and d respectively.

horizon mass fraction	a	σ_a	b	σ_b	c	σ_c	d	σ_d	r^2
100a 0b	7.65	0.42	-7.71	0.51	-360	52	309	62	95.3
91a 9b	8.65	0.70	-8.83	0.91	-384	54	366	77	91.6
75a 25b	7.91	0.54	-7.77	0.73	-235	37	198	62	87.2
50a 50b	8.38	0.50	-7.14	0.60	-265	25	201	30	96.5
25a 75b	7.67	0.60	-5.97	0.70	-215	25	150	29	94.3
0a 100b	7.62	0.33	-5.28	0.35	-192	15	128	17	95.8

The regression coefficients in Table 4.2 were used to model CI for a range of water contents and void ratios. The model shows that soil horizon mixing increases the water content at which cone index becomes limiting to root growth (Figure 4.3). A critical cone index of 2.5 MPa was used. This figure was obtained from the work of Ball and O'Sullivan (1982), which relates cereal yield to cone resistances in silt loam soils (see Section 4.2.3). For the soil horizon mixtures and the B horizon soil, at void ratios less than 0.7 $m^3\ m^{-3}$, critical strengths are attained at water contents wetter than the plastic limit (DCPL).

Cone index is an exponential function of void ratio, water content and an interaction term (Equation 4.2). For given values of void ratio and water content soil horizon mixing increases cone index. Compression tests show that soil horizon mixing increases soil resistance to compaction (Chapter 3, Section 3.4.3). It is now evident that this increase in compressive strength also involves an increase in resistance to penetration. Consequently, there may not be any increase in the penetrability of topsoil as a result of soil horizon mixing.

High soil penetration resistance was limiting to root growth in the non-mouldboard ploughed field soil. Barratt (1985) observed that cone index values greater than 2.5 MPa developed in the non-moulboard ploughed soil between irrigations but not on the mouldboard tillage treatments. Barratt (1985) found that the deep

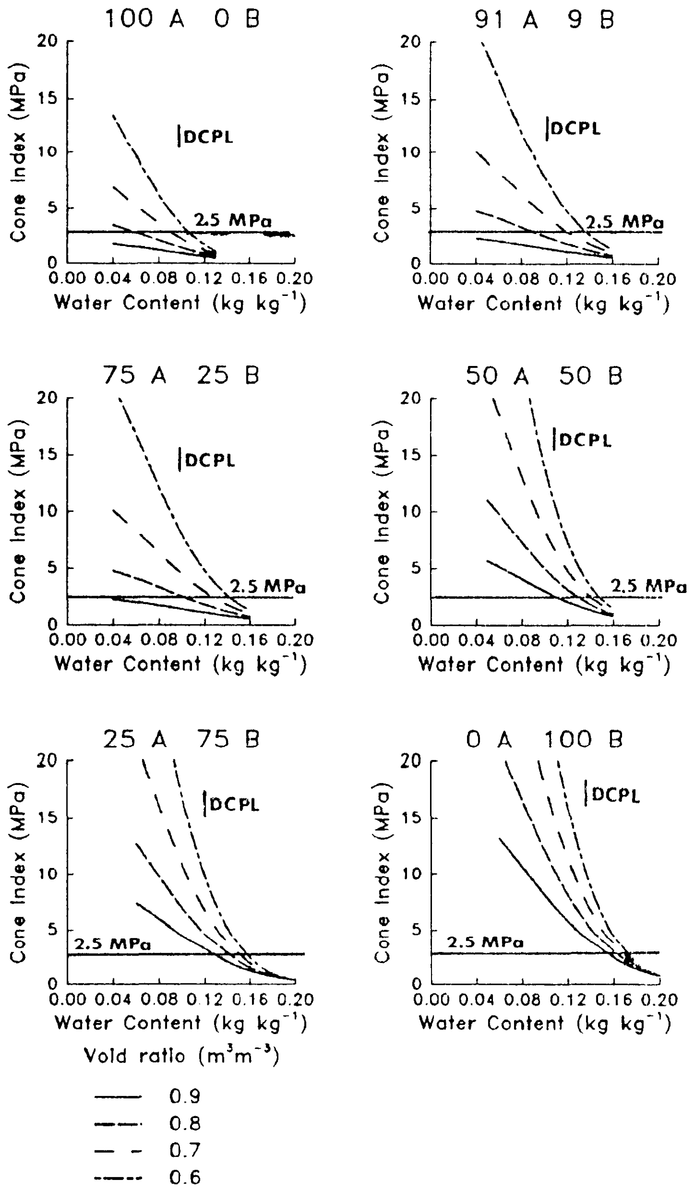

Figure 4.3: CI predicted with the model $\ln CI = a - b \times n - c\theta_g^2 + d \times n\theta_g^2$, versus water content, for the A and B horizons and the soil horizon mixtures. n is void ratio and θ_g is soil water content. The plastic limit (DCPL) and a value of CI which limits root penetration (2.5 MPa) are superimposed.

mouldboard ploughed topsoil was less compact than the control tillage treatment, however the difference was not significant. Field void ratios less than 0.7 m^3 m^{-3} were observed by Barratt (1985) and less than 0.65 m^3 m^{-3} by D. Hall (personal communication) on non–mouldboard ploughed plots. These void ratios are suboptimal for root growth according to the laboratory model (Figure 4.3). Barratt (1985) measured an average void ratio of 0.85 m^3 m^{-3} on the mouldboard ploughed plots. Soil at this void ratio should not restrict root penetration (Figure 4.3). This is consistent with evidence that mouldboard ploughing increased wheat yield in the first season relative to the control treatment but that this declined in subsequent seasons (D. Hall, personal communication).

The mouldboarded soil, though initially less compact, settled and compacted over time to give void ratios similar to those in the control plots. It would be expected that the mouldboarded topsoil would maintain a higher void ratio than the unmoulded topsoil (Section 3.6) if surface traffic is the only agent in the compaction process. The field observation suggests that some other compacting agent is involved. The A and B horizon soil slakes when saturated (D. Hall, personal communication). This would cause the aggregate structure created by tillage to disintegrate and allow primary soil particles to pack to similar void volumes as the soil dried after irrigation. Settling produces a more impenetrable medium for root growth.

Mouldboard ploughing appears to produce a transient reduction in void ratio. Chapter 2 shows that soil horizon mixing, and hence deep mouldboard tillage, increases soil resistance to compaction. However, compactness of the top 200 mm of soil does not vary significantly between tillage treatments one (Barratt 1985) and two seasons after deep mouldboard ploughing (D. Hall, unpublished data). This indicates that factors other than traffic are causing compaction, namely, weakly structured red–brown earths compact when structural aggregates slake as the soil is wet rapidly. Irrigation management for slow wetting and structural amelioration are needed to preserve the beneficial effects of loosening produced by deep mouldboard tillage.

4.4.4 Gypsum

Application of the equivalent of 5 t ha^{-1} of gypsum did not reduce the penetration resistance of the two soil horizon mixtures used in the study. However, gypsum application significantly increased yields in the first season after mouldboard ploughing as well as for non–mouldboarded field tillage treatments (D. Hall, personal communication). The beneficial effect of gypsum may be in its ability to stabilise the surface soil structure by increasing the resistance of aggregates to slaking so that open soil structure produced by tillage persists for longer.

4.5 Conclusions

- Compaction restrictive to root penetration occurs beneath the tilled layer in the field soil. The benefits of deep mouldboard ploughing may result from a deeper tilled layer which does not mechanically impede root growth.

- Cone index values measured in the laboratory on confined cores are not significantly different to field cone index measurements.

- Root restricting penetration resistances develop below a void ratio of 0.73 m^3 m^{-3} in the A horizon and below a void ratio of 0.96 m^3 m^{-3} for the B horizon soil. Compaction to void ratios less than these values may reduce soil fertility.

- Cone index is an exponential function of water content and void ratio. At high water contents void ratio has little effect on cone index. Both void ratio (or density) and water content have to be measured to model cone index.

- At any particular void ratio below the critical value, there exists a critical water content (0.12 for the A and 0.16 kg kg^{-3} for the B horizon) below which soil strength rapidly increases to values in excess of the limiting values for plant root extension.

- Soil horizon mixing increases soil penetration resistance. This will tend to counteract the beneficial effect of an increase in compressive strength on the resistance of the soil to compaction damage.

- The differences between mouldboarded and non–mouldboarded soil may initially result from differences in compactness such that deep mouldboard tillage reduces soil compactness and removes a mechanical restriction to root growth. However, both non–mouldboarded and mouldboarded soil compact over time to similar void ratios, indicating that compaction processes other than traffic compaction are at work, one of which is soil settling after rapid wetting.

- Gypsum application at a rate of 5 t ha^{-1} does not affect the resistance to penetration of the A horizon soil or that of a soil horizon mixture corresponding to horizon mixing performed by deep mouldboard tillage (75 A 25 B horizon soil).