Cranfield University at Silsoe

National Soil Resources Institute

EngD Thesis

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"Linking soil moisture status of winter sports pitches to measures of playing quality"

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Abstract

A review of traction and hardness Performance Quality Standard tests highlighted significant relationships with soil and grass factors. Inadequate guidance to achieve test results through pitch management means that management practices can not focus on injury prevention or playing quality. A clear link between factors that can be managed by Groundsmen and the traction and hardness tests is required.

The concept of effective stress significantly linked moisture status to soil strength in the laboratory. Penetration resistance was shown to be complex and affected by grass roots and bulk density, which prevented a single model encompassing all soil types to be established. Prediction of traction and hardness used grass and soil factors and varied according to soil type and wet or dry test conditions. *In situ* tests showed no variation due to pitch test position and as sand content increased, prediction became less reliable. A decision support model used the regression results to provide Groundsmen with the ability to monitor pitch quality in real-time.

Effective stress successfully linked moisture status and strength although *in situ* verification is required. Regression analysis and the decision support model will assist Groundsmen in managing pitches while targeting playing quality. Further research to understand how management practices impact on quality and to understand the link between injury rates and type, and the results of traction and hardness tests is required. This knowledge will enable a company to simultaneously differentiate itself from competition and create a barrier to potential entrants.

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Contents

Notation

Acronyms

APCST	Asia Pacific Congress on Sports Technology, Tokyo, Sept. 11-14th 2005
CL	Clay soil used in experimentation
CPT	Cone penetration test
E	Evenness (mm)
FA	Football Association
FC	Football Club
GC	Grass cover (%)
GL	Grass length (mm)
IOG	Institute of Groundsmanship
LA	Local Authority
LBD	Lower (50-100 mm) bulk density (Mg/m^3)
LCC	Log clay content
LFSC	Log fine sand content
LSC	Log silt content
M45	Mansfield 45 85:15 sand:soil rootzone material used in experimentation
MC	Volumetric moisture content (%)
MS	Medium sand (%)
PPV	Pay per view
PQS	Performance quality standards
PRG	Perennial rye grass
SSL	Sandy silt loam soil used in experimentation
STRI	Sports Turf Research Institute
TGMS	TurfTrax ground management services
UBD	Upper (0-50 mm) bulk density (Mg/m^3)
WRC	Water release characteristic

List of figures

List of tables

Chapter 1 Introduction

1.1 Football

Association Football (also known as soccer, hereafter referred to as football) is classed as the most popular national game in the UK according to a Mintel report (Mintel, 2000) which found that over 35% of 15+ year olds claimed an interest in it, consistent from 1996 to 1999. Its nearest rival, snooker, had experienced a decline over the same period. This sustained interest has been caused by a number of factors of which an increase in television coverage is most important. The introduction of ‘pay per view’ (PPV) options and a decline in hooliganism (measured by the number of arrests at football matches) has also had a significant effect.

Although increased viewing figures have resulted in substantial financial rewards to clubs, the money is concentrated at Premiership level. The 1999/2000 season showed an increase of 52% on the 1995/6 figure, totalling £458million. Admission prices have also increased in light of the ‘Taylor’ report into seating only stadia, as reported by Mintel (2000). There is increasing pressure on clubs to succeed and the wage bill of Premiership clubs often takes the majority of the operating profit. In 1998/99, Liverpool F.C spent 85.8% of their turnover on wages. The remaining balance was allocated across the rest of the business, from staff wages, to marketing and facility maintenance. Management of the pitch is not a priority in comparison with the need to meet players’ wages, yet the surface needs to withstand high intensity use, by professional athletes and still meet the aesthetic requirements that TV coverage demands, as a judgement on the quality of the surface is often based on appearance (Adams and Gibbs, 1994).

The aim of pitch management is not to simply produce a pitch that is attractive; the pitch must support play through a UK winter, characterised by cold and wet weather, while simultaneously supporting grass growth and enabling damaged grass to recover. A poor quality pitch is not only damaging to the reputation of the groundsman in charge, but can be the cause of injuries to players.

A full review of medical literature pertinent to sports injuries is beyond the scope of this thesis, however, concern regarding sports injuries, as a result of a poor quality playing surface, is a driver of this research. In the professional game the cost of losing a player through non-impact injury i.e. not through contact with an opponent, can be great. Each finishing position within each league holds a monetary prize and the higher up the league table a team finishes, the greater that prize is. Should a team lose a key player and as a result finish lower down the table, the quantity of money available to reinvest into the club in the following season is reduced. Should a club be relegated, the financial penalties are much greater. The cost of relegation from the Premiership at the end of the 2004/2005 season will result in £20,000,000 less income for the 2005/2006 season.

Injury issues are not exclusive to the professional game. The British Government has set itself two “overarching” objectives (DCMS/Strategy Unit, 2002): firstly to encourage the population to exercise more due to the estimated benefits gained via a reduction in costs to the National Health Service. The second target is to produce a sustainable improvement in international success to contribute towards a feel good factor which is claimed to generate benefits throughout society. The first objective is important in the context of this work; an increased rate of participation in sport must not be mirrored by an increase in the number of injuries from participation in sport. The estimated cost of inactivity is £2bn equalling 54,000 deaths per year, principally from coronary disease, diabetes and other obesity related issues. A 10% increase in adult activity could result in a saving of £500m a year and 6,000 premature deaths.

This saving is exclusive of the cost of injuries. The report highlights the need for more up-to date data; however 1991 figures show that the majority of injuries occurred in the male, 16-25 age group, with football accounting for 29% of all injuries recorded. The total cost of injuries was presented at £996m however; it is argued that injury rates should decrease as the standard of coaching improves and therefore the level of skill of the participant. No mention of the quality of the facilities is made.

In response to this drive towards increased participation, 14% of the £1.2bn lottery funds generated for sport have gone to football, while this has been further supported through direct government funds. Importantly, the DCMS report (2002) suggested that funding should be substituted for investment with measurable returns and meet performance targets. A pitch must be an investment by a Local Authority or school for example, and generate a return in order to sustain itself, while simultaneously being a focal point for the local community to increase social inclusion and reduce crime and enabling adult exercise to reduce the demands on the NHS.

It is therefore imperative that pitches are not hazardous to players and management techniques can improve the interactions between a player and the surface. It is feasible that targets will be different for a Local Authority managed pitch and a Premiership standard pitch, and this will be a direct consequence of the budget available. However, any pitch must be safe to play on and minimise the risk of injuries.

Something the pitch must not do is interfere with play or negatively affect the quality of the game. Hence, management techniques must aim to produce a safe pitch, but also produce a pitch that will enable an athlete to play at the best of their ability. The roll of the ball cannot deviate due to variations in surface quality and the athlete must be able to judge how far a ball will roll with the strength of a kick. When the ball is in the air, its landing must also be consistent and predictable. Acceptable ranges for ball bounce and ball roll should increase as the available budget for pitch management decreases.

The highlighted demands and the fear of escalating injury costs have further accelerated the change that has been slowly occurring in the sports turf industry for some time; the move towards a science-based approach to pitch design, construction and management. Research has been conducted on grass species for different sports at the Sports Turf Research Institute (STRI), in Bingley, Yorkshire, since 1929, while advances in the capability and quality of mowers for different sports have also continued. Many of these advances have addressed aesthetics; just one aspect of pitch management. What was required was a means of assessing the quality of a surface in order to ensure that the pitch was safe to play on and would not hinder the quality of the game.

1.2 Performance Quality Standards

Development of the current playing quality standards began in the 1980's. Shildrick and Dye (1983) presented a review of research which highlighted the need for further research into both the development of standards and a code of practice for groundsmen to achieve the desired quality rating. In 1985, a review of playing quality by Bell *et al.*, (1985) identified a need to produce tests of direct relevance to the player, which must be reproducible. The conclusion of this paper was that future research must set standards and limits of acceptability for tests which would analyse different aspects of playing quality for each sport and between sports. After the publication of this review, the STRI performed research to identify tests which would quantify pitch quality, and the range of acceptable values for each test. Overlapping this research, the Sports Council funded a project under the direction of Dr (now Professor) Bill Adams (Soil Science Unit, University of Wales, Aberystwyth) and carried out by Dr Richard Gibbs at the Soil Science Unit and Dr Stephen Baker at the STRI to determine the cost effectiveness of different pitch drainage designs. The STRI research related measures of surface conditions to player feedback, and as a result, established recommended limits. The Sports Council research utilised these limits and was reported primarily in the Journal of the Sports Turf Research Institute, and was also available as reports 1-11 from the Natural Turf Pitches Prototypes Advisory Panel, from the Sports Council. Only reports 6-11 were published, and report 11 was based on further study. Reports 6-10 detailed a four-season long study and report 10 was published in 1992.

Throughout this period, Peter Dury, in conjunction with Nottinghamshire County Council pioneered the introduction of standards by which Local Authority pitches were to be managed. This enabled contractors to receive details regarding the standard that pitches were to be maintained to, rather than a frequency-based specification. These eventually included the player-surface and ball-surface interaction tests, outlined by the STRI. In 2001 the Institute of Groundsmanship released a document detailing all of the relevant tests and the expected outcomes, given the desired quality (IOG, 2001). This document addressed every pitch based sport and also non-turf playing surfaces. The reactions to and adoption of these tests have been varied and the player-surface interaction tests will be discussed in greater detail in chapters 2 and 4, however, there are significant omissions from the document.

There are two player-surface tests (traction and hardness) and two ball-surface tests (ball roll and ball bounce); in the case of the traction test no upper limit was set. Given the torsional forces that are exerted on the knee and lower leg joints during turning while running, it is arguable that an upper limit should be present. This demonstrates that the subject of injury was not considered. Subsequent research has highlighted that excessive traction can be damaging; causing the foot to become ‘locked’ into the surface, transferring forces to the ankle and knee (Lees and Nolan, 1998), and it is arguable that the standards need to be revisited to ensure they are appropriate when considering player safety. Complicating this issue however, is the wide range of football boot designs and their interaction with the surface.

Perhaps most importantly, there are no guidelines to aid a groundsman achieve any of the targets that are presented, and therefore the code of practice, recommended by Shildrick and Dye (1983), is still missing. The outcome of pitch management techniques must be known with respect to their impact on the playing quality of the surface. This will have two main benefits;

- Groundsmen will know which management tools adversely affect the quality of the pitch, but may be beneficial for long-term aesthetic, or grass health, reasons, and these techniques can be timed around games or retained for use within periods of no play.

- The techniques that improve the quality of the surface will be known and therefore should the pitch not meet the required standard for any of the tests, the relevant tool can be used to remedy this.

The pitch, through targeted management must encourage player skill and technique while minimising the risk of injuries, regardless of construction type. It is vital therefore that soil is suitable for supporting sport and any performance criteria can be directly linked to the soil physical attributes in order that they can be managed in such a way that pitch targets can be achieved.

1.3 The role of the sponsor

TurfTrax Ground Management Services (TGMS), and the Engineering and Physical Sciences Research Council (EPSRC) co-funded this research. TurfTrax operates in a fiercely competitive market place, which is evolving as money for pitch development at local authority, school and amateur level becomes available through funding bodies such as Sport England and the Football Foundation. The funding structure and criteria for awards are due for renewal and will be primarily based on performance criteria. The need for high quality, sustainable pitches at cash-rich professional football clubs was traditionally where expensive solutions were used. Now through the availability of funds, such as lottery funding, elaborate and expensive solutions are being offered to those who previously would not have been able to afford it. This situation highlights two important issues;

- The market place in which TGMS operates is being flooded as potential entrants see the quantity of money being made available in order to upgrade facilities and wish to take advantage of this. Therefore, TGMS must be able to create a barrier to entry for potential entrants and set a high standard in terms of the ability to deliver high quality and sustainable solutions, as entry requirements into this market.

- The result of an investment in research must be used strategically to ensure a barrier to entry can be created, and this knowledge is then used to provide high-value solutions that competitors without the correct knowledge, are unable to imitate.

1.4 Aim

The aim of this research is to enhance the health and safety and enjoyment of the participants of football, at all levels of the game. Long-term, improvements in pitch quality will assist the Government meets its target for increased levels of exercise as better quality surfaces withstand more intensive use. Furthermore, improved understanding of the factors that directly impact on pitch quality may result in a lower incidence of surface-related injuries.

To address the practicalities of successfully implementing these principles, this work aims to identify how a consultancy-only firm, such as TurfTrax can incorporate research findings into their business model to achieve market share gains and create a barrier to entry to the market.

1.5 Objectives

To achieve this aim, the following objectives have been identified

1) Specify soil management considerations to achieve optimum player-surface interaction quality of football pitches in the UK, by

    a. Investigating the appropriateness of using the concept of Effective Stress to assess the impact of water on the strength of sports turf soil
    b. Determining the relationship between the current PQS measures for player-surface interaction quality and soil physical parameters
    c. Devising a model which enables easy-to-measure pitch parameters to be used to generate an indication of pitch quality

2) To detail appropriate strategic considerations that must be understood in order for a small consultancy firm to gain market share using the results of out-sourced research by:

    a. Identifying the driving forces in the market place and producing a detailed overview of the industry structure and its dynamics.
    b. Reviewing appropriate strategic options and highlighting which should be focussed on to increase competitive advantage and affect market share.

1.6 Thesis outline

To address the objectives outlined in section 1.5 this thesis will begin with a literature review detailing the tests used to determine player-surface interaction quality and their development.

Chapters 3 to 5 will be used to address objective 1; a to c. Chapter 3 will consider the soil as a support system for sport, incorporating a detailed literature review and laboratory-based experimentation. Chapter 4 will detail *in situ* experimentation used to identify whether the laboratory experiments can be verified *in situ*, and to generate data in order to establish a link between the soil moisture status (and other measured parameters) and the outcome of the two tests for quality. Finally, chapter 5 will utilise the results of chapters 3 and 4 to develop a management tool for groundsmen, by linking a measure of the moisture status of the soil to its quality.

Chapter 6 will address objective 2 using a detailed investigation into the market structure of the sports turf industry followed by an outline of the strategic options available to a small business in order to maximise its return on investment in research.

Chapter 7 will be a concluding discussion addressing each thesis element, and will include conclusions and recommendations for further work.

Chapter 2 Quantification of sports pitch quality

2.1 Background

Quantification of pitch parameters in a repeatable, scientific manner has been a recent development and the current standards are still being integrated into the sports turf industry. They are presented as a viable means of managing construction contracts, or as a basis for identifying pitches in need of renovation work, but often in a watered-down form, such as the Sport England publication on sports pitch improvement strategies (Sport England, 2005).

An employer must make ‘every reasonably practical effort’ to ensure the health and safety of employees while at work (HMSO, 1974). For the professional football player, the football pitch is his or her place of work; therefore the pitch must not be a hazard[1] to health. Furthermore, a recent study has shown that football carries a risk of injury 1000 times greater than high-risk industrial occupations and only marginally less than the risk of injury from rugby, which is a contact sport (Hawkins and Fuller, 1999). This study failed to incorporate PQS measures of pitch quality but it highlighted that 7 years after the publication of a four-season case study into performance standards, sponsored by the Sports Council (Baker *et al.*, 1992), and 14 years since standards, similar to the current standards, were first proposed (Bell *et al.*, 1985), sports injuries were still a major factor in football, and separating those caused by the surface from those caused by contact with other players, was difficult to achieve.

Injuries to the leg are the most frequent sports injuries and it is argued this is a result of the knee and ankle joints being placed under excessive load (Milburn and Barry, 1998), with one study claiming that injuries to the knee and ankle ligaments account for 71% of ball-sport injuries (Heidt *et al.*, 1996). Significant to this research is the proportion of these injuries that can be attributed directly to the surface conditions. Ekstrand and Nigg (1989) suggested that this was the case in 24% of all football

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[1] According to the Health and Safety Executive (HSE) a hazard is anything that presents the possibility of danger (HMSO, 2001).

(soccer) injuries, although they were unable to isolate a single cause, suggesting there was an association between a number of factors, particularly different training and match surfaces and inherent muscular and joint factors.

Sports injury studies have considered the hazards to players at a football ground from the various fixtures that are necessary around the perimeter of a pitch (Fuller and Hawkins, 1997), or the effect of footwear on injury potential (Milburn and Barry, 1998), but none have linked injuries to measures of pitch quality. Indeed, the 1974 Health and Safety Act predated any of the research funded by the Sports Council, into the performance of pitches with different drainage designs and yet absent from reports 6-11 of the Natural Turf Pitches Prototypes Advisory Panel (Baker *et al.*, 1990; Baker *et al.*, 1991; Gibbs *et al.*, 1991a; Gibbs *et al.*, 1991b; Adams *et al.*, 1992; Adams, 1996) (reports 1-5 were unpublished) is any suggestion that a pitch may be a hazard to players, or that different pitch construction types may vary with regard to player safety. The link between player-surface interaction tests and the injury potential of a surface was absent.

Also absent from the PQS guidelines, is an obvious path from pitch management to the achievement of a particular level of quality. Whether, to manage a pitch to improve on an unsatisfactory quality rating or to maintain a quality rating that is desirable for the standard of game it supports.

Regardless of these limitations, measures of pitch quality do exist, therefore before investigating the relationship between soil strength and soil moisture status (chapter 3) and then developing a methodology for predicting the quality rating of a pitch (chapters 4 and 5), a detailed review into the two current methods of establishing the player-surface interaction quality of a pitch is presented in this chapter. This review will examine the historical development of standards, before considering the two player-surface interaction tests and the manner in which they have been used and reported in previous studies, with particular emphasis on their relationship with soil physical conditions.

2.2 Performance Quality Standards (PQS) – a review

2.2.1 History

Stewart and Adams (1968) began the introduction of the quantification of performance characteristics in their 1968 publication into the performance of County standard cricket wickets. It is in this paper that they link the pace of a cricket wicket to the clay content of the soil, as determined by a simple test, called the ASSB[2] test, which has become known as the 'MOTTY' test. Arguably forward-thinking for its time, it did not set a trend in relating sports surface performance to soil physical properties in the way suggested 17 years later by Bell *et al* (1985). Instead, research papers continued to test the hardness of playing surfaces using the heel[3] method while Thornton (1973) described the different degrees of 'squelchiness' underfoot on the different subplots under observation. However, by the 1970's a number of soil factors were being considered and in a paper presented by Baker (1985) he outlined research that been reported in the Journal of the STRI which had considered soil permeability, bulk density, porosity, air-filled porosity, chemical composition, mechanical analysis and soil strength, since the late 1960's. Thornton did attempt to quantify the 'squelchiness' using a shear vane but by 1975, Canaway (1975) had developed equipment to determine traction and this was used to quantify soil strength.

Dury (Dury, Pers. Comm.) described how as early as the 1950's, managers of sports grounds, particularly in councils where contracts were put to tender to manage pitches, required a basis from which to assess the quality of the completed work. The IOG attribute the early pioneering work in standard development to Peter Dury (2004), while Adams and Gibbs, attribute this to the STRI (Adams and Gibbs, 1994). Peter Dury and Nottinghamshire County Council (through the departments of County Playing Fields Service and Sport and Landscape Development) identified the need to use standards in the specification of contracts. In the 1980's the Sports Council (now Sport England) provided funds for research. This research was conducted by the Soil Science Unit at the University of Wales, Aberystwyth, in conjunction with the STRI

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[2] Adams and Stewart Soil Binding test.

[3] A subjective measure of the resilience of the turf to the heel of ones foot developed in Germany.

and the results made available through a range of Sports Council publications, and through the Journal of the STRI.

In 1985, standards and their development began to filter through to the readers of the STRI journal and attendees at sports turf conferences. Baker (1985) discussed how a range of parameters were investigated over four years in order to determine standards for a variety of sports, and this work, separate to the Sports Council project, started in 1983, while later works were still debating which tests to perform, how they should be performed and what the acceptable range of values should be (Bell *et al.*, 1985; Holmes and Bell, 1986). The publication in the STRI journal of the results of the investigation into playing quality standards, took place before the four-year period identified by Baker (1985) had elapsed (Baker and Bell, 1986). Even so, the report detailed the process that was used to determine the acceptable ranges of values and introduced for the first time the need for different values for different levels of the game. The levels proposed were National, Regional and Local.

Interestingly, there were a series of contradictions in the paper. Firstly, the objectives clearly stated (objective f, page 10) that tests should utilise existing equipment where possible and the equipment chosen for that study were selected from the review performed by Bell *et al.,* (1985). By 1985 the traction test equipment had evolved from the original apparatus (Canaway, 1975) into the modified apparatus, reported by Canaway and Bell in 1986 . The designs differed in the stud layout on the base of the metal disk; the original version used studs at different distances from the centre point of the disk, on the modified version the six studs were placed at 46 mm radii and at 60° spacing. In the article by Baker and Bell (1986), the old method of determining traction had been used. Secondly, the evaluation of hardness had been conducted using a Clegg hammer (Clegg, 1976) in the original investigation (Baker, 1985), however, the study by Baker and Bell (1986) used a 5.5 kg sphere, dropped onto the surface. Finally, rolling resistance was to be measured using a standard 1 m high ramp and a ball rolled down it and onto the turf. The distance it rolled from the base of the ramp determined the rolling resistance. During the study, the influence of wind adversely affected results and the test equipment was altered from standard equipment in use already, to timing gates and the deceleration of the ball measured electronically.

The advantage of the study by Baker and Bell (1986) was the manner in which the research findings were linked to player feedback on the surface. The study was able to create a 'team' of players from the Football League which visited each ground at the time the tests were conducted. The results were not complete due to player availability and the variety of pitch types made selecting limits difficult, although those proposed were not too dissimilar to those outlined by the IOG (2001).

After the publication of this report, there were many subsequent papers published which investigated performance standards and attempted to determine limits and acceptable ranges. One study investigated the effect of rootzone composition on playing quality and was reported yearly over a period of three years and in two journals (Baker and Isaac, 1987b; Baker *et al.*, 1988; Baker, 1989a). 2 m x 2 m subplots were constructed with 16 different rootzone mixes and subjected to simulated wear (by machine) over a 3 year period (Baker and Isaac, 1987a). During the three years hardness, traction and ball bounce were monitored, although ball roll resistance was omitted. It was suggested that this was due to the influence of wind (Baker and Bell, 1986), although the 2 m x 2 m trial plots in place at the STRI research centre would have inhibited the use of a ball roll ramp. In these reports, test methods were almost identical to current tests and the paper demonstrated the strong inter-relationship between factors, such as ground cover and traction ($r = 0.82$ $p < 0.001$) and hardness and ball bounce ($r = 0.70$, $p < 0.001$), but the papers also highlighted the effect of rootzone mixture and construction type, concluding that sand rootzones produced surfaces that were of superior playing quality, as long as fine sands were used.

After the report by Baker and Isaac (1987b) was published, recommendations were made to the Sports Council which proposed values and acceptable ranges for two player-surface interaction tests (traction and hardness) and two ball-surface interaction tests (rebound resilience and distance rolled) quoted in Baker *et al.,* (1988). These limits, were used in subsequent research to understand which factors in the construction of sports surfaces, affected the outcome. Interestingly, the earlier recommendation by (1986) had not been followed and different ranges for different levels of play had not been used, instead, 'acceptable' and 'preferred' ranges were presented. Baker *et al.,* (1988) demonstrated that, based on the results of the PQS tests and the frequency with which the results fell into the ideal[4] category, pitches with less than 90% sand would not be suitable for intensively used pitches.

The development of standards had been conducted to determine pitch quality suggesting that at values outside this range a match may be cancelled due to poor conditions. The notion of player safety was never explicitly stated, nor that a game should be cancelled on the grounds of player safety, instead it would be to minimise further pitch deterioration. During a 1988 conference on the characteristics and safety features of playing fields, Canaway *et al.,* (1990) presented the research that contributed to the report to the Sports Council, a year earlier. Once again player surveys were linked to the standard of the pitch as determined by the tests, the tests were by now standardised and included the modified traction equipment and the 0.5 kg Clegg hammer. The majority[5] of the players in this study were from college/university teams and were arguably less sensitive to changes in surface conditions, compared to full-time professionals. Regardless, the paper justified and presented proposed standards for the four tests discussed above, and for evenness (expressed as a deviation, in mm, from a straight edge). Interestingly, the notion of setting a standard for ground cover was discounted; however, this is present in the current standards. The standards proposed were as follows (Canaway *et al*., 1990)

	Units	Preferred Range	Acceptable limits
Rebound Resilience*	%	20-50	15-55
Distance rolled**	m	3-12	2-14
Surface traction***	Nm	>25*	>20*
Surface hardness****	g	20-80	10-100
Evenness*****	mm	8	10

Table 2.1 1988 Performance Quality Standards

* Percentage ball rebound from a drop height of 3 m.

** Ball roll distance from a 1 m high ramp.

*** Torsional shear force using apparatus described in 2.2.3.1. No upper limit.

**** Peak deceleration of a 0.5 kg weight from a 0.3 m drop height. See 2.2.3.2.

***** Calculated as the maximum deviation from a straight edge, this standard was only proposed.

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[4] It is unclear why the term ‘preferred’ has been replaced with ‘ideal’ within the same paper.

[5] No figures were presented with the pie chart

Once standards had been formally introduced, research became more focussed. Using the standards and limits outlined in Table 2.1, Baker and Gibbs (1989) were able to quantify the reduction in quality due to the intensity of play on a variety of pitch types and therefore able to justify recommendations for optimum levels of use.

In 1992 the final report sponsored by the Sports Council was published in the Journal of the STRI and also as a separate Sports Council publication (Baker *et al.*, 1992). It detailed a four-season investigation into the usage levels and playing quality of a variety of pitches; similar to the 1989 study by Baker and Gibbs (1989); it used the same pitches, but analysis occurred over a longer time period. In this paper, the appropriateness of the tests was not discussed; therefore, by 1992 the tests had been accepted as a viable means of determining quality. In 1994, Clegg Hammer drop height was increased to 0.55 m for tests on rugby grounds (McClements and Baker, 1994) and was subsequently adopted for football also (Baker, 1999). The limits presented by Baker were as follows;

	Units	Preferred Range	Acceptable limits
Rebound Resilience	%	20-50	15-55
Distance rolled	m	3-12	2-14
Surface traction	Nm	>25*	>20*
Surface hardness	g	55-140	35-200
Evenness	mm	<8	<10

Table 2.2 1999 Performance Quality Standards.

* No upper limit is suggested

During the 1990's Peter Dury attempted to bring the new standards to the attention of Groundsmen via regular articles in the industry magazine 'The Groundsman'. In September 1995 an article questioned if performance quality standards are the way forward (Dury, 1995a). The article discussed how the standards should be implemented and their future benefits. However, the article was confusing; it did not focus on the objectives of standards or heavily on the benefits to Groundsmen of working to standards, instead, it passed the manner in which standards could be utilised onto the client or the contractor. Had the standards been presented in a structured, positive manner, with direct benefits to Groundsmen and users of the pitch highlighted, they may have experienced more rapid uptake.

Also unclear, is why the proposed standards altered but were not reported anywhere, instead featured in an article in the December 1995 issue of the same magazine (Dury, 1995b). The standards had been separated according to the level of the game they were intended for and the value ranges adjusted accordingly; increasing and pitch quality decreased:

	Units	High	Standard	Basic
Rebound Resilience	%	25-45	20-50	15-55
Distance rolled	m	5-12	3-12	2-14
Surface traction:				
Start of season	Nm	≥45*	≥40*	≥35*
At all times	Nm	≥25*	≥20*	≥20*
Surface hardness	g	65-120	55-140	35-200
Evenness	mm	<12	<18	<25

Table 2.3 Performance standards presented by Dury (1995b)

* No upper limits given

In an August 1996 article, frustration is evident in the opening line; "why are we still same mistakes today we made 40 years ago?" (Dury, 1996). In the article he argued that science had not produced the progression in playing quality that it should have, considering the amount of scientific research that had occurred during the development of standards. During the mid-1990's, Dr Fuller (at the time) from Loughborough University was discussing the implications of the health and safety legislation already in existence, to the professional sports person, in particular concentrating on football players (Fuller, 1995). The subsequent study by Hawkins and Fuller (1999) failed to include playing quality measures of pitches. Had these two ideas met in 1995/1996 and injury rates were investigated with reference to measures of pitch quality, the battle to push quality standards into the scope of the groundsman, may have been easier. Instead, the pitch conditions (wet and dry) were monitored and not discussed in the final report. Further evidence of the need for standards, consistent pitches and the financial implications of injuries came from Drawer and Fuller (2002). They produced a model based on data collected over 4 playing seasons and 91 league clubs. Again, the parameters did not include PQS measures of pitch quality, but the model (based on significant correlations between parameters) demonstrated that as player availability reduced due to injuries, financial losses to the club increased.

2.2.2 Current standing of measures of playing quality

After the 1997 publication on how to manage sport facilities (Dury, 1997), which collated many of the articles that appeared in ‘The Groundsman’ in the preceding years, Dury retired from Nottinghamshire County Council and the council handed ownership of the standards to the Institute of Groundsmanship (IOG). Furthermore, the governing body for each sport influenced the standards and the involvement of both the STRI and the IOG made implementing and maintaining the standards particularly complicated (Dury, Pers. Comm.). Dury did manage to extend standards further than just playing quality and the Performance Quality Standards, first released by the IOG in 2001 and revamped in 2003 contain targets for items such rootzone depth, bare areas and herbage quality.

The current standards for the player-surface and ball-surface interactions are as follows (IOG, 2001) and unchanged for 2003:

	Units	High	Standard	Basic
Rebound Resilience	%	32-42	25-45	20-55
Distance rolled	m	7-10	4-12	2-16
Surface traction:				
No less than	Nm	40*	30*	20*
Surface hardness	g	65-120	55-140	35-200

Table 2.4 Current PQS guidelines for the player-surface and ball-surface interactions

* No upper limit given

Research by Magni *et al.,* (2004) used the same playing standard tests in order to determine the performance of different construction methods, sand types and grass mixtures. The standardisation of test methods has broadened the research pool from which knowledge can be gained but the biggest drawback has been the inability of the IOG to market the standards effectively (Ford, Pers. Comm.).

Two high profile bodies within the industry have recently adopted measures of playing quality. Sport England is providing funds, through the national lottery, to upgrade sports facilities in order to meet the British Governments sport participation targets. Assessment of the current state of a pitch is used to determine whether an application for funds should be submitted and a few of the PQS tests must be conducted (Sport England, 2005). Although only one player-surface and no ball surface interaction tests were included, the tests determine the quality of the pitch prior to improvement, determine the quality of pitch at ‘hand-over’ (immediately after renovation work has been completed) and one year later.

The second body to adopt the use of playing quality standard tests was the Football Association (FA). The standards are the same as those used by Sport England and were developed in conjunction with Sport England and the STRI. The recommended minimum values for a ‘club site or park’ (Football Association, 2004) are given, however the standards used are those for basic quality pitches even though their use is being touted for club pitches. This wide range of values (see Table 2.4; ‘basic’) is not suitable for club level football; hence the reason for the three levels of quality. The narrow range of figures in the ‘high’ category is to minimise the variability in the surface, which should improve its safety. It seems that again, player safety at the top level of the game is still not considered a priority by the governing bodies.

Dury argued repeatedly (Dury, 1995a; Dury, 1996; Dury, 1997) that standards had to be flexible, adapted to site conditions and the extent of the client-contractor relationship. He attempted to demonstrate that standards at the start of the playing season would be unrealistic during the middle of the season and an attempt was made to incorporate this into his version of the standards (see Table 2.3; ‘traction’). He argued that a full PQS analysis should be conducted at the start of the season or once per year and subsequent visits should be simplified in order to gain a overview of the conditions at that time (Dury, Pers. Comm.). This represents Dury’s background in Local Authority and council operated pitches. It is arguable perhaps, that in the professional game where the athletes have to perform regularly on natural turf pitches, ‘high’ standards should apply at all times.

2.2.3 Player-surface interaction tests

2.2.3.1 Traction

The absence of a quantifiable, repeatable test for surface traction (also referred to as surface friction) was highlighted by Canaway (Canaway, 1975). In response, equipment was designed to simulate and measure rotational forces on the turf. A 150 mm diameter metal disk of 12 mm thickness had six football boot studs attached to the underside. The spacing of the studs was equal, but their distance from the centre point varied in order that they did not overlap. Once weights were applied (45 kg + the weight of the test equipment), the unit had to be lifted and dropped from a height of 0.25 m. Results were presented as a turf coefficient rather than a torque reading. By 1986, both torque readings (Holmes and Bell, 1986) and turf coefficients (Baker and Bell, 1986) were being used, making the results of studies difficult to compare. From 1987, torque values, in Nm were predominantly used. A further modification was the use of a compression spring to exert pressure on the disk, rather than weights. This was presented in a paper outlining the need for tests to be consistent and use existing methods; it seems the spring was only used once (Baker and Bell, 1986). At the end of the 1975 paper, Canaway, discussed the possibility of using studs spaced equally and at identical radii from the centre.

The modified traction equipment, detailed in the British Standard for assessing artificial turf playing quality (BSi, 1990), was detailed 11 years after the original (Canaway and Bell, 1986) in response to a number of drawbacks of the original. Canaway argued that the stud pattern complicated analysis, the short shaft (32.5 cm) made usage and transportation of the equipment difficult, the one handled torque wrench made operation awkward and variation in drop height between operators resulted in variation in the results. The redesigned equipment featured identical disk dimensions however the six studs were set at 46 mm radii and spaced at 60°. Applied weights were standardised to 40 kg[6], a two-handled torque wrench was recommended and the shaft made longer and incorporated handles to aid lifting and dropping.

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[6] Although this was altered to a total equipment weight of 46±2 kg in BS 7044-2.2:1990 (BSi, 1990)

This design of traction equipment has been used in all studies after 1986 where traction was measured including recent research in Europe (Grossi *et al*., 2004; Magni *et al*., 2004).

Traction and soil moisture content

The study by Baker and Bell (1986) established moisture content from cores taken at the time the mechanical tests were conducted. The relationship between (the original) traction test is not explored further, but using the data presented, the correlation can be determined. Conversion of the results to a torque reading used a rearranged version of the formula provided (Canaway, 1975: 108) and correlation analysis used Microsoft Excel. The data were separated into regions of the pitch; goal mouth, centre circle and wing and the correlation coefficients were 0.83, 0.75 and 0.27 respectively (see appendix I). Positive correlations were also presented by Bell and Holmes (1988) and although significant ($p<0.001$) were weak (0.16). Two years earlier, Holmes and Bell (1986) showed negative correlations between traction and moisture content using the original and modified[7] traction equipment. They were -0.25 and -0.40 respectively and were both significant ($p<0.005$). They also used multiple regression to identify the linear relationship between traction and the ground conditions ($R^2=0.72$) although the regression was not utilised further;

$$\text{Traction (Nm)} = 36.28 + 0.286\,\text{Ground Cover (\%)} - 0.354\,\text{Moisture content (\%)} - 1.374\,\text{Roughness (s)} \quad \textbf{(Eqn 2.1)}$$

Finally, Baker (1991) demonstrated that traction values decreased for increasing moisture content on 1:0.5 (sand:soil) rootzones when ground cover was between 21 and 100 percent, but at <20 percent ground cover, traction increased as moisture content increased. On the sand-only rootzones, traction increased with increasing moisture content up to 30 percent groundcover, while there were no relationships on sand between traction and moisture content over 30%. The cause of these results were not clearly discussed by Baker, but highlighted the overall trend that traction reduced as ground cover was lost.

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[7] This was not the modified equipment, but the original equipment with a spring to exert force, rather than weights.

Traction and grass factors

Research investigating the relationship between traction and grass species showed perennial rye grass to provide significantly ($p<0.05$) greater traction values than creeping red fescue and colonial bentgrass (Canaway, 1975). Conversely, Canaway (1983) demonstrated that perennial rye grass exhibited significantly lower traction values than creeping red fescue, but tests were performed on different rootzone materials. McNitt *et al.,* (2004) demonstrated that variation between species existed and perennial rye grass and red fescue were not significantly different, although the use of different traction equipment made comparison difficult.

Where grass was maintained at lower cutting heights, traction increased (McNitt *et al.*, 2004), although the authors did suggest that time was an important factor as the plants had to adapt their morphology; only after this adaptation would traction values be higher. The studies by Canaway (1975; 1983) maintained a single cut height throughout the trial, while the study by Bell and Holmes (1988), which formed the basis of the recommendations to the Sports Council, did not consider the effect of grass length nor grass species on traction values. Richards and Baker (1992) investigated the effect of sward height on ball roll, and simultaneously measured traction and hardness. They discovered no discernible relationship although initial results (1990) demonstrated a reduction in traction values as grass length increased, while in May 1991, this pattern did not continue. Even at sward lengths of 125 mm or more, traction values were within the preferred range.

Holmes and Bell (1986) presented correlation coefficients for the original and 'modified'[8] traction equipment against grass cover and both were significantly positively correlated; 0.55 and 0.67 respectively ($p<0.001$). Baker and Isaac (1987b) used the modified traction equipment and determined a correlation coefficient of 0.82 ($p<0.001$) which was attributed to the effect of grass roots, rather then the above ground biomass directly. van Wijk argued that the effect of grass roots could still be

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[8] Although called 'modified' the equipment used the same stud pattern as the original, however, a spring was used to exert pressure, rather than weights.

noticed, even after ground cover percentage had dropped (1980). Bell and Holmes (1988) suggested that low traction values recorded on the wing areas of the pitch could be due to increased ground cover, although their correlation coefficient was positive (0.67 $p<0.001$). Reduced traction due to reduced grass cover was noted by Baker and Gibbs (1989), while the final paper on the same study (Baker *et al.*, 1992) ground cover and traction correlations were not performed. In a study of rugby pitches, McClements and Baker (1994) did investigate the link between traction and ground cover (measured using a reflectance ratio meter rather than the method outlined in BS 7370 (BSi, 1991)) and established a correlation coefficient of 0.44 ($p<0.05$).

Finally, a recent study investigated the effect of biomass accumulation on traction values and the effect of different management practices (Sherratt *et al.*, 2005). Although the equipment proposed by Canaway and Bell (1986) was used in the study, the results were not discussed. Using a similar piece of equipment with shorter studs (12.7 mm compared to 15 mm), the authors noted that topdressing increased traction due to the increase in the density of the thatch and concluded that traction would be determined by the surface components, rather than conditions below the surface.

Traction and rootzone construction type

Holmes and Bell (1986) compared a soil-based pitch against a sand-carpet construction method. The sand carpet construction gave consistently higher traction readings than the soil based pitch, and the range of values was more uniform. Statistics were not presented, however the mean values were 52.4 Nm for the sand-based pitch and 28.6 Nm for the soil-based pitch while the moisture content for the sand-carpet pitch was half that of the soil based pitch throughout the study (21.3 % and 43.2 %). Increasing traction was significantly correlated with decreasing moisture content (-0.25 and -0.40) for the original and spring-loaded version respectively. The study by Baker and Isaac (1987b) demonstrated that traction values varied between sand-only and sand-soil mixed rootzones, but this was also dependant on wear and moisture content. Overall however, they detected the lowest traction values for the pure sand plots, especially after intensive wear. In wet conditions, the lowest recorded values were from 1:0.5 (sand:soil) mixtures. Grass establishment was problematic on sand rootzones due to poor nutrient status (1989b), however on sand based constructions, every attempt must be made to achieve adequate cover. It was shown that on medium-fine and medium-coarse rootzones, traction increased linearly with increasing ground cover, producing correlation coefficients of 0.95 and 0.96 respectively.

The papers by Baker and Gibbs (1989) and Gibbs and Baker (1989) and final paper based on the project, by Baker *et al.,* (1992), investigated 6 different pitch constructions at two sites in the UK in a study that formed the basis of the current performance standards. Although detailed soil investigations were conducted (Gibbs and Baker, 1989), the results were not explicitly linked to the playing characteristics of the surface. Ground cover and traction were both measured but no attempt was made to correlate the results in the early study, no attempt was made to link the particle size distribution to any of the test results while a measure of the overall quality was determined and this was shown to vary for each pitch construction type (the most commonly occurring rating was ‘B’; Approximately equal to the ‘acceptable’ range previously described), but the results of individual tests were masked by the grouping method. Traction test results were related to the prevailing weather conditions and degree of wear on the surface, while on sand-based surfaces, traction values were low due to break-up of the soil surface in heavily worn areas. The final report in 1992 (1992) focussed on usage intensity and the range of values for the standards, however data demonstrated that traction values fell below the optimum on all pitch construction types throughout the four-season long study.

In a study on rugby pitches, McClements and Baker (1994) investigated the relationships between measures of playing quality and pitch construction type and soil physical conditions in detail. Particle size analysis enabled the correlation between traction and the percentage of clay, sand and silt to be determined. There were no significant relationships between soil texture and traction, leading to authors to reiterate the conclusion that traction is more closely related to ground cover.

2.2.3.2 Hardness

Prior to the development of a test to determine the intrinsic strength of a surface to compactive forces, methods such as the ASSB or MOTTY tests were used, or the resilience of the turf to the heel of a shoe were used to qualitatively assess the strength of the surface. The heel test was utilised by van Wijk (1980) to assess surface resilience and rated on a scale of 1 to 10. A score of 7 was indicative of a surface condition suitable for football use. The disadvantages were in the repeatability of the observations and the need to use a single tester.

Although initially developed for pavement base course evaluation, the Clegg hammer (Clegg, 1976) was an engineering option for the turf industry that overcame the problems highlighted by van Wijk, and others. The 0.5 kg weight (hammer) housed an accelerometer which was dropped from a fixed height, inside a tube. On contact with the ground, the hammer decelerated and a value in gravities (g_{max}, simply known as g) was provided on the digital read-out. Harder surfaces caused more rapid deceleration than soft surfaces and thus the g figure was higher for harder pitches.

It was first utilised by the STRI in a four-year football study starting in 1984 (Baker and Isaac, 1987b) and discussed further by (Bell *et al*., 1985). Lush (1985) reported the benefits of using the hammer on cricket pitches in Australia, although she noted unexpected results and concluded that the weight of the hammer and contact area with the ground may need to be adapted for each sport.

The STRI experimented with other methods such as the DIN 18035 part 6 method devised in Germany called the Stuttgart Artificial Athlete (cited inBell *et al*., 1985), and a Sports Council method that utilised a 5.5 kg sphere containing an accelerometer (cited in Baker and Bell, 1986), but the Clegg hammer became the preferred method of assessing hardness.

Researchers elsewhere however were using different hammer weights. In the UK, the hammer weight was 0.5 kg (dropped from 0.3 m initially then raised to 0.55 m from 1994 (McClements and Baker, 1994) onwards although (Baker, 1994) chose 0.3 m drop height), but American research investigated the use of 0.5, 2.25 and 4.5 kg weights (Rogers III and Waddington, 1990) dropped from 0.47 m. They discovered that the 0.5 kg weight was affected by vegetation and cutting height, but the results from the 2.25 kg hammer were strongly correlated with those from the 0.5 kg hammer. They did not draw a conclusion with regards to the selection of a particular hammer weight, but more recent American research used a 2.25 kg hammer (McNitt *et al.*, 2004; Miller, 2004).

Hardness and soil moisture content

The relationship between pitch or surface hardness (as measured using the Clegg hammer) and the soil moisture content at the time of the test, has only been considered in a few studies. The general trend is that Clegg hammer readings reduce as moisture content increases. This has been shown with correlation statistics -0.28 (NS) (Holmes and Bell, 1986) -0.51 ($p<0.001$) (Bell and Holmes, 1988) -0.85 (p not given) (Baker, 1989b) -0.38 ($p<0.05$) (McClements and Baker, 1994) and-0.34 ($p<0.01$) (McNitt *et al.*, 2004). Generally hardness decreased as moisture content increased, although Baker and Isaac (1987b) argued that this was more pronounced in rootzone mixtures containing soil. Sand based rootzones did not exhibit such a marked decline in hardness through the playing season. Baker (1989b) also suggested that excessive hardness, encountered on sand-based rootzones, could be ameliorated with irrigation.

Hardness and grass cover parameters

Studies have investigated the correlation between hardness and percentage grass cover (Holmes and Bell, 1986; Baker and Isaac, 1987b; Bell and Holmes, 1988; McClements and Baker, 1994) giving coefficients of 0.46 ($p<0.001$; $n=72$), 0.07 (NS; $n=160$), -0.16 ($p<0.001$; $n=650$), -0.38 ($p<0.05$; n unknown) respectively. Some results suggested an increase in hardness with increasing grass cover, some suggested a decrease.

Baker and Isaac (1987b) separate their data by sample date and found that the overall non-significant result of 0.07 (see above) became -0.26 ($p<0.05$; n unknown) for October. This suggested cushioning in the early part of the season when ground cover was high. The idea of grass cushioning the impact of the hammer is also argued by Richards and Baker (1992) who found a general trend of reduced hardness with increasing sward length. Although not explicitly discussed, the data presented by Baker *et al.,* (1988) showed the greatest hardness values to be concentrated in the centre and goal areas of the pitch, with the lowest values concentrated to the wing area. The centre and goal areas are areas of intensive wear in soccer and grass cover would have been reduced. The lower numbers on the wing supports the argument that the grass may have cushioned the impact.

The influence of vegetation on pitch hardness was discussed by Rogers III and Waddington (1990) who tried to eliminate the effect of vegetation and measure only soil surface hardness. This led to the selection of a 2.25 kg hammer. While Sherratt *et al.,* (2005) demonstrated that practices such as verticutting and scarification (both practices to thin the grass sward) increased hardness values.

Hardness and rootzone construction methods

Holmes and Bell (1986) demonstrated that sand-based pitches gave almost identical hardness readings to soil based pitches, however, the soil-based pitches exhibited greater variability across the pitch. Later research (Baker and Isaac, 1987b) showed that significant differences existed between pure sand and sand-soil pitches at different mixing proportions, although a soil-based pitch was not included for comparison. The same study was reported repeatedly (Baker, 1989b).(Baker, 1991) The conclusion to the 4-season long study into the appropriateness of the proposed standards and the levels of use different construction types could withstand, failed to explicitly state the relationships between hardness and construction type, as with traction, the results were masked in an overall assessment of pitch quality. However, data demonstrated that all six construction types produced hardness readings below and in excess of the maximum recommended limit, throughout the period of study.

In 1994, McClements and Baker presented for the first time correlations between hardness and the quantities of sand, silt and clay. No significant relationships were present.

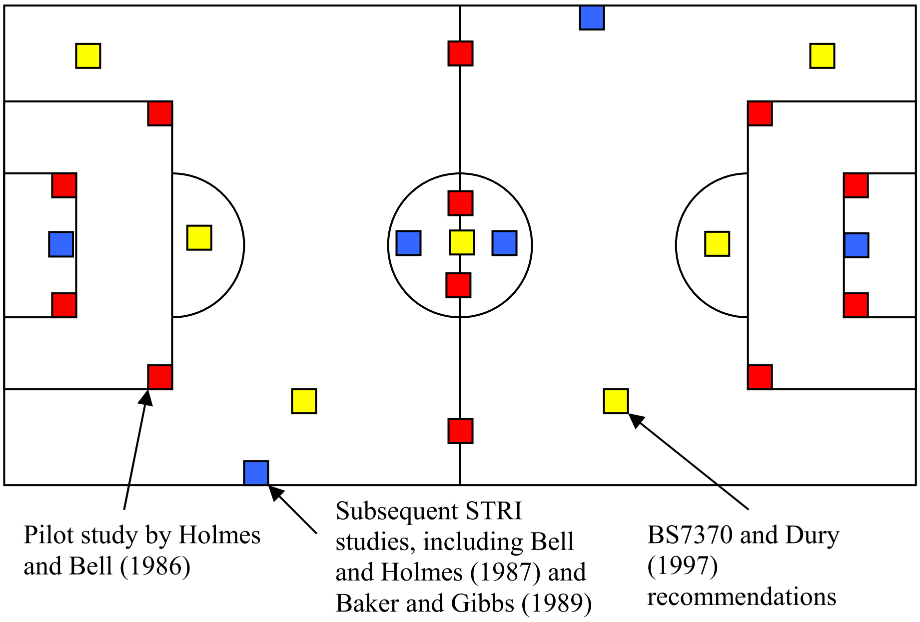
Few studies have sufficiently studied the effect of management practices or researched the effect of management practices on the quality rating of football pitches. The grass cover component with respect to the degree of traction or surface hardness (Baker and Isaac, 1987a; Reyneri and Bruno, 2004) has been studied although neither study recommended aeration or decompaction routines to alleviate this. Baker and Canaway (1992) investigated the effect of top dressing on playing quality, discovering variations in quality depending on the rate and particularly the timing of additions while Baker (1994) attempted to determine the effect of slit tining on traction and hardness, and presented mixed results. Traction test results reduced with frequency of aeration on one occasion on one pitch throughout the study, and hardness was significantly reduced on two occasions with increased tining frequency and increased significantly once. The reasons for this anomaly were not discussed further.

2.2.3.3 Pitch test locations

Pitch wear patterns generally follow a diamond-shape (Adams and Gibbs, 1994) and pitch tests must ensure a representative sample of the pitch has been analysed. A recent study used a complex and labour-intensive system, taking samples at each intersection of a grid laid out over the pitch (Miller, 2004) however this would not be feasible for regular testing, especially for commercial purposes.

Initial STRI investigations conducted tests at 12 pitch locations (Holmes and Bell, 1986), although for subsequent studies this was reduced to 6 with three in each half of the pitch in the same locations; one test in each goal mouth, one test in each half of the centre circle and one test in two of the opposing corners (Bell and Holmes, 1988; Baker and Gibbs, 1989). Four test positions have also been used (Cereti *et al.*, 2004).

In contrast, the BS 7370 (BSi, 1991) method is recommended by the IOG (IOG, 2001) and Dury (Dury, 1997) for conducting a detailed site investigation. The methodology is a minimum 7 point analysis following a ‘W’ pattern across the playing surface.



Pilot study by Holmes and Bell (1986)

Subsequent STRI studies, including Bell and Holmes (1987) and Baker and Gibbs (1989)

BS7370 and Dury (1997) recommendations

Figure 2.1 Historical positions of PQS tests on a football pitch

Figure 2.1 demonstrates how the pilot study by (Holmes and Bell, 1986) was over-detailed while the reduced intensity testing (blue squares) incorporated the key wear areas on the pitch. The downside with the BS7370 methodology is that heavily worn areas outside of the centre circle were missed as the methodology requires an assumption of a uniform site. Sampling on the basis of wear also has drawbacks due to differing grades of wear across the surface.

2.2.3.4 Overall quality assessments

Following test completion the overall quality of the pitch was determined. The method devised by Baker *et al.,* (1988) required both player-surface interaction tests to fall within the 'ideal' range for the pitch to be classed accordingly. If one parameter fell outside this range, the overall quality would be classed as 'acceptable'. The same method was used to decide if a pitch was acceptable or unacceptable. These do not equate exactly to the current High, Standard or Basic quality levels as the ranges are slightly different (see Table 2.2 and Table 2.4).

Contrary to the idea of consistency advocated by Bell *et al.,* (1985) another new method was devised by Baker and Gibbs (1989). The method utilised four grades A, B, C and F where grade A pitches had all test values in the desired range (corresponding to ‘ideal’). Grade B pitches exhibited values in the desired range and some in the preferred range (approximately equal to the ‘acceptable’ range), while grade C pitches exhibited values outside the acceptable range, failing the test, but were unlikely to cause a game to be cancelled. Pitches that failed all tests and were considered unfit for play were classed as F.

Instead of utilising either of these two methods, Coriani (2004) developed a scoring system for the change in playing quality before and after the Euro 2004 championships, on one of the football pitches used. The three quality classifications were high, standard and basic and points for each were 5, 3 and 1 respectively. The pitch was scored before and after the competition and although equipment failures prevented all tests being conducted before and afterwards, the author noted a ‘moderate’ reduction in playing quality.

2.3 Chapter Summary

The development of performance quality standards has been haphazard and their history difficult to piece together, made more complicated by the few studies by the STRI generating many similar reports, published in their own journal and others. There has not been a clear, systematic investigation into the link between the results of the tests and injury rates. The 0.5 kg Clegg hammer had been shown to be affected by the above ground biomass and yet a heavier hammer was not recommended. Traction tests have yet to be correlated with non-contact knee and ankle injuries to establish whether the current standards are protecting players. Furthermore, there has not been a clear investigation into what may affect the outcome of the tests and how a pitch can be managed to optimise quality. Some reports, it was shown, did consider soil particle analysis and the physical condition of the soil, but failed to relate the results to test results. Others did collect soil specific data particularly moisture content, but the analyses suggested above were not conducted.

What is required is a thorough study which investigates the player-surface interaction tests (as these are fundamentally based on the soil condition either directly through compaction, or indirectly as a medium for grass to thrive) and their relationship with soil physical conditions.

Although not a consideration of this study, the need to establish the link between injury rates and type, and the quality of the surface is paramount. The decline in competitive balance between football teams (Michie and Oughton, 2005) suggests that to succeed, a club must be able to select a team from a squad that is not limited through injuries. Once the surface and soil factors that directly impact on the outcome of the tests are known and can be used to predict the quality of a surface, studies regarding the aetiology of sports injuries should incorporate these measures.

Chapter 3 Soil as a support system for sport

Chapter 2 reviewed the research and development of the two tests for player-surface interaction quality. It was shown that results varied according to pitch construction type and moisture content and that the relationship between soil physical conditions was generally unclear. However, the results of PQS tests for player-surface interaction quality were influenced by soil conditions. The traction test considers the rotational force required to shear soil using a studded metal plate. Hardness tests measure the deceleration of a hammer dropped from a set height onto the surface to assess its ability to resist deformation. Playability and perhaps injury potential is a function of soil strength. Reference was also made to studies that have linked the results of PQS tests to the moisture status of the soil using correlation coefficients, although resultant relationships were used to suggest management practices.

It is understood that soil strength changes with changing moisture status; therefore this chapter investigates the appropriateness of using moisture status as a predictor of soil strength. Moisture status of the soil can be easily measured and managed through intensive drainage or irrigation and it may therefore be feasible for player-surface interaction quality to be established on a real-time basis if a link between moisture status and strength can be established.

3.1 Soil strength

For a sports pitch to offer a player grip on the surface, and the ability to turn, accelerate and decelerate, the surface must offer a degree of traction (Adams and Gibbs, 1994). Traction as a performance criterion for sports surfaces is measured in Nm (see chapter 3) and measures the resistance of soil particles to move over other soil particles while under load, the resistance to this type of failure is termed shear strength (Smith and Smith, 1998). Where an applied external force exceeds the (maximum) shear strength of the soil, failure will occur.

The Coulomb equation is used to predict soil strength and although Kezdi (1974) suggests this is a simplification of reality, determining the extent of every factor that influences soil strength is almost impossible. The Coulomb equation presented by Kezdi is as follows:

$$\tau = \sigma \tan \Phi + c \qquad \textbf{Eqn 3.1}$$

This linear relationship for the shear strength of the soil (τ) is made up of two parts; the internal friction (tanϕ) and *c*, the cohesion properties of the soil. σ is the normal stress applied to the soil.

Internal friction is proportional to the normal stress acting on it (Kezdi, 1974) and this will vary according to variations in applied load (Smith and Smith, 1998). Baver *et al.,* (1972) suggest that two processes work towards increasing the angle of internal friction; the resistance to sliding of one particle over another and the interlocking of particles. To move interlocked particles greater force will be required in order to move the particle vertically then horizontally over the other particle. Cohesion is the shear strength at zero normal stress (Kezdi, 1974), however this will vary for a given soil type (Smith and Smith, 1998). The relationship between these factors is demonstrated by Figure 3.1 below:

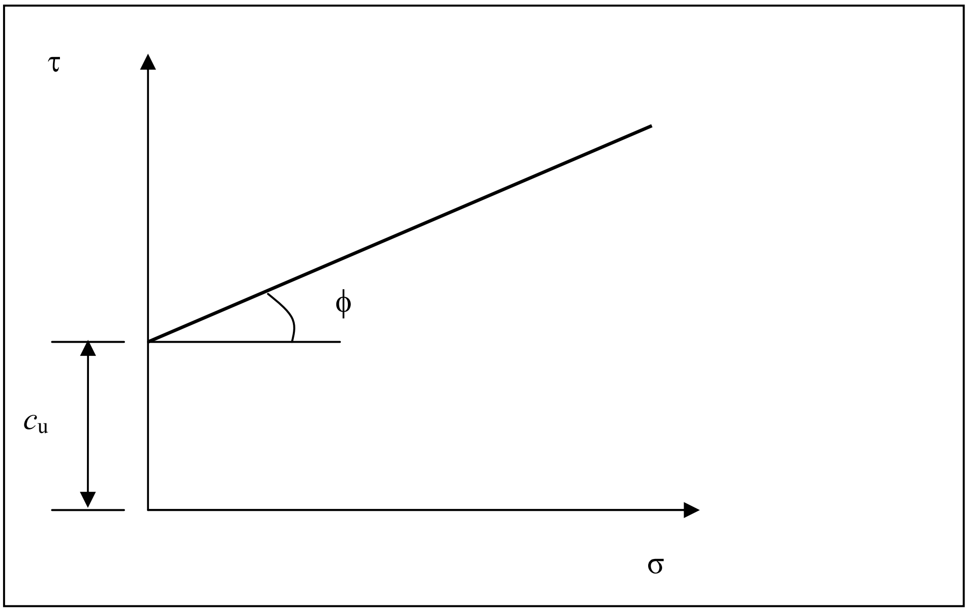


Figure 3.1 Coulombs Law of soil shear strength. C_u is the shear strength of a soil when the normal stress equals zero.

Figure 3.1 shows that with increased normal loads (σ) the strength of the soil increases. As Baver *et al.,* (1972) argued, this is the result of more force required to move soil particles over other particles and the applied load will also resist volume changes.

This equation has been used to provide satisfactory predictions for sands and gravels although clays have been less successfully predicted. Smith and Smith (1998) argue that this is due to the drainage conditions and the rate of the applied load to the soil. However Kedzi (1974) and 24 years later, even after presenting reservations, Smith and Smith (1998) both suggest it provides satisfactory prediction results and its use can be confidently applied in general soil strength calculations.

Saturated conditions

Strength normally decreases with increasing moisture content as bonds holding soil particles and structural units together are weakened (Marshall *et al*., 1996). The forces themselves may be weakened or the sites of attraction are damaged by the loosening effect of excess moisture in the soil. Furthermore, the strength of the soil can be increased by making the soil pore water pressure more negative (Smith and Smith, 1998). These authors detail the work of Terzhagi (1883-1963) who pioneered research into effective stress (σ'). He demonstrated that an increase in applied normal stress (Δσ) is proportional to increases in pore water pressure (Δu) and these two values are equal. He concluded by arguing that only a fraction of the applied stress is responsible for measurable changes in soil volume and the difference between the applied stress and the pore water pressure is the *effective stress*.

Marshall *et al.,* (1996) demonstrated that when pore water pressure is positive, the applied load will not be supported wholly by the soil and hence the effective stress will be less than the normal stress:

$$\sigma' = \sigma - p \qquad \textbf{Eqn 3.2}$$

In a soil with no normal load (or applied stress) the equation can be written as;

$$\sigma' = -p \qquad \text{Eqn 3.3}$$

Soil failure in unsaturated conditions

Under unsaturated conditions, Hillel (1990) argues that the soil has no pore pressure, only matric potential, although previous (Bishop and Blight, 1963; Kezdi, 1974) and subsequent authors (Marshall *et al*., 1996; Smith and Smith, 1998) have continued to use the term pore pressure when dealing with unsaturated conditions. To emphasise that pore water pressure is negative (i.e. gauge pressure is negative) and soil water is held under tension, the term matric potential will be used.

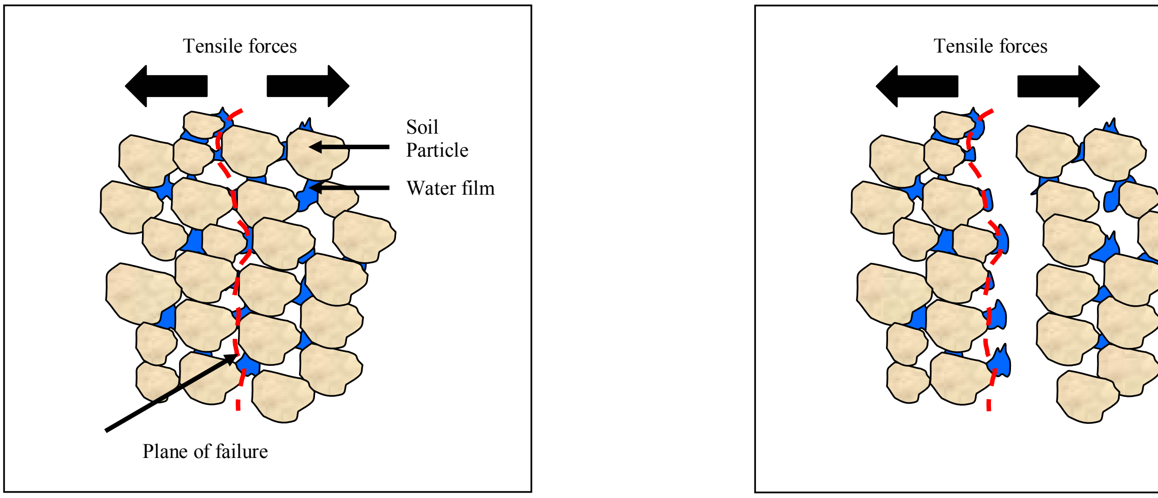


Figure 3.2 Tensile failure in unsaturated soil. The left figure shows the unsaturated soil matrix before being placed under a tensile stress. The right hand figure shows the result of the tensile failure. The relative saturation term equals the number of water films along the plane of failure.

Water that remains in the soil after drainage is held under tension and this contributes to the strength of the soil. Figure 3.2 shows the resulting plane of failure if the soil is placed under stress in opposing directions and the soil mass is pulled apart. The water films along the plane of failure equate to the relative saturation of the sample. This is a function of the water release characteristic (WRC) of the soil being tested; with increasing matric potential, relative saturation will decrease, but the water will be retained under greater tension. However, this relationship is not linear; the reduction in relative saturation with increasing matric potential will match the WRC for a given soil and is a function of the pore size distribution. This phenomenon can be investigated further with the use of the closed-form equation presented by van

Genuchten (1980). Figure 3.3 shows the WRC of an example clay and sand soil, based on values for those soils presented by van Genuchten:

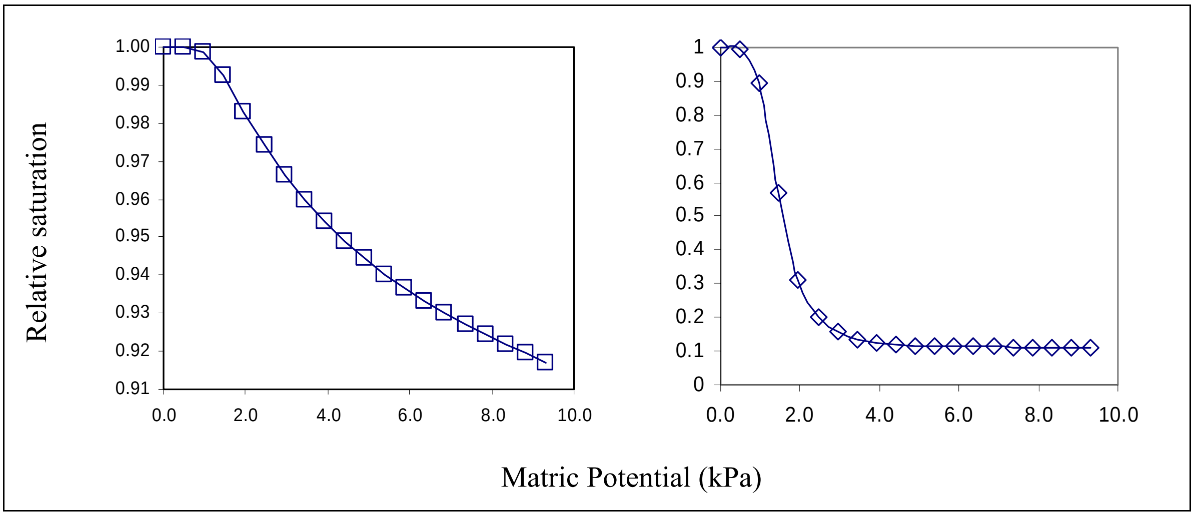


Figure 3.3 the effect of increasing matric potential on the relative saturation of an example clay (-□-) and sand (-◊-) dominated soil

Figure 3.3 demonstrates the effect of the pore size distribution in each soil and its effect on the water release characteristic. The heavy textured clay soil, dominated by fine particles and small pores has a higher relative saturation at a given matric potential than the sand soil. The sand is characterised by large particles and large interconnected pores that are of a diameter that drain rapidly as matric potential increases. The concept of effective stress indicates that as relative saturation decreases and the water retained within the soil is held increasingly tightly, the strength of the soil increases where sufficient quantities of small pores exist.

The application of the concept of effective stress to unsaturated conditions has been an on-going debate. Many authors presented theoretical arguments for its existence, even as early as 1925 (Haines, 1925) but it was not until a conference in 1960 that all the schools of thought were brought together to address the issue (Jennings and Burland, 1962). Their subsequent paper, based on experiments using silt, silty sand and a silty clay at a variety of matric potentials, presented the following formula for effective stress;

$$\sigma' = \sigma + \chi P'' - u_a$$ **Eqn 3.4**

P" indicates matric potential (termed pore water pressure deficiency by the authors) and u_a is the pressure in the gaseous phase of pore fluid. The factor χ was intended to take a value between zero and one and would be a function of the relative saturation (*S*) of the soil with an assumption that $\chi = S$. A value of unity would equal a fully saturated soil and zero would equal fully dry. Only one year later, Bishop and Blight (1963) questioned the validity of the above equation and presented their own:

$$\sigma' = \sigma - u_a + \chi(u_a - u_w)$$ **Eqn 3.5**

Where u_a is pore air pressure and u_w is the water pressure. Eqn 3.5 attempted to combine the two stress variables that constitute effective stress using the same correction factor χ. By assuming pore air pressure (u_a) equals zero, the formula was simplified by Mullins and Panayiotopoulos (1984), to:

$$\sigma' = \sigma + \chi\psi$$ **Eqn 3.6**

In Eqn 3.6, matric potential (ψ) has been substituted in favour of pore water pressure term ($-u_w$). A study by Bradford *et al.,* (1971) demonstrated that overburden pressures significantly affected root development only under very high densities, or when the root mass was greater than 1% of the soil-core cross sectional area. If these criteria are not met, Eqn 3.6 can be simplified further to:

$$\sigma' = \chi\psi$$ **Eqn 3.7**

Under conditions near the wet end (Mullins *et al.*, 1992) and dry end (Weaich *et al.*, 1992) of the water release characteristic from the same soil, a positive linear relationship between effective stress and penetration resistance was established using Eqn 3.7.

The χ factor

The difficulty was determining a value for χ that would satisfy this equation in order to generate a reliable prediction equation. Jennings and Burland (1962) investigated the possibility that $\chi = S$ and discovered that there were critical values of relative saturation, after which the model failed. The critical values of χ varied from as low as 20% for sand, to 40-50% for silt and as high as 90% for clay. Furthermore, they concluded that the experimentally determined values of χ had “little relation” to the values of χ required to satisfy the equation. This work however had been conducted on volume changes to the soil. It was assumed that these relationships would apply equally well to measures of shear strength.

In response to this, Bishop and Blight (1963) suggested for the first time that effective stress for use in shear strength predictions is more reliable than predicting volume changes, due to shear strength being primarily controlled by the inter-granular forces at the time failure. The authors also attempted to satisfactorily determine values for χ and concluded that this did change as relative saturation changed (S) and that $\chi = S$ for all soils, breaking down at a ‘cross-over’ point between χ and S. Similarly to Jennings and Burland (1962) they found the relative saturation limits varied between soil types and concluded that the cross over occurred at higher degrees of saturation as clay content increased. The different degrees of saturation were found at similar matric potentials; furthermore, there had been an assumption that compressive (applied) stress and matric potential had the same effect on pore water pressure.

Building on the argument by Bishop and Blight, Smith and Smith (1998) highlighted the work by Wheeler and Karube (1995) to argue that the determination of a single effective stress equation was impossible due to water in fine textured soils being held so strongly that it is effectively part of the soil skeleton. Any estimation of effective stress based on S will be too high and an alternative was needed.

The difficulty with a single correction value (χ or S) to encompass all soils is demonstrated by Figure 3.3; at the same matric potential, relative saturation will be different and therefore the effective stress will also be different, for two different soils. This can be displayed further by Figure 3.4, which highlights not only the difference in effective stress (kPa) between the two soil types, but also the presence of a localised peak in soil strength under low matric potentials for sand. After which soil strength diminishes rapidly before beginning a steady rise.

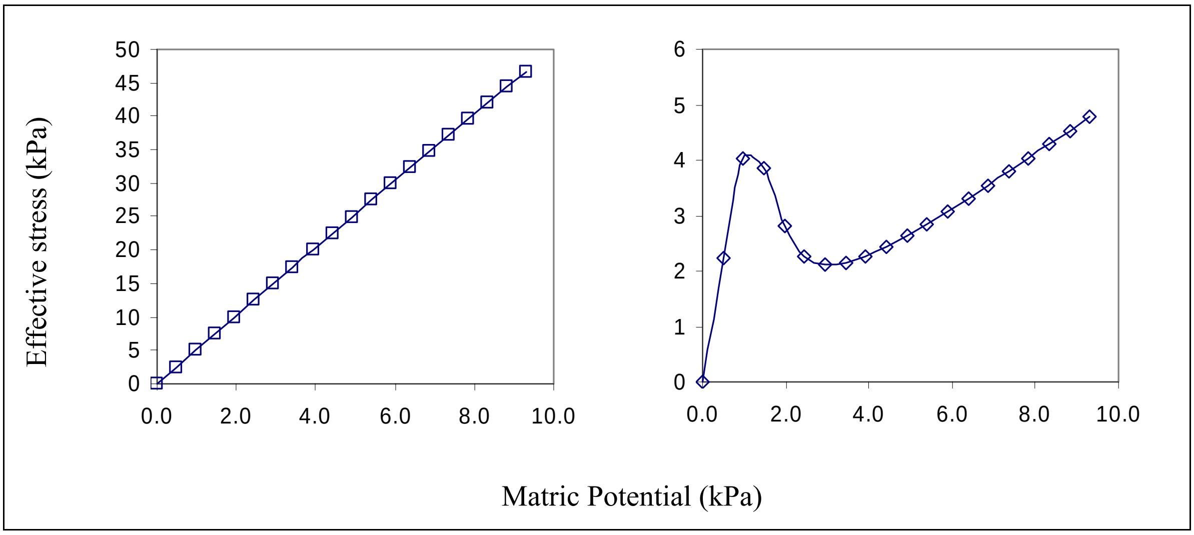


Figure 3.4 The effect of increasing matric potential on the effective stress of an example clay (-□-) and sand (-◊-) dominated soil

Alternative approaches to determine σ'

In 1965, Barden presented an alternative approach that Smith and Smith (1998) recommend for soil engineers; not using an χ factor to encompass all soils, instead to separate the stress-state variables and determine each for a given soil. Barden separated S into five increments to predict the consolidation of clay. He concluded that when $S \geq 0.9$ the soil behaved as if it was saturated and $\sigma' = (\sigma - u_w)$. As an exception, for fine soils drier than this recommended optimum, $\sigma \neq (\sigma - u_w)$ and would actually become $\sigma' = \sigma$ in very dry soil.

As an extension to the above work, Fredlund and Morgenstern (1977) developed the theory that soil is a four phase system: soil particles, air, water and a contractile skin (the air-water interface). They developed stress state parameters measurable through the application of multiphase continuum mechanics to a cube of soil, assumed to be in continuum. As a result they created two independent stress matrices for the soil particles and contractile skin, using the water phase as a reference. They suggested that the air phase or the total stress could be used as a reference and this gave rise to three possible normal stress variables for defining the stress state of the soil. They are

1) ($\sigma - u_w$) and ($u_a - u_w$); 2) ($\sigma - u_a$) and ($u_a - u_w$) or 3) ($\sigma - u_a$) and ($\sigma - u_w$), of which any two could be used.

They verified, through experimentation on a limited range of soil types, that the theoretically proposed stress state variables did fit the proposed model. Later, Fredlund and Rahardjo (1993) based all of their analysis on unsaturated soils on this principle, removing the need to determine a single-valued effective stress equation for predicting soil shear strength, but for the model to work the pore air pressure was required, therefore its use was primarily in laboratory assessment.

Predicting soil strength using σ'

Mullins and Panayiotopoulos (1984) used a simple concept of effective stress (Eqn 3.7) to predict the strength of hardsetting soils, manufacturing soil samples from a sand/clay paste using coarse and fine sand, then performing triaxial compression tests. They accepted the assumption that $\chi = S$, although they did present the limitations of doing so. For fine grained soils, a reliable prediction was gained, for coarse material it was less reliable, however, as they were studying cracking, they suggested that the cause of cracking in the coarse material was by propagation, rather than tensile failure and thus affected the results. They derived the following formula for tensile strength determination:

$$Y = c + \chi\psi \qquad \textbf{Eqn 3.8}$$

Y is the predicted tensile failure stress, *c* is the cohesion in the sample, χ is assumed to be equal to *S* and ψ is the matric potential. They suggest that despite the agreement between measured and predicted data being limited, the general trends and relationships between moisture content and strength and pore water pressure and strength is well explained.

Further work by Snyder and Miller (1985) altered the equation presented by Mullins and Panayiotopoulos (1984) (Eqn 3.8) in two ways; they removed the cohesion component (*c*) element and added a term to represent the shape of pores and cracks in the soil (*f*(*S*)). Presented using the nomenclature of Mullins and Panayiotopoulos, the equation is as follows;

$$Y = \frac{-\chi\psi}{\left(f(S)\right)}$$

Eqn 3.9

It assumed pore water pressure deficiency was equal to matric potential, and this coupled with the adaptation for the shape of pores and cracks, did explain the variability in failure patterns on unsaturated soils. The removal of the *cohesion* was disputed in a later paper by Mullins *et al.,* (1992) who argued that in saturated, heavy textured soils, cohesion is evident and may be due to the strength of adsorption bonds between particles. As a result, the formula was adapted once more to;

$$Y = c - \frac{\chi\psi}{f(S)}$$

Eqn 3.10

Eqn 3.9 and Eqn 3.10 both attempted to incorporate soil factors into the determination of soil strength using effective stress. The work presented by Fredlund and Morgenstern (1977) then developed further by Fredlund and Rahardjo (1993) suggested that this simple modification was still not suitable for predicting the tensile strength of the soil. They presented the following equation for shear strength of unsaturated soils:

$$\tau_{ff} = c' + (\sigma_f - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi^b$$

Eqn 3.11

Where

τ_{ff} = Shear stress on the failure plane at failure

c' = Effective cohesion (when normal

stress is zero)

$(\sigma_f - u_a)_f$ = Net normal stress on the plane of failure

ϕ' = Angle of internal friction of the net normal stress variable

$(u_a - u_w)_f$ = Matric potential on the failure plane at failure

ϕ^b = The angle of the rate of increase in shear (relative to $(u_a - u_w)_f$)

The use of this equation would require that the pore-air pressure is known at the start, which is assumed to be the same at failure and possibly the case in soils with a well connected pore system connected to the soil surface. Under these conditions, air pressures can easily dissipate in the soil and return to equilibrium.

More recently, Whalley *et al.,* (2005) applied the simple concept of effective stress suggested by Mullins and Panayiotopoulos (1984), Eqn 3.7, to predict penetrometer resistance in unsaturated soils, although simplified further by removing the normal stress term (σ) to reflect an assumption of zero soil overburden in shallow penetration depths. Utilising six remoulded soils, a rotating and fixed penetrometer was used to determine the relationship between penetration resistance and effective stress. Data were log-transformed to remove variability in the residuals; however, a good linear agreement was detected between effective stress (labelled σ_e rather than σ') and penetration resistance (kPa). The model failed to encompass all soil types at high bulk densities and this, it was concluded, was a function of reduced void space, into which displaced soil particles could be accommodated.

3.2 Laboratory investigation

Constructed football pitches are typified by shallow drainage schemes, often no more than 40cm deep. The low matric potential this creates would suggest that effective stress could be used to predict the strength of soil on a sports pitch.

The method selected to determine soil strength was the penetrometer. Although the concept of effective stress was developed for use in tensile failure situations, the studies by Mullins *et al.,* (1992), Weaich *et al.,* (1992) and Whalley *et al.,* (2005) demonstrated that a linear relationship between penetration resistance and effective stress existed. To justify the selection of the cone penetrometer, the following arguments are presented;

1. Field evaluation of the relationship would be required therefore laboratory and *in situ* methods should be matched
2. The penetration of studs and the effect of grass roots cannot be characterised by the triaxial test method
3. Due to the expensive nature of constructed sports pitches and injury issues on any sports pitch, a measure was required that would produce minimal surface damage and not require samples to be removed, as requested by the Groundsmen contacted for the *in situ* study, detailed in chapter 4.

3.2.1 Review of the cone penetrometer test (CPT)

The most common form of *in-situ* soil testing is the cone penetration test (CPT) and has become increasingly important in soils where it is undesirable or difficult to remove samples for laboratory analysis (Lambe and Whitman, 1969). The resistance of soil to penetration is the result of a combination of factors, including, soil compaction, moisture content, texture and type of clay mineral (Baver *et al*., 1972) and therefore does not measure soil strength, rather a composite parameter (Hillel, 1990).

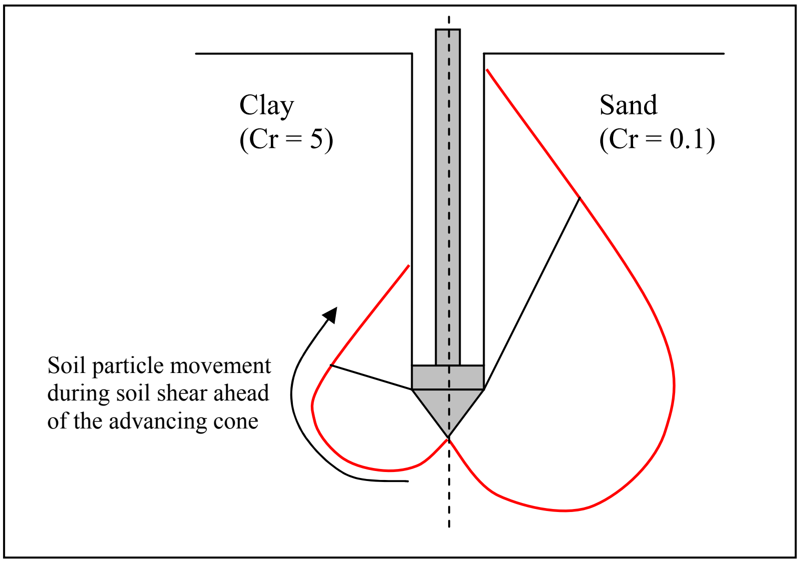


Figure 3.5 The relative size of the pressure bulb formed at the tip of a cone penetrometer for a clay (clay ratio = 5) and sand (clay ratio = 0.1). The plane of failure is shown in red and the path of particle movement also shown. Along the plane of failure, water films will be broken (as in Figure 3.2), however, inter particle friction will also be a factor, and increasingly significant as density increases. Adapted from Elbanna and Witney (1987).

As the cone moves through the soil, complex failure occurs around the cone as a result of resistance to compression, friction between the soil and the metal, and the shear strength of the soil (Baver *et al*., 1972). Figure 3.2 demonstrated how in tensile failure often a clear plane of failure is apparent and the strength of the soil is a direct result of the strength with which the water is retained in soil pores. Failure around the tip of an advancing cone is more complex featuring three dimensional shear, mobilising the entire shear modulus of the soil (Rohani and Baladi, 1981) and due to the movement of particles, friction becomes a feature that is more significant than in tensile failure, as shown in Figure 3.5. The combination of these processes and the exact dimensions of the cone will determine the result (Hillel, 1990). Penetration resistance is therefore a measure of soil strength under the conditions present at the time of the test.

Based on research by Ayers and Perumpral (1982) an idealised penetration resistance curve with increasing moisture content, for a 50% sand – 50% clay soil can be drawn. The effect of bulk density and moisture content changes are discussed in the following sections, using Figure 3.6 as reference.

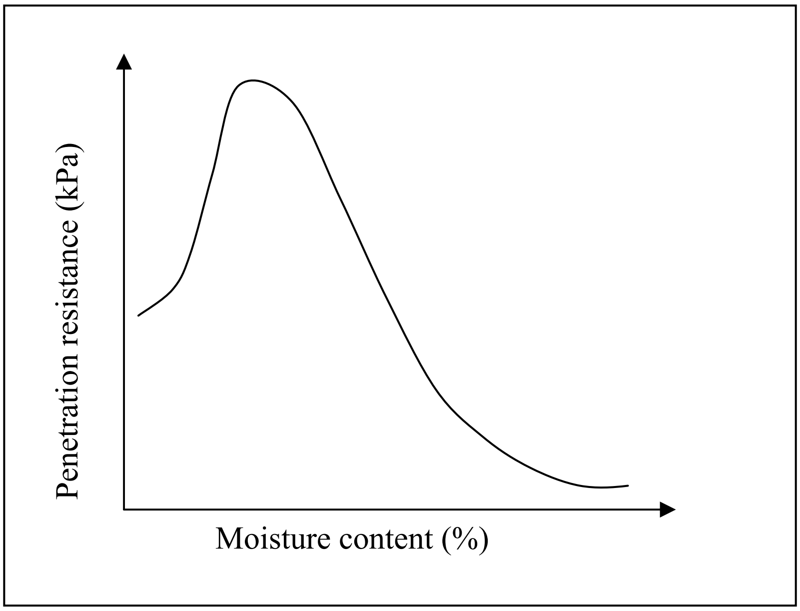


Figure 3.6 idealised curve for the change in penetration resistance with increasing moisture content. Based on a 50% sand – 50% clay soil, adapted from Ayers and Perumpral (1982).

Cone index (CI)

Although soil strength increases with depth (Rohani and Baladi, 1981), the ASAE methodology recommends determining the mean force over the depth of penetration in order to calculate the cone index (CI) of the soil. The load on the cone is actually calculated as the force per unit area (and if presented can be called shear stress or penetration resistance), but the CI is presented without values and used as a comparative figure between test locations. Analysis must discard readings taken prior to the cone being fully embedded in the soil (Bradford, 1986).

Effect of cone angle

As the cone angle decreases and the length increases, the soil to metal friction increases; the increase in friction negates the mechanical advantage of the wedge shape. The cross-over point, where friction negates the mechanical advantage, occurs at 30° (Bradford, 1986), resulting in this being the most common design for soil testing (Bengough and Mullins, 1990). Research has demonstrated a non-linear relationship between cone angle and penetration resistance, reporting a reduction in resistance as cone angle increased (Rohani and Baladi, 1981; Hernanz *et al*., 2000).

Rate of penetration

The CPT has applications in both civil engineering and soil science and the penetration rate varies according to the intended use. For the determination of the load bearing capacity of soils, a very rapid penetration rate of 1800 mm/min was advised (ASAE, 1999) and used in a number of studies (Wells and Treesuwan, 1978; Ayers and Perumpral, 1982).To identify hard pans in soils, penetration rates were usually 20 mm/s (Whitlow, 2001) and 30 mm/s (Bradford, 1986). Where the penetration resistance of the soil was being linked to root exploration and penetration, penetration rates were usually much lower, in the region of 0.02 to 2 mm/s (Vepraskas, 1984; Bengough and Mullins, 1990). Bradford (1986) argued that the relationship between penetration resistance and the rate of penetration was influenced by the pore water pressures generated as a result of the act of penetration and their ability to dissipate in the soil. Furthermore, he suggested that the ability of the soil to dilate should determine the rate of penetration. This requirement was clearly demonstrated by Graecen *et al.,* (1968) who demonstrated that bulk density decreased as the distance from the hole left by the probe increased.

The effect of bulk density

Increases in bulk density have the effect of increasing the recorded penetration resistance, at a given matric potential or moisture content (Wells and Treesuwan, 1978; Vepraskas, 1984; 1986). Research has demonstrated however that this relationship is not linear, and a sharp rise in soil strength has been observed as bulk density increased, at a given matric potential (Taylor and Gardner, 1963; Mulqueen *et al*., 1977; Rohani and Baladi, 1981; Hernanz *et al*., 2000). Whalley *et al.,* (2005) argued that at low densities penetration resistance can be explained by soil matric potential (via the concept of effective stress) but at higher densities, particle rearrangement will be restricted therefore penetration resistance will depend on bulk density and effective stress. The model encompassed all soils successfully at low densities but was unable to accommodate the same soils at high densities. Therefore for a particular soil type at a given matric potential, the effect of increasing bulk density will be to shift the curve in Figure 3.6 upwards. Based on the arguments above, a doubling of the bulk density will result in a greater than double increase in penetration resistance.

Rohani and Baladi (1981) also discussed the effect of the free surface during penetration. They argued that the upward movement of particles reduced penetration resistance readings. This probably results from the issues raised in the above discussion; near the surface, soil particles are more able to rearrange due to the absence of a confining pressure. Lower down the profile, this was shown to be less possible and the authors suggested that the effect of the free surface could be discarded when the depth of penetration (z) exceeded 6 times the length of the cone (l). It is arguable therefore, that high bulk densities may not be satisfactorily detected by penetration resistance at penetration depths of <6l.

The effect of moisture content

For any bulk density, the effect of increasing moisture content is to reduce penetration resistance (Taylor and Gardner, 1963; Elbanna and Witney, 1987). The effect of moisture seems to be a lubricating effect on soil particles effectively reducing penetration resistance with increasing moisture content exacerbated by increasing clay content (Ayers and Perumpral, 1982; Elbanna and Witney, 1987), due to a reduction in inter particle friction and increase in cohesion. The studies by Ayers and Perumpral (1982) and Vepraskas (1984) also demonstrated that at high moisture contents the effect of increasing bulk density was negated and penetration resistance converged.

Although the general trend for reduced penetration resistance with increasing moisture content has been noted, and used in the determination of models to predict penetration resistance (such as Elbanna and Witney (1987) and Ohu *et al.,* (1988)) Figure 3.6 suggests this is not the case. Ayers and Perumpral (1982) and Vepraskas (1984) demonstrated that a localised peak in penetration force is apparent as soil moisture content increased, before reducing rapidly.

Clay soils

Increasing clay content did not alter the pattern of penetration resistance but it did have an impact on the moisture content at which the maximum penetration force is determined (Ayers and Perumpral, 1982; Elbanna and Witney, 1987). However this generality was complicated by alterations in bulk density, as shown by Mulqueen *et al.,* (1977) and the interaction between cohesion and moisture content. The study by Mulqueen *et al.,* (1977) argued that users of penetrometers had failed to acknowledge the limitations of the equipment; particularly that the final result is dependent on many factors. They highlighted the effect of moisture content on the cohesive properties of clay and argued that soil built up ahead of the cone and changed the force/depth profile. They argued that supplementary data would need to be collected (such as moisture content) at the time of testing and only results obtained under similar conditions and from similar soil types were comparable.

Sand and sand dominated soils

Few studies that investigated use of the cone penetrometer incorporated pure sand samples into the experimental investigations. On fine sandy loam soils Taylor and Gardner (1963) demonstrated that penetration resistance increased with increasing matric potential and bulk density. Studies that manufactured soil samples from coarse granular material demonstrated a poor relationship between effective stress and the cone penetrometer under relatively wet conditions (Mullins *et al*., 1992), although the fine sand samples produced good agreement. Ayers and Perumpral (1982) did incorporate 100% sand samples in their studies and discovered that for identical compaction, the penetration resistance of pure sand was significantly less than any of the mixtures containing clay. Furthermore they also determined that at different bulk densities, moisture content did not influence penetration resistance. Vepraskas (1984) demonstrated that the range of values for sand was narrow for penetration resistance against effective stress, but the results demonstrated an increase in resistance as effective stress increased, although the relationships may also depend on bulk density.

3.2.2 Initial investigation – needle penetrometer

Building on the work by Whalley *et al.,* (2005) a non-rotating ‘needle’ penetrometer of identical dimensions (2 mm cone diameter and 30° semi-angle) was used. Unlike the research by Whalley *et al.,* (2005) and despite the difficulties identified by Mullins and Panayiotopoulos (1984) in applying the concept of effective stress to coarse grained materials, 2 pure sand mixes were incorporated into the study.

Testing occurred on the five soil types at a range of matric potentials, in order to address the following hypotheses;

- Shear strength is a function of the water content and tension combined in some way.
- The relationship will hold true for different soils/rootzone mixes.

3.2.2.1 Materials and Methods

The penetrometer

The penetrometer cone was 2 mm in diameter at its base with a semi-angle of 30° and although ANOVA showed no significant difference in penetration resistance between 2, 50, 100 and 200 mm/min penetration speeds (appendix II), a speed of 2 mm/min was chosen for the following reasons;

1. Smallest standard deviation and standard error
2. At this speed, the frequency of data logging ensured a high resolution of data points. Any anomalies could be revisited and detailed information would exist.
3. Air and water pressures that may build ahead of the advancing cone would be able to dissipate (as discussed in section 3.2.1)

All data were removed until the cone was fully embedded into the soil, and the last 60 seconds (2 mm) of data were removed to ensure that build-up of soil ahead of the cone did not skew the readings, as shown in Figure 3.7;

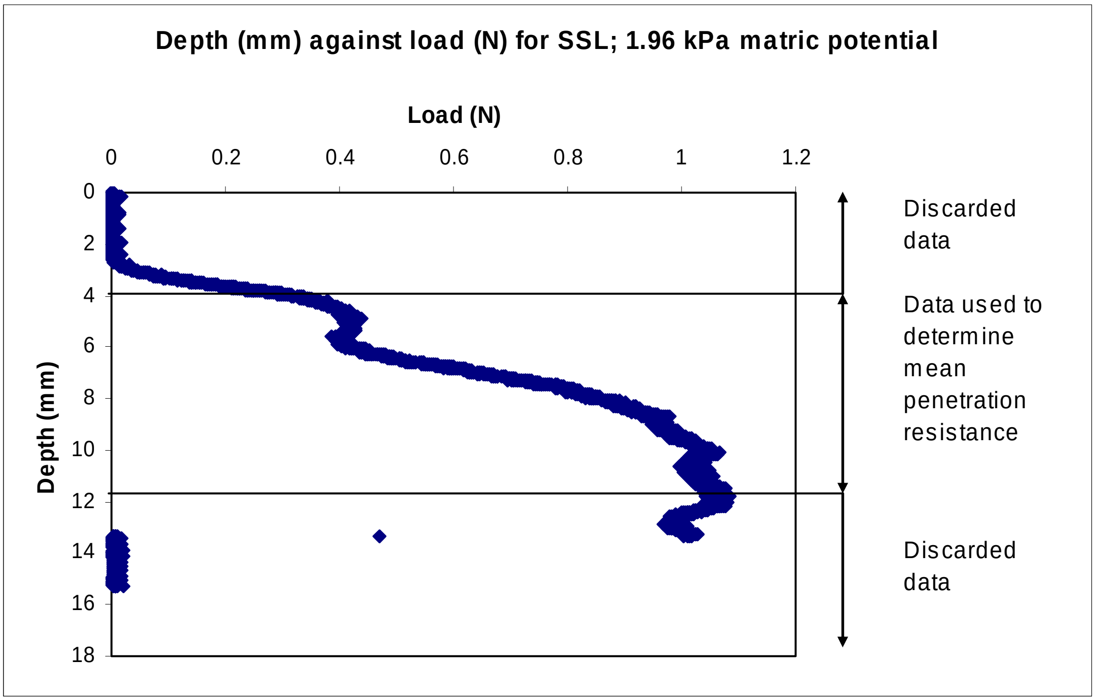


Figure 3.7 data used to determine mean penetration resistance

The mean load calculated from the remaining data was used to determine mean penetration resistance (kPa) over the depth of penetration.

The samples

Five soil types were used for these experiments and are detailed in Table 3.1:

	Percentage of			
Sample label	Sand	Silt	Clay	Textural class
CL	33	22	45	Clay
SL	72	16	12	Sandy Loam
SSL	48	40	12	Sandy Silt loam
US	100	0	0	Sand (USGA)
Sand	100	0	0	Sand (sieved)

Table 3.1 Particle size distributions and textural classification of the five soils

	Percentage of particles within the size ranges indicated (mm)					
	>2	1-2	0.5-1	0.25-0.5	0.15-0.25	receiver
USGA sand	0	1	10	69	17	3

Table 3.2 Particle size distribution for USGA specification sand

The sieved sand possessed a narrow particle size range with 100% of particles passing through a 0.150 mm sieve and collected on a 0.125 mm sieve. The USGA sand conformed to the guidelines set out by the United States Golf Green Association (USGA) and used in the UK winter sports pitch industry to specify rootzone specifications (see Table 3.2 and appendix III for more details).

The three soils were air-dried, ground and passed through a 2 mm sieve and then mixed with water until they began to bind. The mass of soil was equal for each soil type, however the volume of added water was not measured. Samples were packed into cylinders 52 mm in diameter and 19 mm deep, saturated, and then placed on sand tables to equilibrate to the required matric potential. Equilibration had been reached when mass change was less than 1% of the previous recorded mass. The matric potentials used were (kPa) 0, 0.98, 1.96, 3.92, 5.89, 7.85, 9.81, 14.72. Each sample had five penetration tests performed and there was no replication of samples. Figure 3.8 and Figure 3.9 show the testing procedure.

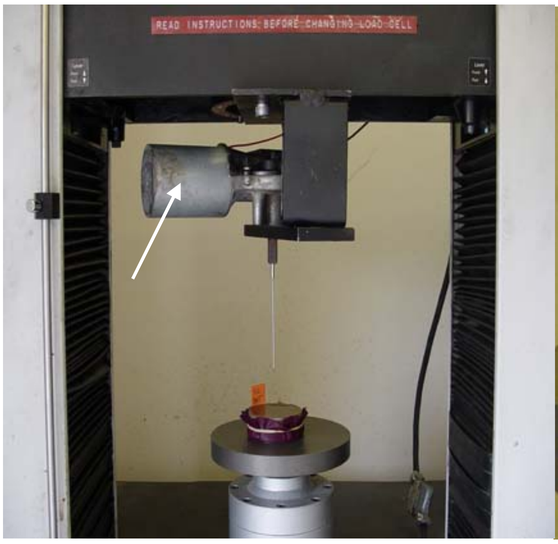


Figure 3.8 (left) A sample on the Instron loading machine. (Arrow indicates a motor to rotate the penetrometer which was not used during this study)

Figure 3.9 (right) A saturated sample being tested.

Testing equipment

An Instron loading machine (Figure 3.8) was used to measure the force (N) on the penetrometer during penetration. The penetrometer was attached to a cross head which descended into the sample at the set speed. The sample was placed on a load cell which recorded the load 10 times per second. This was fed back to a data shuttle where the analogue signal was converted to a digital signal and captured by a bespoke program created using the Daisy Lab™ software. The output was saved onto a laptop computer and a chart of load (N) against time (s) was produced for each replicate. The motor beneath the crosshead shown in Figure 3.8 (arrowed) enabled the penetrometer to be rotated if desired. For this investigation, the penetrometer was not rotated. The sample in Figure 3.9 was for photographic purposes only; when SAT (saturated) samples were tested they were placed in a dish of water to prevent drainage. The five penetration tests within each density ring occurred at evenly spaced intervals.

Calculation of σ'

Eqn 3.7 was used to calculate effective stress. With penetration testing occurring when samples were at the 'wet-end' of the water release characteristic, the values for S would fall within the range identified by Bishop and Blight (1963) for different soils and therefore $\chi = S$. Slow penetration rates ensured air pressures would not become important and changes in pore water pressures ahead of the advancing cone would dissipate and equilibrate in the soil. The shallow penetration depths enabled an assumption of zero overburden pressure. S was determined by dividing the moisture content of the test sample by the moisture content at saturation. ψ represents matric potential and is positive which represents increasing soil water tension.

3.2.2.2 Results

Raw data

As tests were performed on each sample, there was a systematic increase in the load readings and this held true for the majority of samples. This was attributed to either the sample drying or drainage during the course of the test. Testing one sample five times took approximately an hour to complete and during this time, the soil surface was exposed and evaporation was occurring. Placing the samples in a Petri dish of water was only acceptable for the saturated samples; all the rest had been equilibrated to a set tension and would have absorbed the water from the petri dish, further confusing the results. Figure 3.10 shows the effect of sample drying.

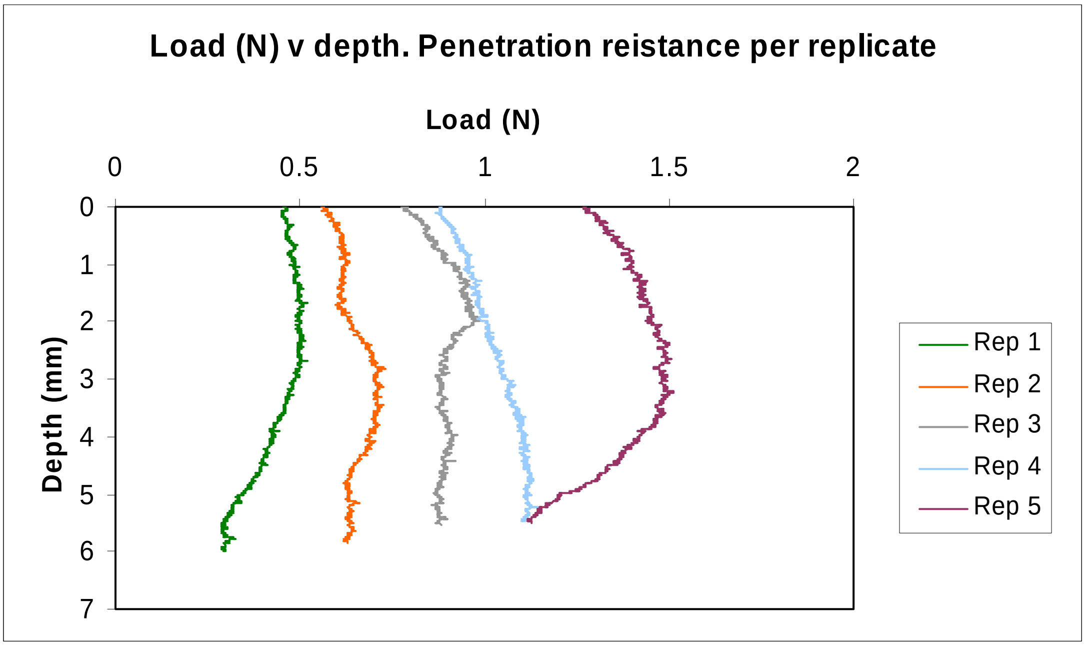


Figure 3.10 The increase in load (N) readings during the hour-long test, SSL sample; 0.98 kPa.

Further analysis

The mean of each replicate test was taken then the mean of the five means determined in order to present a mean load (N) per sample. This load reading was converted into a stress (penetration resistance; kPa) and used to produce Figure 3.11. Standard error bars are drawn where they extend beyond the point.

Penetration resistance was plotted against effective stress for each soil type and the results shown in Figure 3.11. Although some separation by soil type is evident, the objective was to analyse the data for a single model, encompassing all soil types. Figure 3.12 shows the total data set and a regression line fitted through the points. The resulting R^2 value is displayed on the graph.

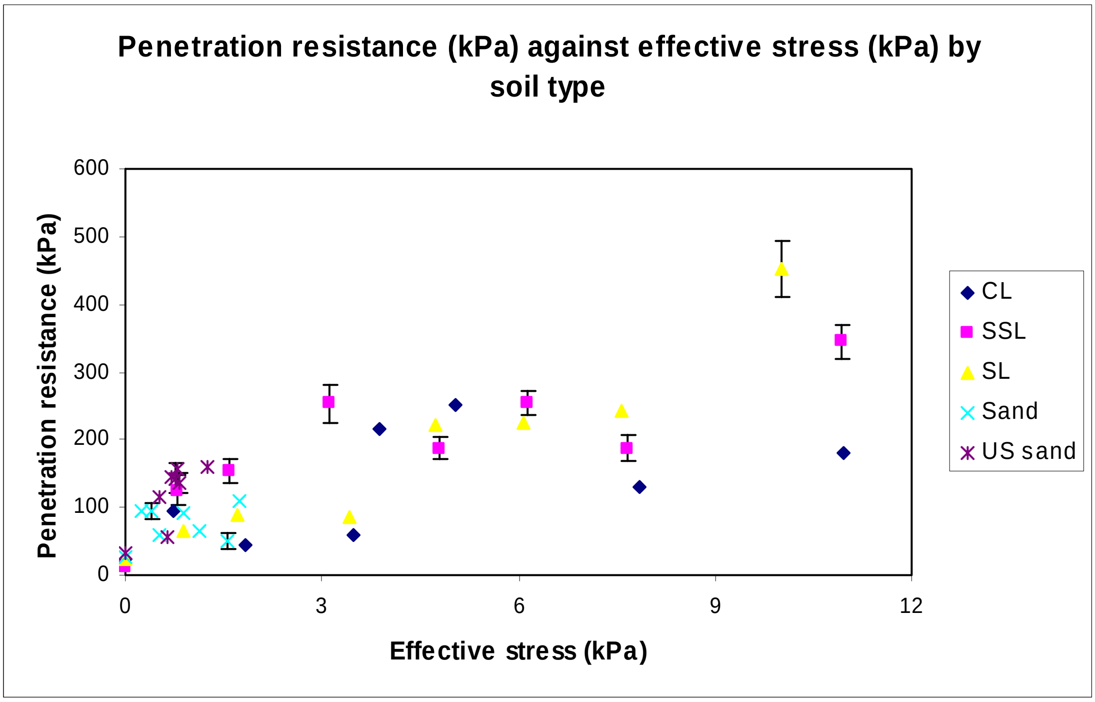


Figure 3.11 Penetration resistance against effective stress for the five soil types tested.

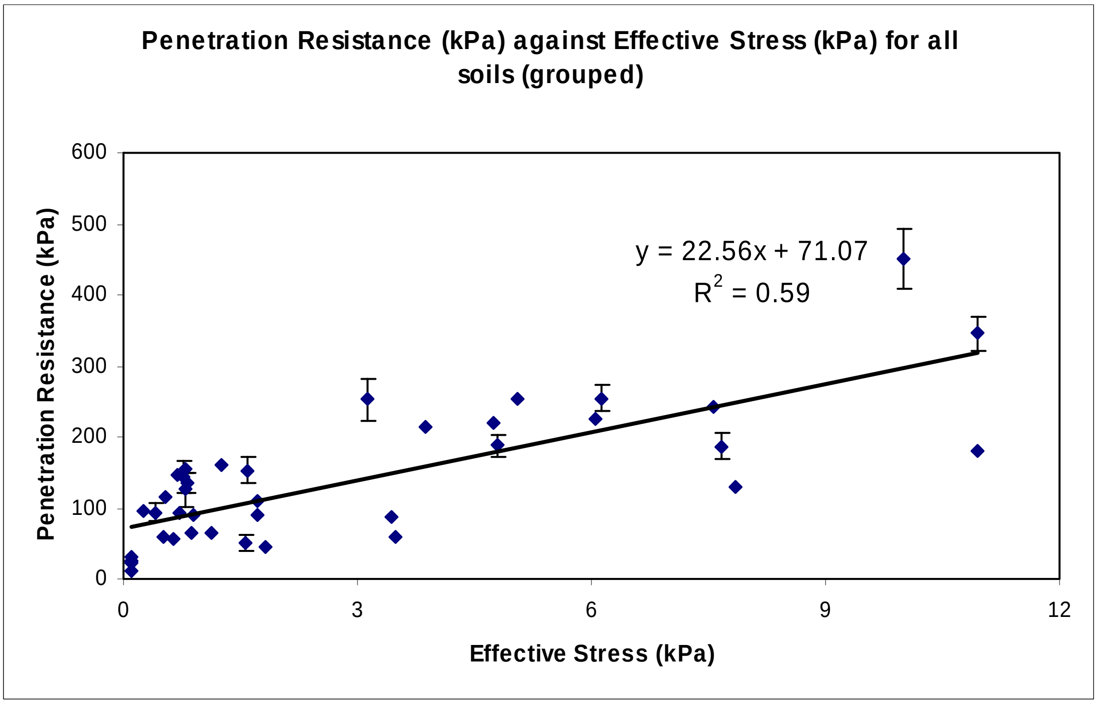


Figure 3.12 Penetration resistance against effective stress for all soils (grouped).

Penetration resistance (kPa) = 22.56 (effective stress) + 71.07, $p < 0.001$.

A log-log plot was created in order to reduce variability in the data and determine if the relationship became stronger.

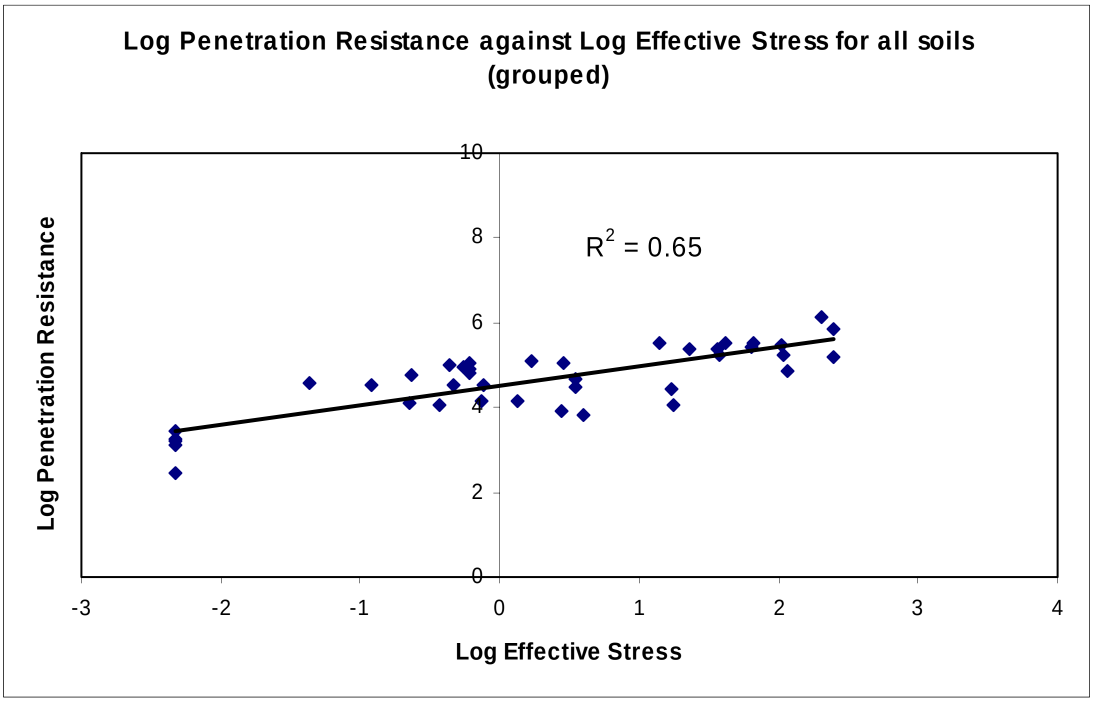


Figure 3.13 Log-log plot of penetration resistance against effective stress.

Log Penetration resistance = 0.46 (log effective stress) + 4.50, $p<0.001$.

Bulk densities were not controlled and while effort was made to follow similar procedures for each sample, the result was a varied range of bulk density values as highlighted in Table 3.3.

	Bulk density (Mg/m^3)	
Soil type	Min	Max
Clay	1.17	1.28
Sandy Loam	1.36	1.64
Sandy Silt Loam	1.36	1.54
Sand	1.17	1.73
US Sand	1.61	1.74

Table 3.3 The range of bulk densities for each soil type tested during initial experimentation

3.2.2.3 Discussion

The analysis by Vepraskas (1984) considered the changes in penetration resistance with respect to moisture content. The data presented were from carefully controlled bulk densities; likewise, the relationship against relative saturation (representing both moisture content and particle size distribution) was also presented for loamy sands. Due to the lack of controlled densities in these experiments this analysis has not been possible, but the results by Vepraskas (1984) demonstrated that cone index initially increased as moisture content increased, before decreasing rapidly. This may indicate why previous authors have failed to produce a model that encompassed all soils; relative saturation at a particular matric potential will be different for each soil type as a result of different pore size distributions.

However, it is clear from Figure 3.12 that the use of effective stress did produce a relationship between penetration resistance and effective stress for all soils combined. However, it was heavily influenced by the 3 soils, with the two sand samples having little impact on the equation. The log-log plot indicated a slight improvement over the untransformed data.

The effect of bulk density has a significant effect of penetration resistance (Ayers and Perumpral, 1982) therefore the failure in this experiment to control bulk densities for each soil type resulted in difficulties when separating the effect of tension (and hence effective stress) and bulk density on strength. This is a significant point for commercial companies when specifying pitch details as a result of laboratory tests; the actual conditions must match those generated in the laboratory in order for the test results to be applicable. The speed at which samples would equilibrate would also have been different, perhaps suggesting that some samples had not yet reached equilibrium once testing commenced. More likely is the possibility that the water retained in the sample would have required greater matric potential to remove it. This is what may have led to unexpected variation in moisture contents; the moisture content for the clay soil at 0.98 kPa matric potential was less than that at 1.96 kPa matric potential while the respective bulk densities were 1.2 Mg/m^3 and 1.28 Mg/m^3 respectively. However, the use of effective stress did successfully encompass different soil types at a wide range of bulk densities and produce a statistically significant prediction equation. This is contrary to the research work described by both Mullins and Panayiotopoulos (1984) and Whalley *et al.,* (2005).

Figure 3.10 also highlights possible drying or drainage during tests, resulting in the water in the soil being held more tightly and therefore contributing more to the strength of the soil. This was evident from the increase in load readings for each subsequent replicate. Although a threefold increase, it was negligible compared to the increase caused by increases in matric potential. However it does suggests that future tests may need to be performed quicker to prevent this. Furthermore 2 mm/min penetration speed is not representative of penetration speed used in field conditions and for future experiments, this should be increased. In spite of this, the data showed clear trends and confidence in the use of the simple concept of effective stress to link moisture content and strength can be gained.

The size of the penetrometer used for these experiments was particularly small. For the sand samples, the size of the cone was close to the size of the individual particles and hence a larger cone should used in future. To accommodate a larger penetrometer, samples need to be larger in both cross sectional area and depth in order to perform tests representative of in-situ conditions.

Continued investigation was justifiable; with the following changes to the experimental procedure based on the experience of the initial tests;

1. Larger samples would be prepared in cylinders measuring approximately 100 mm in diameter and 150 mm in height.

2. The penetrometer size would be increased to match that used in field testing conditions, measuring 25 mm in length, have a 30° cone angle and a base area of 113.1 mm^2.

3. Three soils would be used rather than five; the clay and sandy silt loam soils currently in use and a Mansfield 45 rootzone material used in sports pitch construction.

4. Each soil type would be packed to three bulk densities. The selection of density will be based on the assumption of a compact sports pitch subject to intensive use, while also being achievable via hand packing.

5. A faster penetration rate of 200 mm/min would be used.

6. There would be three replicates of each cylinder and three replicate tests performed in each cylinder.

7. The experiment would be run with and without grass present.

3.2.3 Further investigation – field scale penetrometer

The results of the initial investigation into the use of effective stress to predict the strength of soils (measured by penetration resistance) confirmed the results of previous studies that also demonstrated the possibility of doing so. In contrast to the previous studies, the study detailed in section 3.2.2 incorporated two pure sand samples and a wide range of bulk densities for all soils, and yet a single model was still established. Based on these results the experiments were continued, adopting the changes outlined in above. Samples with grass were labelled WG and without; NG.

3.2.3.1 Materials and Methods

The Penetrometer

The penetrometer measured 25 mm in length, with a cone angle of 30° and a base area of 113.1 mm^2. This was attached to a metal shaft 200 mm in length in order to facilitate penetration to the base of the cylinder. Penetration was conducted at 200 mm/min. The WG experiments utilised three identical penetrometers, each with different length shafts. The shortest was used first and the longest last to ensure the same depth of penetration had been achieved each time. The presence of roots inhibited the removal of the penetrometer after each test as this would have destroyed the integrity of the sample.

The soil samples

	Percentage of			
Sample label	Sand	Silt	Clay	Textural class
CL	33	22	45	Clay
SSL	48	40	12	Sandy Silt loam
M45	100	0	0	Sand

Table 3.4 Particle size distributions and textural class for the three soils. Despite being an 85:15 sand:soil mixture; M45 was classed as 100% sand following pipette method analysis.

	Percentage of particles retained on the sizes indicated (mm)								
	2	1	0.5	0.25	0.15	0.125	0.063	0.053	Receiver
M45	0.0	1.9	17	59.4	17.3	1.8	2	0.2	0.4

Table 3.5 Particle size distribution for Mansfield 45 85:15 sand:soil rootzone mix.

The three soils are detailed in Table 3.4. The clay soil and sandy silt loam were identical to those used in section 3.2.2 but for contrast a typical rootzone material was added. For this, a Mansfield 45 85:15 sand:soil rootzone mix was procured. A Proctor compaction test showed the maximum achievable bulk density was 1.71 Mg/m3 at a moisture content of 13.8%.

The cylinder dimensions were 100 mm diameter and 150 mm in height, producing an internal volume of 1178 cm^3.

Bulk densities

Ground air dry soil (2 mm sieved), adjusted to reflect the residual moisture content, was packed into the cylinders described above. The volume of added water was less than the maximum amount for that bulk density according to Proctor results. A packing procedure was also established using trial and error e.g. two scoops of soil per 20 hits with a tamping device, on practice cylinders until the optimum procedure had been determined. This was then performed for each soil type at each bulk density. Table 3.6 shows the densities used in both the NG and WG tests.

	Bulk density (BD; Mg/m^3)		
Soil type	BD1	BD2	BD3
Clay	1.10	1.15	1.22
Sandy Silt Loam	1.10	1.25	1.30
Mansfield 45	1.56	1.60	1.65

Table 3.6 The bulk densities selected for use in the NG and WG experiments.

NG tests consisted of three soil types, three bulk densities and three replicates of each cylinder, placed at matric potentials of 0, 0.98, 2.94, 5.89 and 9.81 kPa totalling 135 cylinders.

WG tests consisted of three soil types, three bulk densities and three replicates of each cylinder, however, a reduced number of matric potentials were used; 0, 5.89 and 9.81 kPa totalling 81 cylinders.

Grass type

The WG experiments were sown with *lolium perenne* ; csv 'Dali' (labelled henceforth as PRG) at the recommended seed rate of 35 g/m^2. The surface of each cylinder was raked and kept moist to encourage germination.

The NG cylinders were sown in June 2004, kept in a glass house, watered twice daily and received an 8:12:8 N:P:K slow-release fertiliser application once. The grass was trimmed to 40mm on reaching 70mm and the cuttings discarded. In September 2004 penetration tests were conducted.

WG cylinders were packed and sown during September 2004. They were watered frequently and also kept in the glass house, which was heated to maintain a temperature suitable for growth. As before, an 8:12:8 fertiliser was applied once and the grass maintained at 40mm. In January 2005 penetration tests occurred.

Achieving the desired tension (NG)

Each cylinder was saturated until the mass stabilised to within ± 1% of the previous recorded mass. Saturated cylinders were placed on tension tables until equilibrium had been reached, and assessed in the same way as before. Tension was set from the centre point of the cylinder (75 mm from the top of the cylinder) to represent the mean tension within the sample. This would also represent the mid-point of the penetration test.

Achieving the desired tension (WG)

It was deemed inappropriate to place the WG samples on tension tables, fearing that this would interfere with root development and exploration of the soil. Bespoke tensiometers (see appendix IV for designs) were fabricated and one inserted into each cylinder. A 10 mm hole was augured into the centre of the cylinder, 2 mm smaller in diameter than the ceramic cap to ensure optimum cap-soil contact. Auger and insertion depth were carefully controlled to ensure the mid point of the ceramic cap was situated at the mid point of the cylinder. Tension was monitored using a reader which was placed over each septum. The needle pierced the septum and tension recorded. Figure 3.14 shows the cylinders after grass establishment and installation of the tensiometers:

Figure 3.14 Tensiometers in each WG cylinder

The 81 cylinders were arranged in three completely randomised blocks of 27 cylinders.

Testing Procedure (NG)

Once equilibrated to the desired matric potential, the samples were transferred to the Instron loading machine, previously detailed. Data was captured in the same way; however the recording rate had been halved to five readings per second. As before a trace of load (N) against time (s) was produced. Figure 3.15 below shows a cylinder on the Instron. 0 kPa (saturated) samples were placed in a container of water to prevent drainage.

Figure 3.15 A NG cylinder on the Instron loading machine. (The arrow indicates a swell of particles on the soil surface as a result of upwards movement)

Each cylinder was subject to three tests and each cylinder was replicated three times. Therefore for each bulk density at each level of tension and each soil, there were nine test results. Arrowed in Figure 3.15 is the swell left on the sample surface caused by the upward flow of particles during penetration, possibly due to the free surface enabling upward movement of particles, as discussed by Rohani and Baladi (1981).

Testing procedure (WG)

Immediately the desired matric potential was reached, the cylinders were tested using the Instron. Due to the presence of grass roots, a single penetrometer was not used; withdrawal would have damaged the integrity of the sample. Instead, three penetrometers were used, manufactured to identical specification, but each having different shaft lengths. The short was used first, and then the medium length shaft then the longest. This ensured the cone had penetrated to the same depth each time. The grass was cut immediately prior to testing as shown in Figure 3.16:

Figure 3.16 WG cylinder testing; three penetrometers and the tensiometer are visible.

Data analysis (NG)

To calculate effective stress, the degree of saturation was determined by the moisture content at the time of the test divided by the moisture content at saturation. The weight of each cylinder was recorded at saturation and the time of the test. On completion of the tests, the soil was removed from the cylinder and oven dried at 105°C for 48 hours. After which the oven dry weight was recorded. To calculate effective stress, Eqn 3.7 was used.

Data were recorded over the entire depth of penetration (150 mm total depth, 200 mm/min penetration speed and five readings per second). Similarly to Figure 3.7, recorded load data were removed until the cone was fully embedded in the soil (25 mm at 200 mm/min is 7.5 seconds) and the final 9 seconds were removed to prevent a bias entering the results from soil building ahead of the cone. Once this had been completed, the mean load (N) for each test was established from the remaining data.

On completion of all the tests, penetration resistance (kPa) was calculated and plotted against effective stress in order to determine whether a single relationship covering all soils, as discovered in section 3.2.2, was still evident using the altered test methodology. ANOVA tests were conducted in order to establish whether the difference between soils, tensions and bulk densities were significant.

Data analysis (WG)

Saturation of each cylinder prior to grass establishment did not occur, therefore in order to determine the saturated moisture contents, a further set of 27 cylinders were packed, saturated, weighed then oven dried. It was not possible to determine bulk density after testing due to the destructive process of removing the penetrometers from the samples and the difficulty containing all the soil during the removal procedure. As a result, the bulk density figures and relative saturation figures from the additional set of cylinders was used to determine effective stress.

The Instron output and treatment of the data was identical to the NG data. There were 9 penetration tests per tension and per bulk density and this data was analysed using ANOVA to establish the significance of difference between the results.

Comparison analysis (NG and WG)

The NG and WG data were combined and analysed using ANOVA to examine the effect of the addition of grass roots on the penetration resistance of each soil type.

3.2.3.2 Results

Bulk densities

	Bulk density (BD; Mg/m^3)		
Soil type	BD1	BD2	BD3
CL	1.09 (0.004)	1.19 (0.001)	1.21 (0.007)
SSL	1.13 (0.001)	1.24 (0.004)	1.34 (0.003)
M45	1.51 (0.002)	1.56 (0.0007)	1.65 (0.004)

Table 3.7 Achieved bulk densities and associated standard error (NG)

Table 3.7 shows the achieved bulk densities and the standard errors for the NG experiments. There were 5 matric potentials, and three replicate cylinders each; therefore the mean values and standard errors are calculated from fifteen values.

	Bulk density (BD; Mg/m^3)		
Soil type	BD1	BD2	BD3
CL	1.13 (0.005)	1.15 (0.006)	1.20 (0.004)
SSL	1.14 (0.001)	1.28 (0.002)	1.33 (0.001)
M45	1.58 (0.001)	1.62 (0.002)	1.66 (0.001)

Table 3.8 Achieved bulk densities and associated standard error (WG)

Table 3.8 shows the achieved bulk densities and the standard errors for the WG experiments. There were 3 levels of tension, and three replicate cylinders each; therefore the mean values and standard errors are calculated from 9 values. These were not the tested samples, but representative samples constructed following the same methodology before being saturated, weighed and then oven dried.

Penetration resistance and soil moisture status (NG)

The relationship was investigated for penetration resistance against both matric potential and effective stress. Table 3.9 shows R^2 values by soil type and bulk density.

	Bulk density							
	All (grouped)		BD1		BD2		BD3	
	σ’	ψ	σ’	ψ	σ’	ψ	σ’	ψ
CL	0.51	0.51	0.82	0.82	0.80	0.79	0.81	0.82
SSL	0.15	0.09	0.84	0.84	0.89	0.86	0.95	0.95
M 45	0.23	0.27	0.77	0.94	0.43	0.95	0.57	0.63

Table 3.9 R^2 values for penetration resistance against effective stress and matric potential for NG experiments

Figure 3.17 and Figure 3.18 show the results when attempting to determine a relationship for all soils, against matric potential (R^2 = 0.16) and effective stress (R^2 = 0.03) respectively.

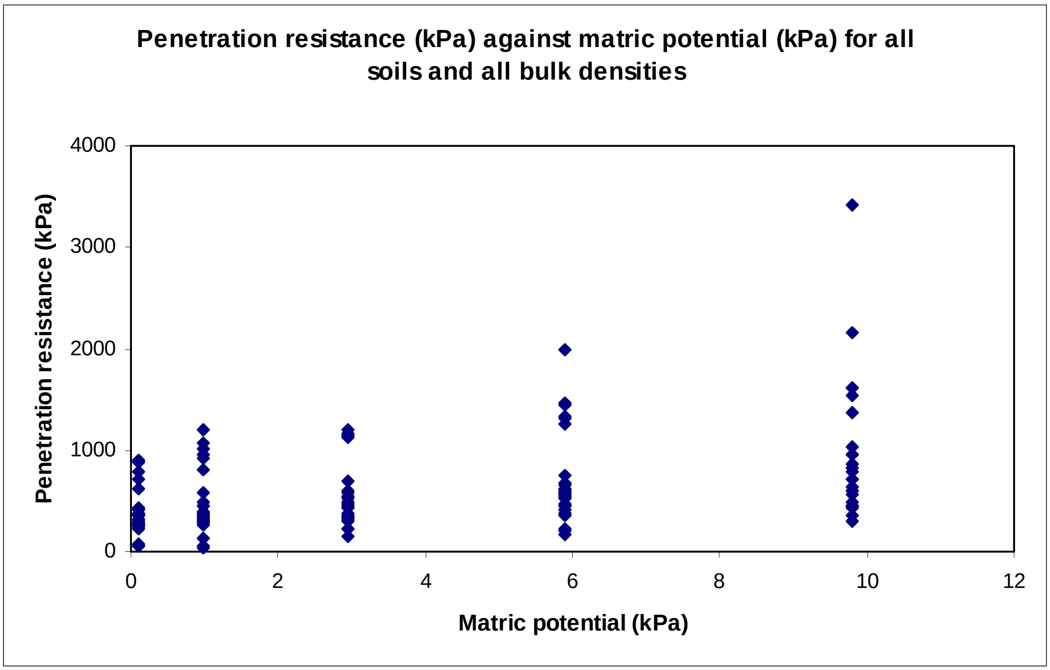


Figure 3.17 Penetration resistance against matric potential for all soils (NG)

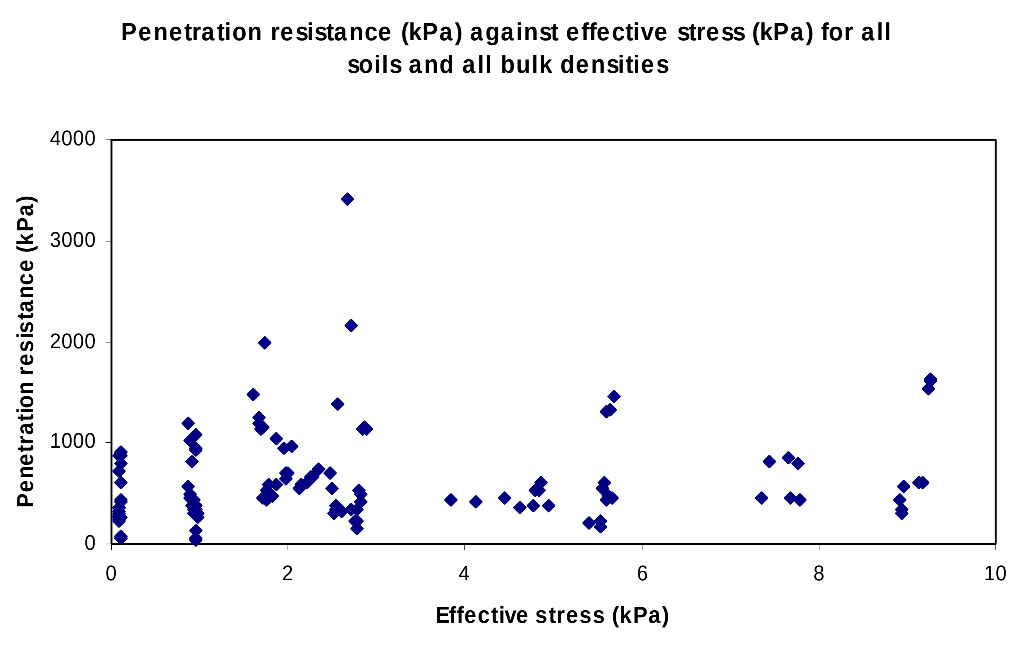


Figure 3.18 Penetration resistance against effective stress for all soils (NG)

Figures for penetration resistance against effective stress and tension for all three bulk densities and soil types are in appendix IV. Figure 3.19, Figure 3.20 and Figure 3.21 show the relationship between penetration resistance and effective stress by soil type and at each bulk density used.

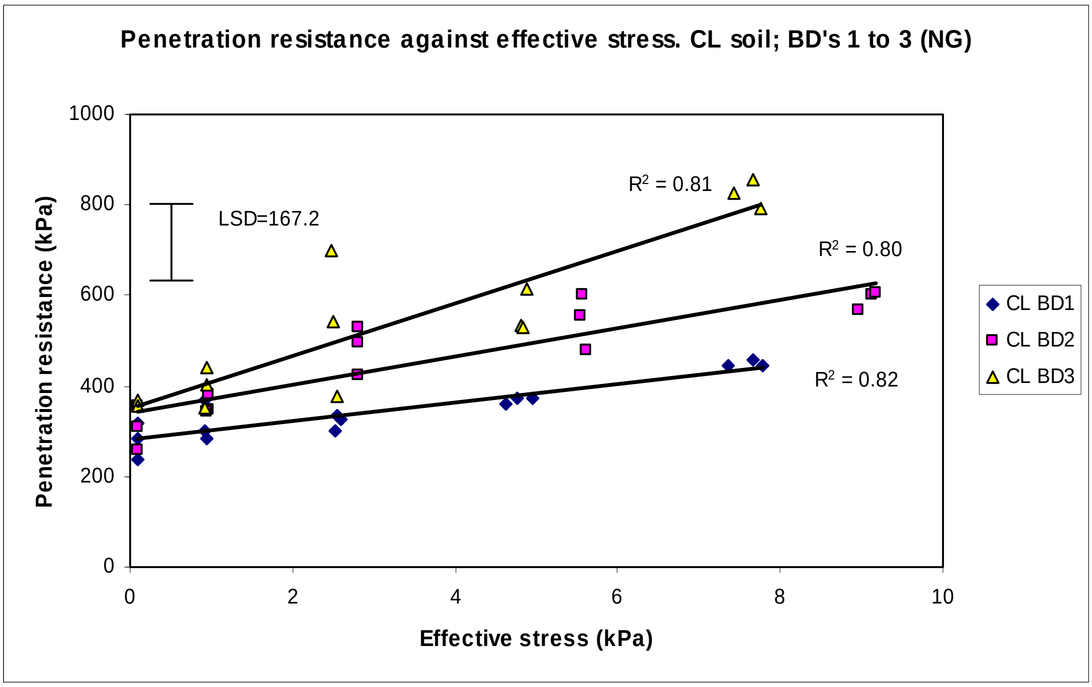


Figure 3.19 Penetration resistance against effective stress for the CL soil (NG). Error bars shown where they extend beyond the point.

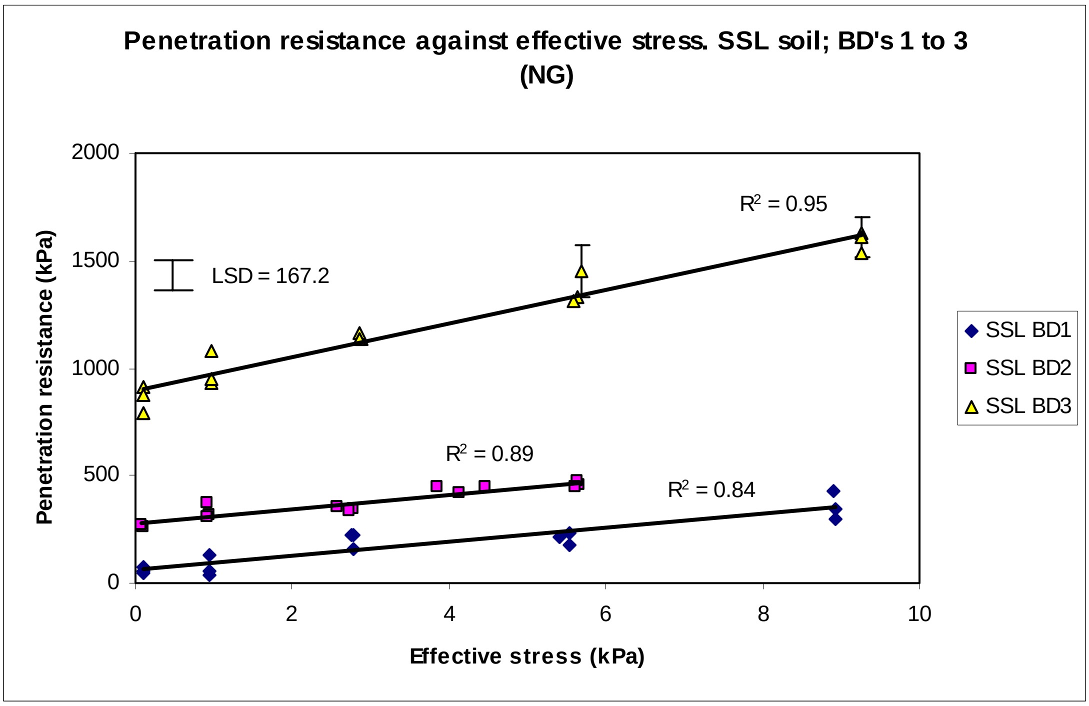


Figure 3.20 Penetration resistance against effective stress for the SSL soil (NG). Error bars shown where they extend beyond the point.

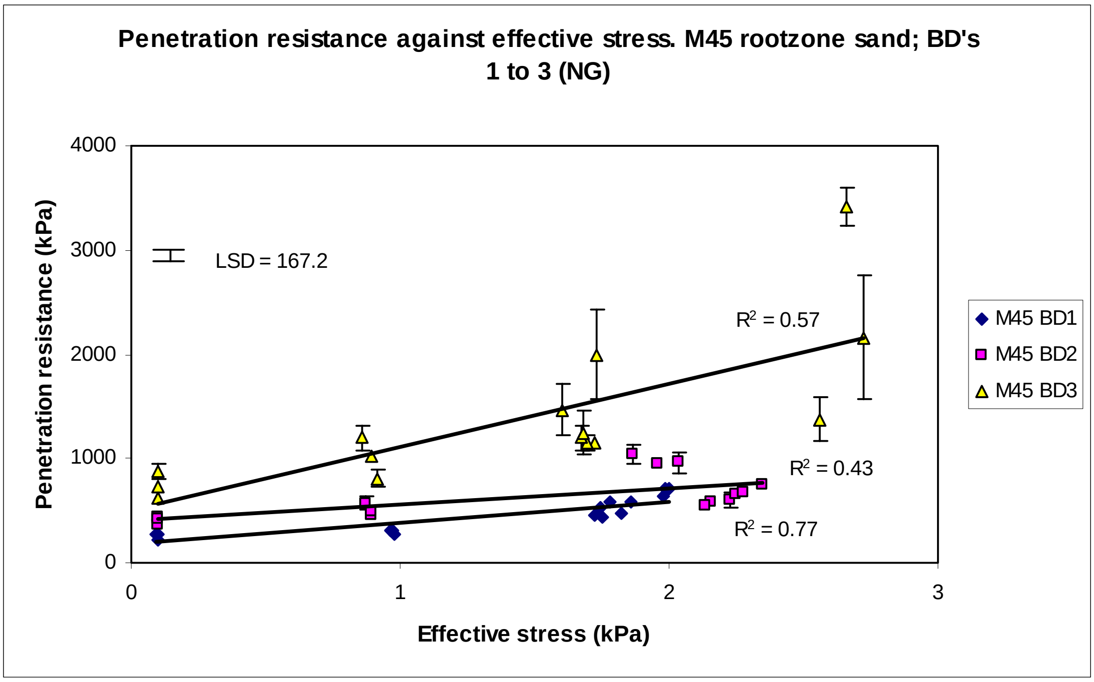


Figure 3.21 Penetration resistance against effective stress for the M45 rootzone sand (NG). Error bars shown where they extend beyond the point.

- ANOVA

A matrix showing the significant differences between each soil type at each matric potential is shown in appendix V. The interaction between treatment, bulk density and soil type was not significant (0.284), however the treatment (no grass [NG] and the matric potential) and bulk density interacted significantly ($p<0.05$), which showed a systematic increase in penetration resistance with an increase in tension, at each bulk density. The results are shown in Table 3.10. The LSD is 74.8.

	Mean Penetration resistance (kPa)		
Treatment*bulk density	Low	Med	High
NG 0	202	332	667
NG 0.98	232	407	816
NG 2.94	331	477	950
NG 5.89	388	569	1193
NG 9.81	506	692	1613

Table 3.10 The significant interaction between the treatment and bulk density on the penetration resistance (kPa) at each bulk density LSD = 74.8 (NG). The treatment label indicates no grass (NG) and the matric potential (kPa).

Omitting bulk density, there was a significant interaction ($p<0.05$) between the treatment and the soil type. A systematic increase in penetration resistance as matric potential increased resulted for each soil type. The results are shown in Table 3.11 and the LSD is 74.8

	Mean penetration resistance (kPa)		
Treatment*soil type	CL	SSL	M45
NG 0	316	407	479
NG 0.98	358	477	621
NG 2.94	448	579	731
NG 5.98	491	689	970
NG 9.81	621	824	1365

Table 3.11 The significant interaction between the treatment and soil type on the penetration resistance (kPa) of each soil type LSD = 74.8 (NG). The treatment label indicates no grass (NG) and the matric potential (kPa).

- Regression equations

The regression equation from each line in Figure 3.19, Figure 3.20 and Figure 3.21 is shown in Table 3.12:

Soil type	Bulk density	Equation	p value
CL	1	Penetration resistance (kPa) = 20.68 (σ’) + 281.38	$p<0.001$
CL	2	Penetration resistance (kPa) = 31.08 (σ’) + 341.84	$p<0.001$
CL	3	Penetration resistance (kPa) = 57.80 (σ’) + 351.30	$p<0.001$
SSL	1	Penetration resistance (kPa) = 33.19 (σ’) + 62.40	$p<0.001$
SSL	2	Penetration resistance (kPa) = 34.73 (σ’) + 284.55	$p<0.001$
SSL	3	Penetration resistance (kPa) = 80.10 (σ’) + 920.02	$p<0.001$
M45	1	Penetration resistance (kPa) = 209.50 (σ’) + 185.37	$p<0.001$
M45	2	Penetration resistance (kPa) = 160.31 (σ’) + 413.72	$p<0.001$
M45	3	Penetration resistance (kPa) = 613.89 (σ’) + 525.78	$p<0.001$

Table 3.12 Regression equations for CL, SSL and M45 soils at each bulk density (NG), regression determination used Statistica.

Penetration resistance and moisture status (WG)

As before the relationship was investigated for penetration resistance against tension and effective stress. Table 3.13 shows the R^2 values by soil type and bulk density.

	Bulk density							
	All (grouped)		BD1		BD2		BD3	
	σ’	ψ	σ’	ψ	σ’	ψ	σ’	ψ
CL	0.78	0.82	0.94	0.95	0.96	0.95	0.95	0.98
SSL	0.84	0.27	0.85	0.86	0.60	0.85	0.87	0.89
M 45	0.60	0.67	0.91	0.99	0.86	0.92	0.91	0.93

Table 3.13 R^2 values for penetration resistance against effective stress and tension (WG)

Figure 3.22 and Figure 3.23 show the results for all soils and bulk densities for penetration resistance plotted against tension (R^2 = 0.24) and effective stress (R^2 = 0.07).

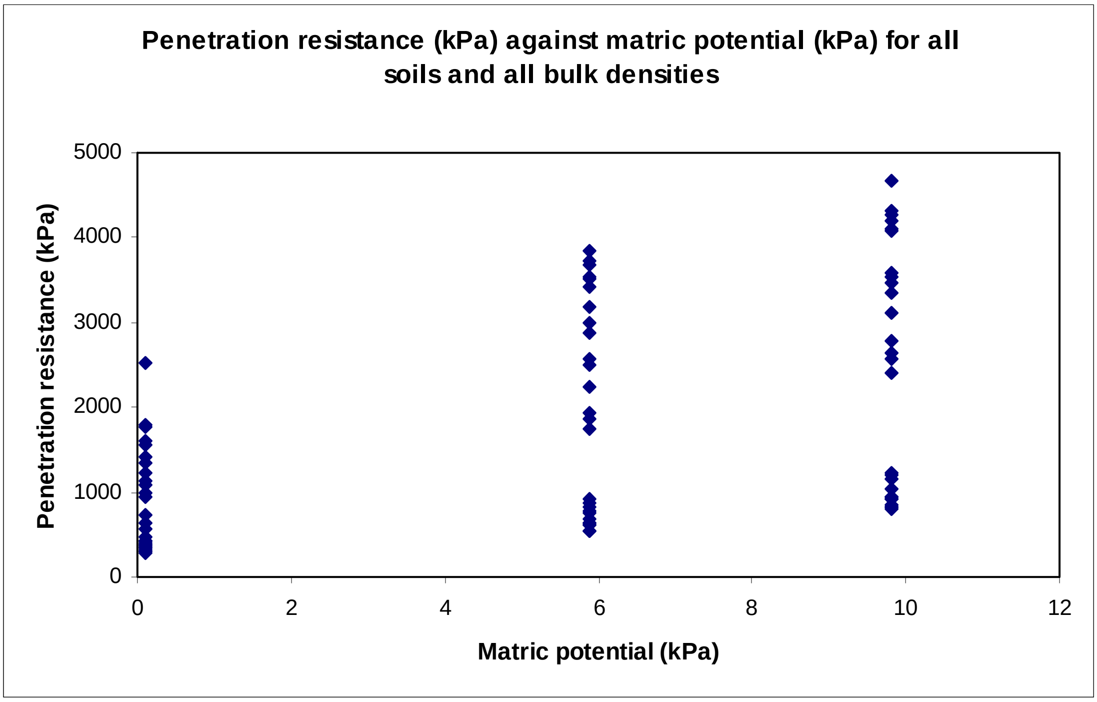


Figure 3.22 Penetration resistance against effective stress for all soils and bulk densities (WG)

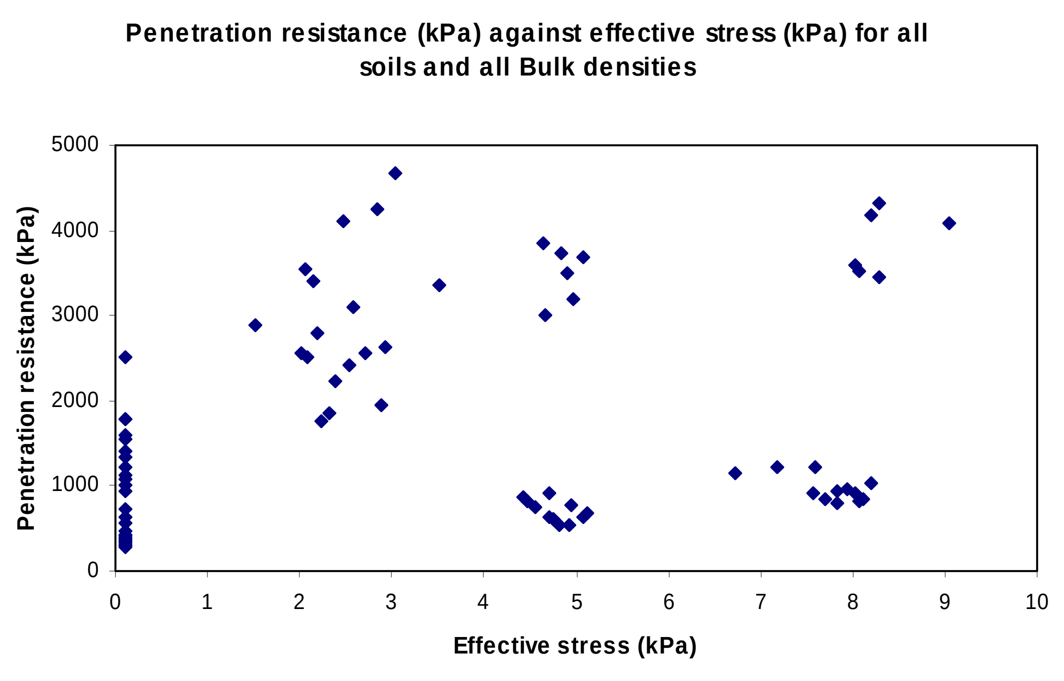


Figure 3.23 Penetration resistance against tension for all soils and bulk densities (WG)

Figures for penetration resistance against effective stress and tension by soil type and bulk density are shown in appendix VI. Figure 3.24, Figure 3.25 and Figure 3.26 show the relationship between penetration resistance and effective stress.

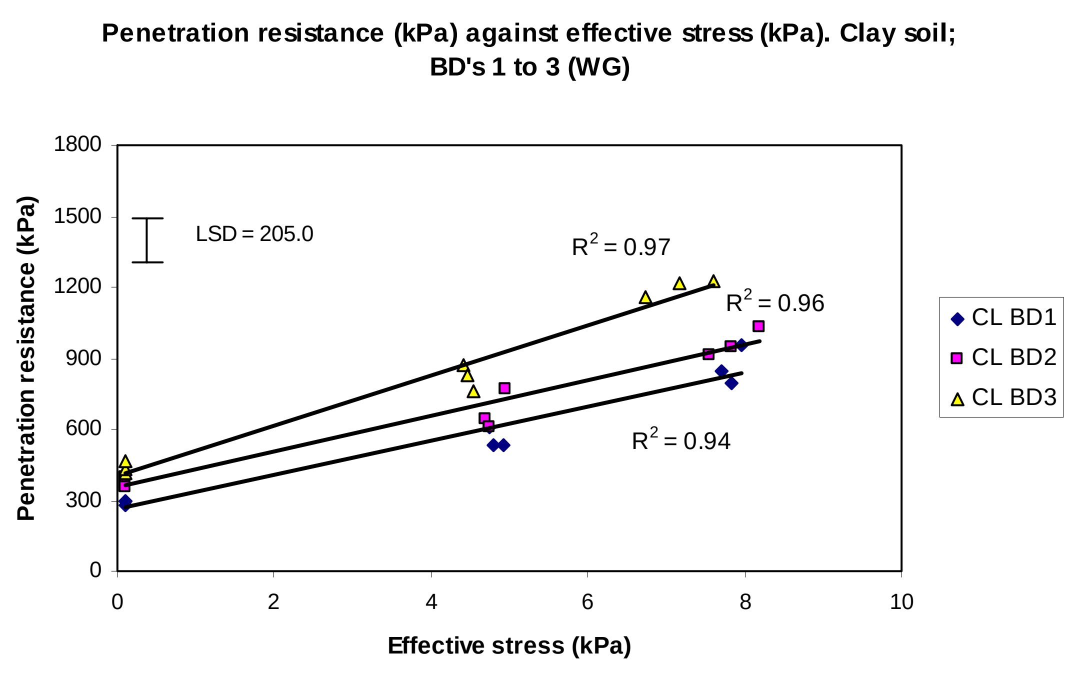


Figure 3.24 Penetration resistance against effective stress in Clay soil (WG). Error bars shown where they extend beyond the point.

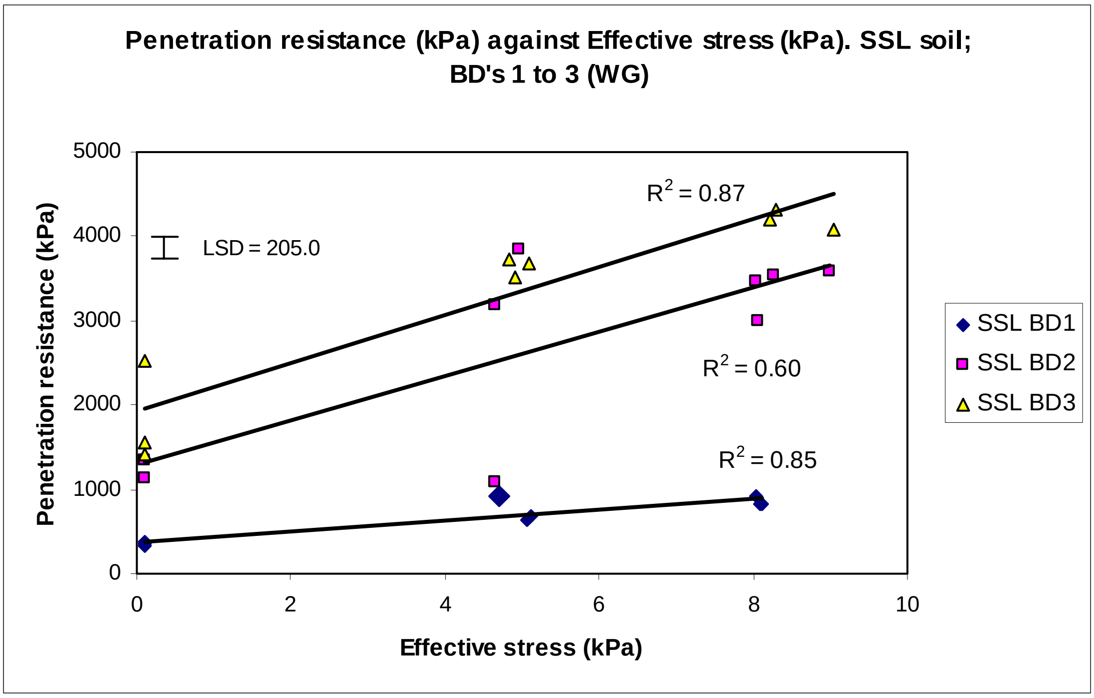


Figure 3.25 Penetration resistance against effective stress in SSL soil (WG). Error bars shown where they extend beyond the point.

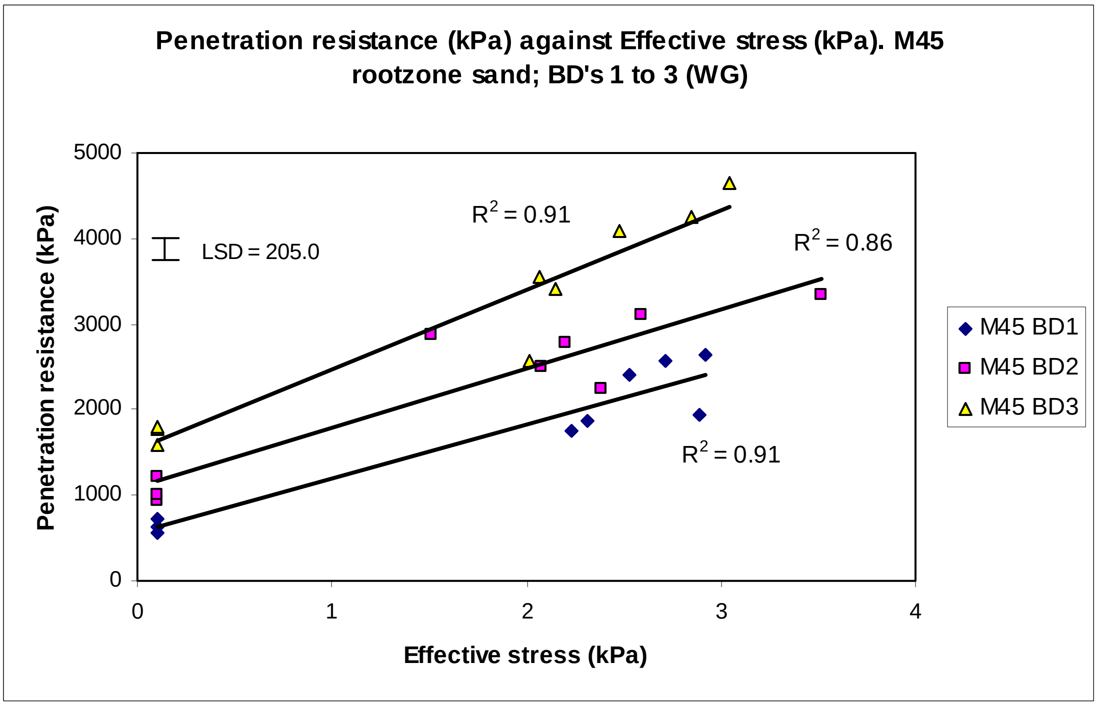


Figure 3.26 Penetration resistance against effective stress in M45 rootzone material (WG). Error bars shown where they extend beyond the point.

- ANOVA

A matrix highlighting significant differences between each treatment, soil type and density is shown in appendix VII. In summary, there was a significant interaction between the treatment, bulk density and soil type. The mean penetration resistance is shown Table 3.14 and the LSD is 355.

		Mean penetration resistance (kPa) by soil type		
Treatment	Bulk density	CL	M45	SSL
WG 0	Low	293	645	358
	Medium	381	1051	1182
	High	437	1722	1826
WG 5.89	Low	560	1852	742
	Medium	675	2541	3344
	High	797	3173	3645
WG 9.81	Low	863	2539	857
	Medium	965	3080	3524
	High	1199	4339	4195

Table 3.14 The interaction between treatment, bulk density and soil type on the penetration resistance (kPa). LSD = 355 (WG). The treatment indicates with grass (WG) and the matric potential (kPa).

- Regression equations

The regression equation from each line in Figure 3.24, Figure 3.25 and Figure 3.26 is shown in Table 3.15:

Soil type	Bulk density	Equation	p value
CL	1	Penetration resistance (kPa) = 72.22 (σ') + 264.88	$p<0.001$
CL	2	Penetration resistance (kPa) = 74.63 (σ') + 355.88	$p<0.001$
CL	3	Penetration resistance (kPa) = 104.98 (σ') + 399.74	$p<0.001$
SSL	1	Penetration resistance (kPa) = 63.25 (σ') + 375.12	$p<0.001$
SSL	2	Penetration resistance (kPa) = 301.15 (σ') + 1379.42	$p<0.001$
SSL	3	Penetration resistance (kPa) = 284.74 (σ') + 1934.62	$p<0.001$
M45	1	Penetration resistance (kPa) = 627.16 (σ') + 571.41	$p<0.001$
M45	2	Penetration resistance (kPa) = 691.06 (σ') + 1103.28	$p<0.001$
M45	3	Penetration resistance (kPa) = 924.39 (σ') + 1547.50	$p<0.001$

Table 3.15 Regression equations for CL, SSL and M45 soils at each bulk density (WG). Analysis used Statistica.

The effect of grass roots on soil strength (WG-NG)

To determine the net effect on soil strength as a result of the addition of grass roots into the soil matrix, the NG and WG results were compared using ANOVA. The NG experiments originally used 5 matric potentials but this was reduced to three (0, 5.98 and 9.81 kPa) to match the matric potential data available for WG.

Initially, all the data for WG and NG were plotted in order to determine whether a single relationship existed. Figure 3.27 below shows this, $R^2 = 0.03$

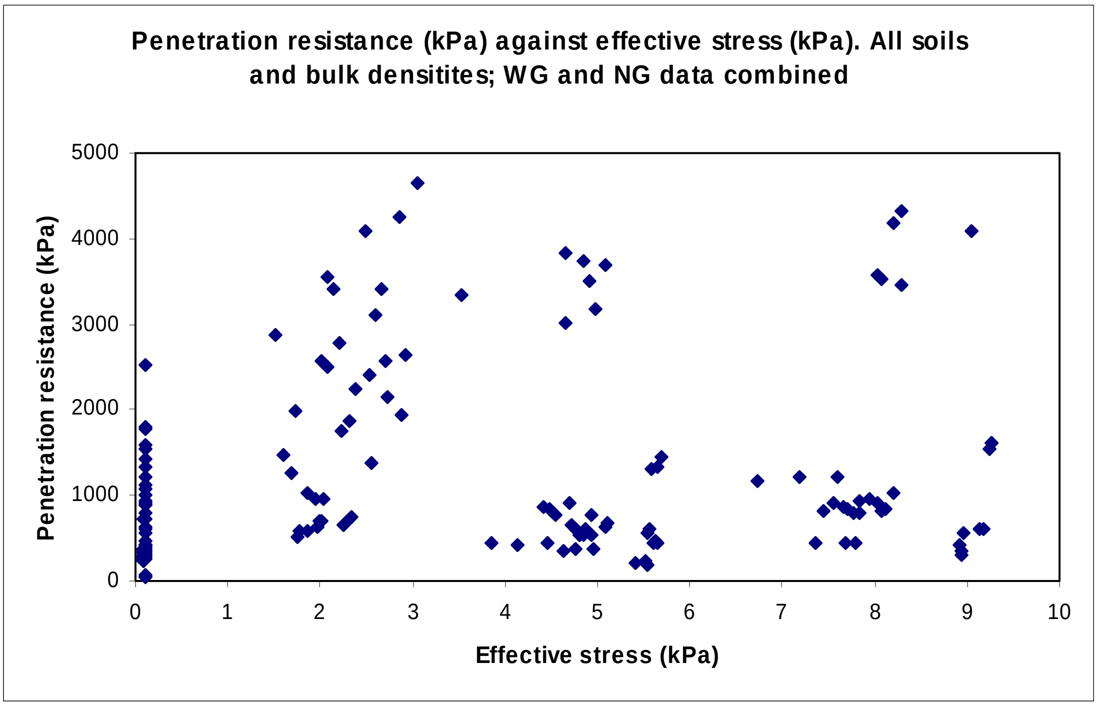


Figure 3.27 Penetration resistance against effective stress for all soil types and bulk densities; WG and NG combined

The following three figures show the results by soil type and bulk density. The LSD is shown on each figure.

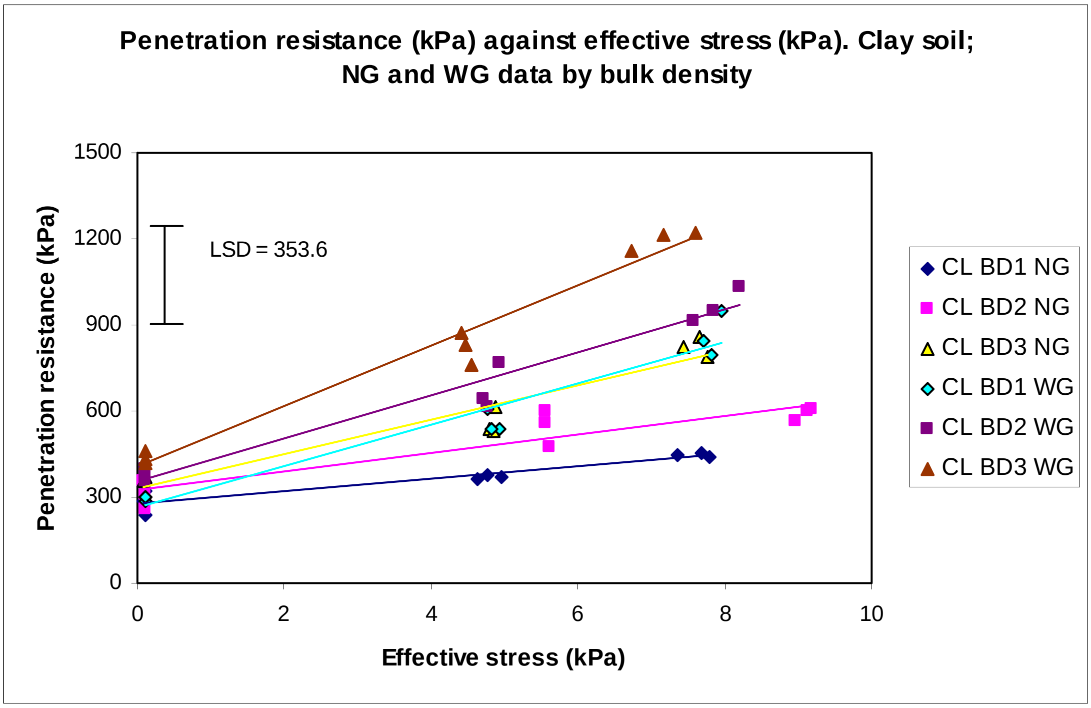


Figure 3.28 Penetration resistance against effective stress for Clay; NG and WG. Error bars are shown where they extend beyond the point.

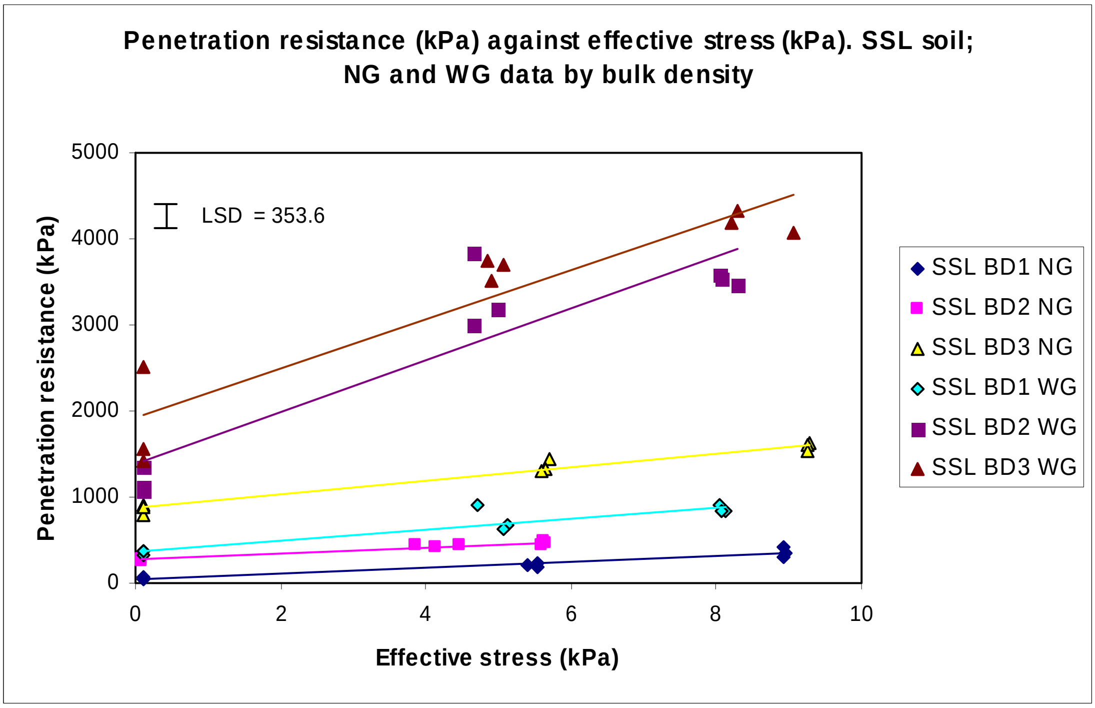


Figure 3.29 Penetration resistance against effective stress for Sandy Silt Loam; NG and WG combined. Error bars are shown where they extend beyond the point.

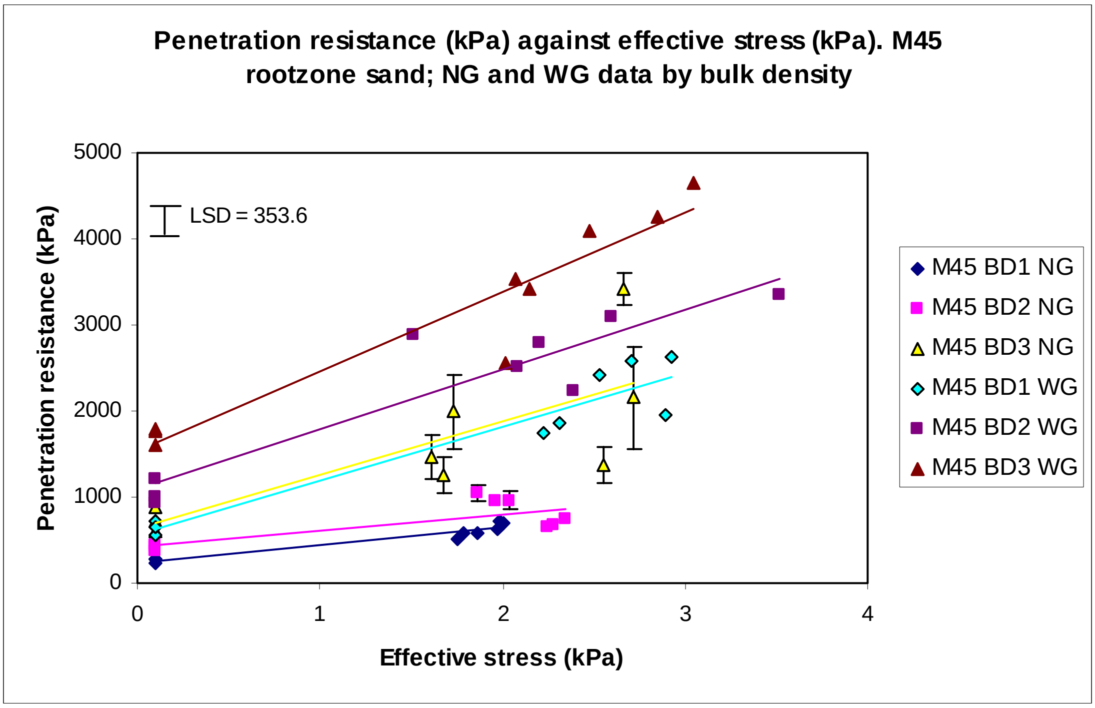


Figure 3.30 Penetration resistance against effective stress for Mansfield 45; NG and WG combined. Error bars are shown where they extend beyond the point.

- ANOVA

		Mean penetration resistance (kPa)		
Treatment	BD	CL	M45	SSL
NG 0	1	281	262	62
	2	308	415	273
	3	359	759	884
NG 5.89	1	369	581	214
	2	545	713	449
	3	560	1616	1403
NG 9.81	1	448	704	367
	2	591	1011	473
	3	825	2381	1634
WG 0	1	293	645	358
	2	381	1051	1182
	3	437	1722	1826
WG 5.89	1	560	1852	742
	2	675	2541	3344
	3	797	3173	3645
WG 9.81	1	863	2539	857
	2	965	3080	3524
	3	1199	4339	4195

Table 3.16 ANOVA results for penetration resistance (kPa); NG and WG (LSD = 353.6). The treatment indicates no grass (NG) or with grass (WG) and the matric potential (kPa).

The significant difference matrix in appendix VIII shows all the significant differences between the data points. However, Table 3.16 shows the significant interaction between treatment, bulk density and soil type. The mean penetration resistance is shown and the LSD is 353.6. Differences greater than 353.6 are significant at $p<0.05$.

The effect of grass roots on the WRC and σ'

Further to Figure 3.3 and Figure 3.4 the effect of the addition of grass on the WRC is demonstrated for CL and M45 soils at the lowest bulk density, but is indicative of the trend observed at each density.

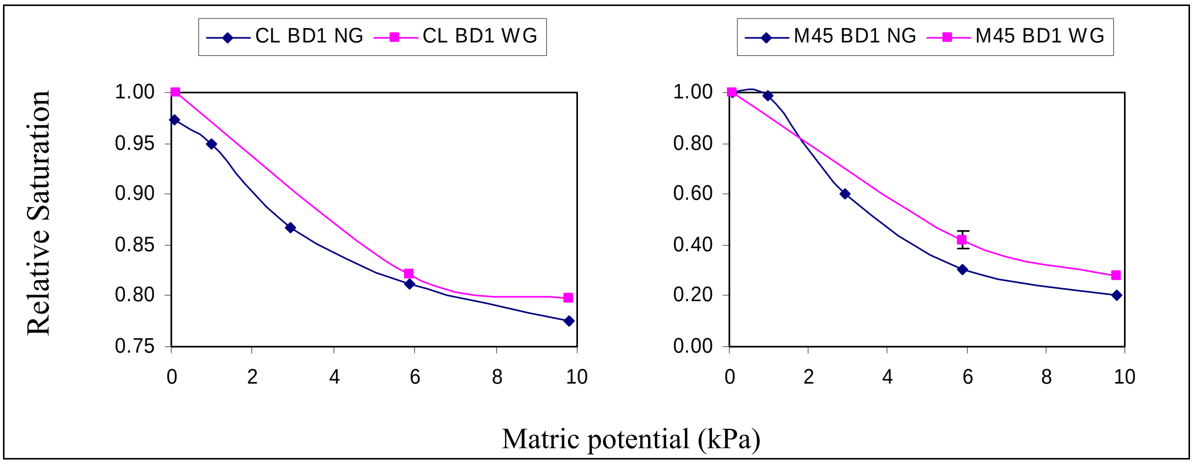


Figure 3.31 The effect of increasing matric potential (kPa) on the relative saturation of the CL soil (left) and M45 rootzone (right). The effect of grass roots is also demonstrated. Bulk Density (BD) 1 values are used and error bars are shown where they extend beyond the point.

The effect of grass roots was to increase the relative saturation at any given matric potential. The crossing of the lines in Figure 3.31 for the M45 soil is likely to be due to a lack of data points; WG experiments only used three matric potentials, NG experiments used five.

The change in effective stress with increasing matric potential due to the addition of grass roots is also demonstrated. Figure 3.4 demonstrated that the relationship between them may not be linear and this is a function of the soil type. Using the CL and M45 results, Figure 3.32 is presented:

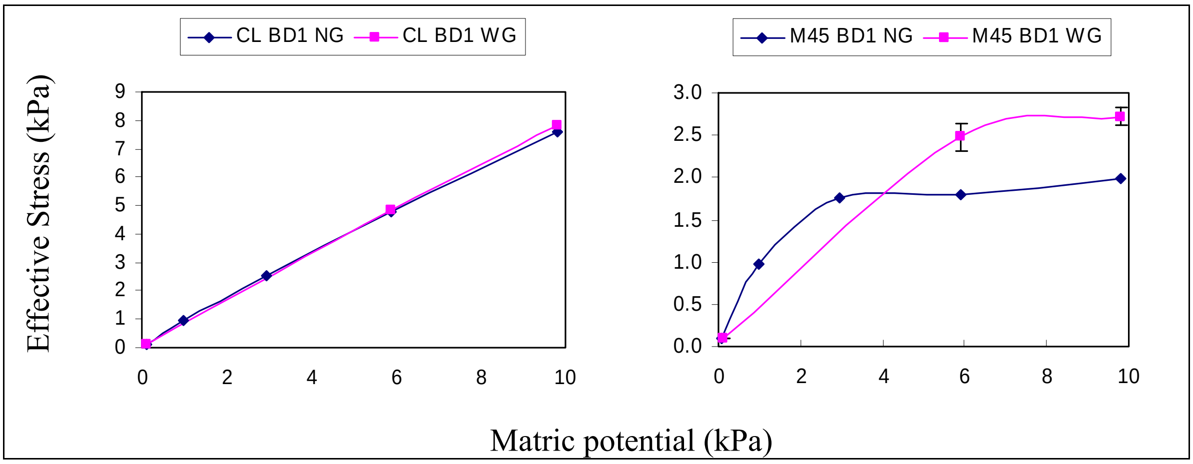


Figure 3.32 The relationship between effective stress and matric potential for the CL and M45 soils. The effect of grass roots is also shown. Only the lowest bulk density is shown and error bars only used where they extend beyond the point.

Although the relative saturation of the sample was greater for a given matric potential due to the addition of grass roots, the effective stress of the soil was greater as a result of grass inclusion. For CL, this occurred after approximately 5 kPa matric potential and 4 kPa for M45. However, as with Figure 3.31, the crossing of the two lines may be a function of reduced data points and therefore, reduced detail.

3.2.4 Chapter discussion

The objective of this chapter was to determine the appropriateness of using the concept of effective stress to predict the strength of soil intended to support sport. The results of the initial study, using a needle penetrometer and utilising extremely slow penetration speeds, were not corroborated by the later study under conditions representative of those found *in situ*; generally compact soils of a heavy nature found in poor quality sites such as local authority pitches and sands used in the construction of playing pitches for wealthier clubs. A relationship between effective stress and penetration resistance was established during the initial phase which was contrary to other published research investigating the use of effective stress to explain soil strength when using a cone penetrometer. In particular this study failed to control bulk density and a wide range of values were apparent on completion, and still a single model was determined, although primarily reliant on the 3 ‘soils’ and the effect of the two sand types were limited.

The changes instigated for the second phase of experiments resulted in a single relationship covering all soils and bulk densities not being discovered. A number of factors may have caused this: The rate of penetration was increased from 2 mm/min to 200 mm/min. Increased penetration speeds may caused soil build-up ahead of the cone (as discussed by Mulqueen *et al.,* (1977)) or prevented pore water pressure build-up ahead of the cone from dissipating in the soil (Bradford 1986). The size of the cone may also have influenced the result; the cone used in section 3.2.2 was closely matched to the size of the sand particles and may not have effectively detected changed in density due to reduced friction and shear around the advancing cone. The larger cone would have had greater soil-metal friction, but would also have produced a greater pressure bulb ahead of the cone (Figure 3.5), identifying differences due to density and soil type more effectively. Finally, 3 replicates may have been too many in the cylinders used in section 3.2.3, and edge effects became significant; the pressure bulb around the advancing cone was contained by the cylinder dimensions, resulting in an exaggerated increase in penetration resistance. Figure 3.5 suggests this is likely to have been the case in the SSL and M45 samples.

Also contrary to previous studies, the use of log transformed data was not necessary in order to obtain a linear relationship.

Even noting the above issues, the results demonstrate strongly significant R^2 values are achievable when using effective stress as a predictor of soil strength, assessed using penetration resistance, for each soil type and bulk density, only falling below 0.5 on one occasion (M45 BD2 NG). The results were linear and the increase in bulk density resulted in an upwards shift of the relationship, for any matric potential. This demonstrated by the regression equations in Table 3.12 and Table 3.15; a systematic increase in both the slope of the line and intercept is exhibited for each increase in bulk density, in each soil type, even with the addition of grass roots. For the NG experiments, the effect of bulk density was negated by moisture content for CL (Figure 3.19) and M45 (Figure 3.21); at low matric potentials, the differences between the densities were not significant, but as the sample dried, the differences became significant. The SSL samples were not significantly different between BD1 and BD2 however the increase to BD3 resulted in a significant increase in penetration resistance. This is probably due to inter particle friction that became apparent at the higher density, but was not an issue at lower densities. This demonstrates difficulties with managing this soil type, especially if high penetration figures wish to be avoided; the density of the soil must be managed to prevent inter particle friction becoming a significant factor. The WG experiments exhibited similar results; differences between densities became more significant as soil drying occurred and this was accentuated by the increase in bulk density. This also highlights a management issue; where higher bulk densities are required to aid soil strength, benefits will be lost if the soil is poorly drained, and the effect of grass roots on soil strength will be lost, or minimised.

The results of Anova demonstrated differences between the soil types and between the NG and WG experiments, explaining why a single model could not encompass all the data. Figure 3.18, Figure 3.23 and Figure 3.27 demonstrate the relationship between effective stress and penetration resistance for the NG, WG and NG and WG combined, respectively. On no occasion was there a significant R^2 value to encompass all the data. Data were not log transformed to prevent difficulties when untransforming data, and because the effect of bulk density was clearly a factor that had to be addressed. The R^2 values presented in Table 3.9 demonstrate that for each soil type, grouping the three densities produced mixed results; only the CL soil had an R^2 value greater than 0.5. However, when grass was present, it was possible to group the three bulk densities together from each soil type and three R^2 values greater than 0.5 were generated (Table 3.11). It seems that the effect of grass roots was to minimize the variability between the bulk densities; with the rise in penetration resistance being the greatest in the lower density samples, and least in the higher density samples. This is a function of the pore spaces available for root exploration being greatest in the lower density samples, enabling denser rooting to be more likely within the soil sample, rather then between the sample and the inside edges of the container, which was observed in the laboratory.

The results found in the second phase of experimentation demonstrate significant differences between each soil type. The differences are a function of the degree of cohesion and friction for each soil type, but given the discussion on the change in effective stress with changes in matric potential, the pressure change over the depth of the sample may have had an impact and will be developed further.

Matric potential differences within samples

As discussed in section 3.2.3.1, tension was set to the mid point of the samples, whether using a tension table or individual tensiometer. Figure 3.33 demonstrates the difference in tension between the top and bottom of a sample when placed on a tension table set to 60cm (5.89 kPa). The actual matric potential at the top and bottom of the cylinder is shown in red:

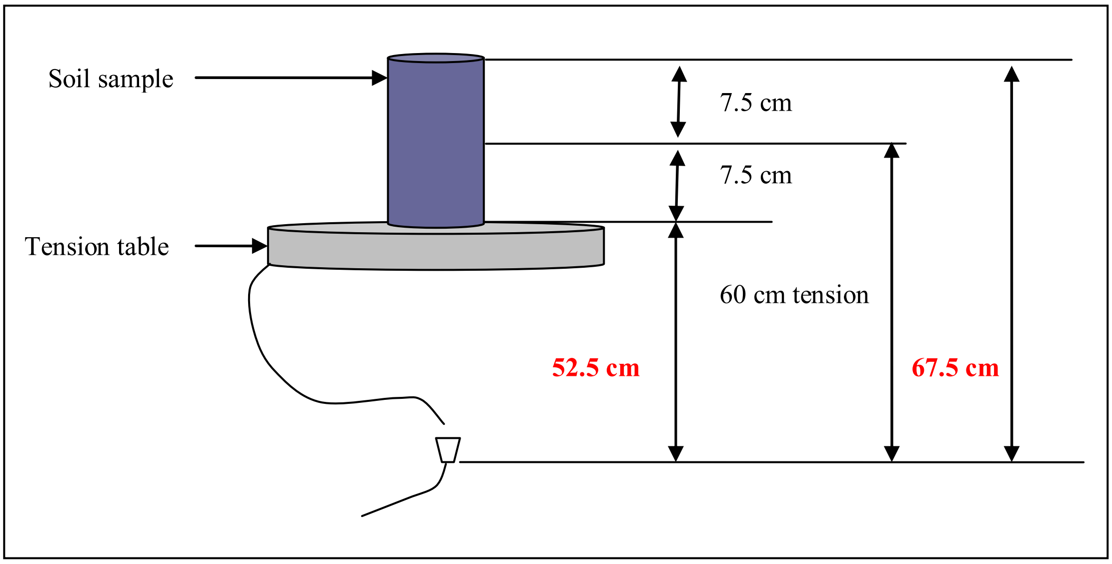


Figure 3.33 Differences in matric potential at the top and bottom of a sample set to 5.89 kPa at its mid-point on a tension table

The matric potential at the top of the cylinder is 6.6 kPa and 5.1 kPa at the base. The difference this makes to the relative saturation of the sample and ultimately the effective stress profile can be demonstrated by adapting Figure 3.31and Figure 3.32. This gives Figure 3.34 and shows the WRC for the CL soil and M45 rootzone and the relative saturation at the top and bottom of each cylinder for BD1; NG and WG:

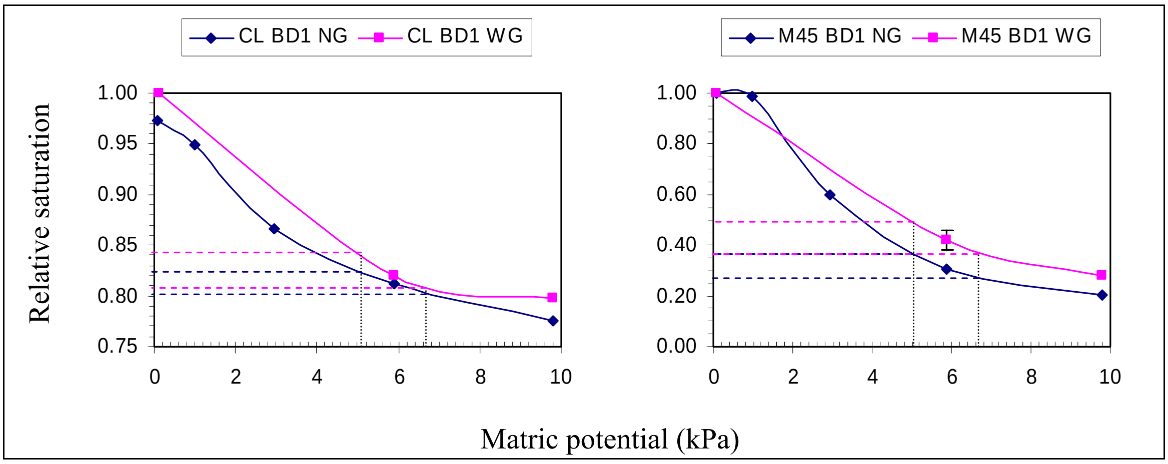


Figure 3.34 relative saturation at the top and bottom of each cylinder for CL and M45 soil, BD1; NG (blue line) and WG (pink line). The dotted lines represent the matric potential at the top of the cylinder (6.6 kPa) and the bottom (5.1 kPa) and using the y axis, the difference in relative saturation due to this can be determined using the dashed lines, coloured to match their respective WRC curve.

Figure 3.34 shows that the heavy textured CL sample had little difference in relative saturation between the top and bottom and the difference between them was approximately equal for both the NG and WG data; 0.83 (bottom) and 0.80 (top) for NG and 0.84 (top) and 0.81 (bottom) for WG. The M45 rootzone sand however demonstrated a greater change across the profile; 0.35 (bottom) and 0.27 (top) for NG and 0.50 (bottom) and 0.35 (top) for WG. These differences will also affect the effective stress, as shown in Figure 3.35:

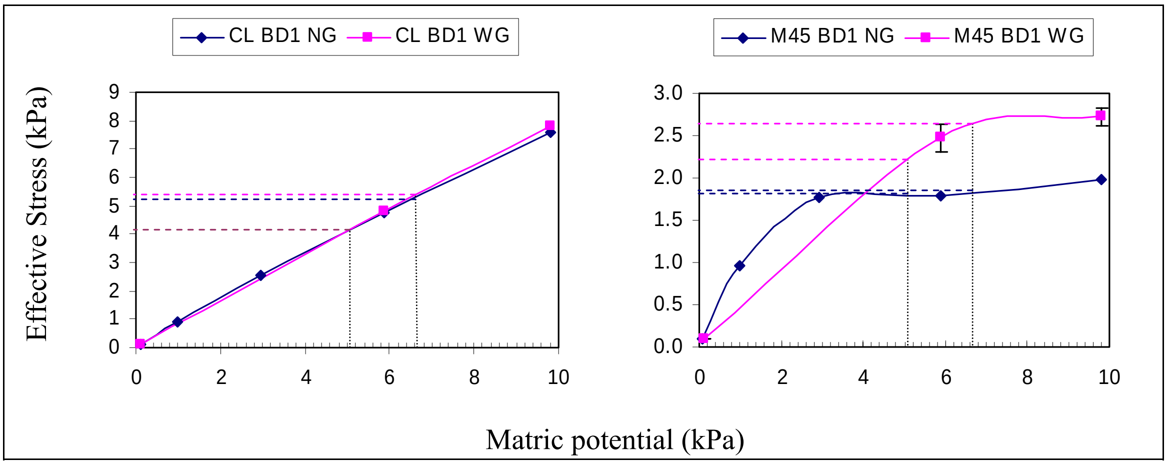


Figure 3.35 Effective stress profiles through the cylinder. Differences at the top (6.6 kPa) and bottom (5.1 kPa) of the cylinder are shown by the dotted lines. The coloured dashed lines indicate the difference in effective stress at the top and bottom of the cylinder, set to 5.89 kPa matric potential.

- Clay

Although the relative saturation change is very small over the depth of the sample (0.03), the change in effective stress is one kPa. At the top of the sample, the effective stress for both the NG and WG is greater and reduces towards the base of the sample. It would be expected therefore that the curve of penetration resistance against depth for the CL soil would display this.

- M45 rootzone sand

Figure 3.35 shows the effect on effective stress for the NG samples was effectively zero. The flattening of the curve indicates that a change of matric potential did not increase effective stress over this range and therefore a trace of penetration resistance against depth would be expected to approximate a straight line. The WG samples demonstrated a different relationship between effective stress and penetration resistance, indicating greater strength at the surface of the sample than at the base. Once again, a peak in strength near the surface would be expected, before decreasing as a result.

Figure 3.36 shows traces of penetration resistance over the depth of the sample. As before, CL and M45 soils are used at BD1 for each. NG and WG data are shown and the traces are from samples set to 5.89 (kPa) tension.

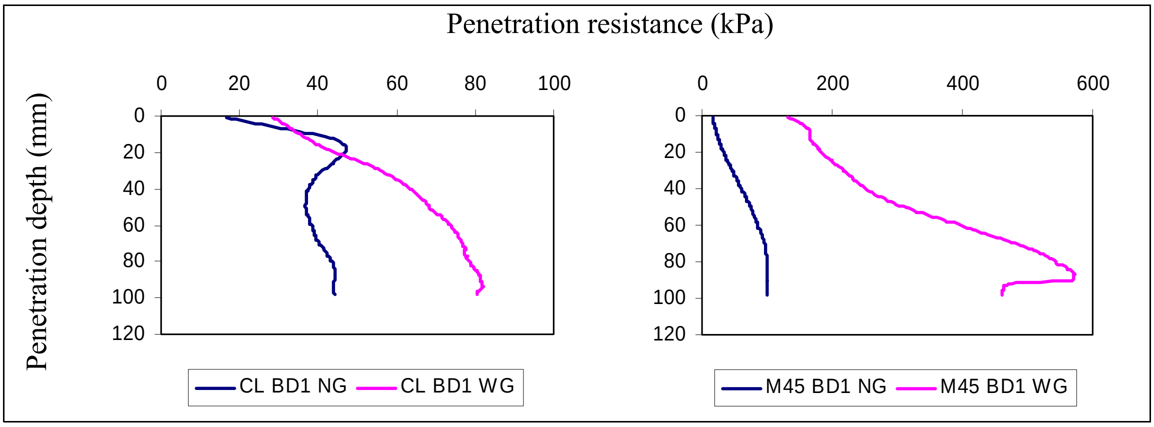


Figure 3.36 Penetration resistance over the depth of the sample. Data shows CL and M45 samples, NG and WG; set to 5.89 kPa matric potential.

- Clay

The discussion above suggested that penetration resistance may peak near the surface and steadily decline as a result of relative saturation differences at the top and bottom of the cylinder. The NG data does exhibit this. An initial peak is followed by a reduction in strength. At this point the type of failure has possibly altered from one dominated by shear, to one dominated by soil compression ahead of the cone and a steady state has been achieved. The results of the WG penetration test show a higher penetration resistance at depth compared to the surface. This is likely to have been caused by the same process as above but the addition of grass roots would have resisted the forces of compression, requiring the roots to have been broken, ultimately adding to the forces resisting the advancing cone.

- M45 rootzone sand

Both the NG and WG traces demonstrate higher penetration resistance forces at depth, rather than at the surface. These results support the argument by Rohani and Baladi (1981) that until the cone is embedded six times its length, the effect of density will not be accurately detected (in all the phase two experiments this equates to 150 mm; the depth of the sample). But this is also a function of the relationship between effective stress and matric potential. For the NG results, Figure 3.35 demonstrated no increase in soil strength with the difference in matric potential witnessed. The trace of penetration resistance against depth increases with depth (rather than a straight line) but only fractionally and probably as a result of friction between the sand particles. The WG result demonstrates the combined effect of roots and friction; Figure 3.35 would suggest that the effective stress is greater at the top of the sample than the base; however, this was not apparent. The effect of friction and the addition of roots was to greatly increase the penetration resistance with depth, beyond the strength attributable to effective stress.

It is clear from the above discussion that grass roots have two primary effects on the samples: Firstly, the WRC curves (Figure 3.31) demonstrate that for any matric potential the addition of grass roots increases the relative saturation of the sample.

Secondly, it is clear that where grass roots exist, soil strength cannot be described by the concept of effective stress alone, and therefore grass roots are adding to the strength of the soil. Both of these elements will be discussed in more detail.

The effect of grass roots on the moisture status of the soil

The impact of grass roots on the moisture status of the two contrasting soil types used so far in the discussion has been the same; for a given matric potential, the relative saturation of the sample is greater. This may be the result of grass roots occupying the larger pore spaces, preventing drainage. Therefore for a given potential, the sample will retain more water, as a greater potential is required to empty the smaller pores. To test this hypothesis as simple experiment was conducted to establish the effect of grass roots on the hydraulic conductivity of each of the soils used, at each of the bulk densities. The experiment (detailed in appendix IX) was conducted over two months to ensure that root decay had not occurred and the roots could only explore existing pores primarily, rather than explore the bulk soil and create new channels. The samples were produced to the same densities used in the analysis of effective stress, but packed to a depth 50mm below the height of the cylinder. This enabled a constant 50 mm head of water to be applied to each sample and the drainage water collected over a known time period. Once completed, the samples were sown with PRG; cultivar Dali, and tended for two months. After two months, the grass was trimmed to 10 mm and the experiment re-run.

It was found that in the CL soil and M45 rootzone sand, a significant reduction in saturated hydraulic conductivity (K_{sat}) was evident ($p<0.05$). For the SSL rootzone the increase in K_{sat} was significant, however for both the CL and SSL soil types, the actual values were very low.

These results support the hypothesis that grass roots use existing large pores initially and affect the WRC as shown. Over a longer time period, root decay may have occurred and the WRC could have returned to the original position (shown by blue lines in Figure 3.32).

The effect of grass roots on soil strength

The comparison of the NG and WG data demonstrated that grass roots increased soil strength by a factor of approximately 2-3, for each bulk density and matric potential (see Table 3.16) in the M45 rootzone material and SSL soil. The CL soil exhibited less of an increase, typically a factor of 1 – 1.5, measured using penetration resistance. Using bespoke apparatus (described by (Adams and Jones, 1979)) to determine soil shear, Adams *et al*., (1985) demonstrated a factorial increase in shear strength of between 2 and 3, as result of grass roots, in pure fine sand. In agriculture, soil management attempts to minimise soil strength to facilitate optimum crop growth (Wild, 1988), bioengineering however, is the term used to describe the process of adding plant roots into the soil matrix to enhance strength properties (Coppin and Richards, 1990).

The addition of plant roots creates a composite material made up of a weaker porous matrix and elements (roots) of a high tensile strength, relative to the soil (Styczen and Morgan, 1995). The authors also argue that the angle of soil friction (ϕ) is unaltered and the only effect is to move the line upwards. This was shown by *Adams et al*., (1985) however, Tengbeh (1989) found this only occurred in sand soils but not clay, while van Wijk (1980) presented data for sand over a silty clay loam and pure sand rootzone and in both cases the angle of the line had increased. Styczen and Morgan (Styczen and Morgan, 1995) also suggested that the greatest benefit is near the soil surface where the root density is highest and soil is often at its weakest. 60-80% of grass roots occur in the top 50mm of the soil surface (Coppin and Richards, 1990) and van Wijk (1980) noted that although grass cover was thinning, the strength of the soil was still enhanced by the roots beneath the surface.

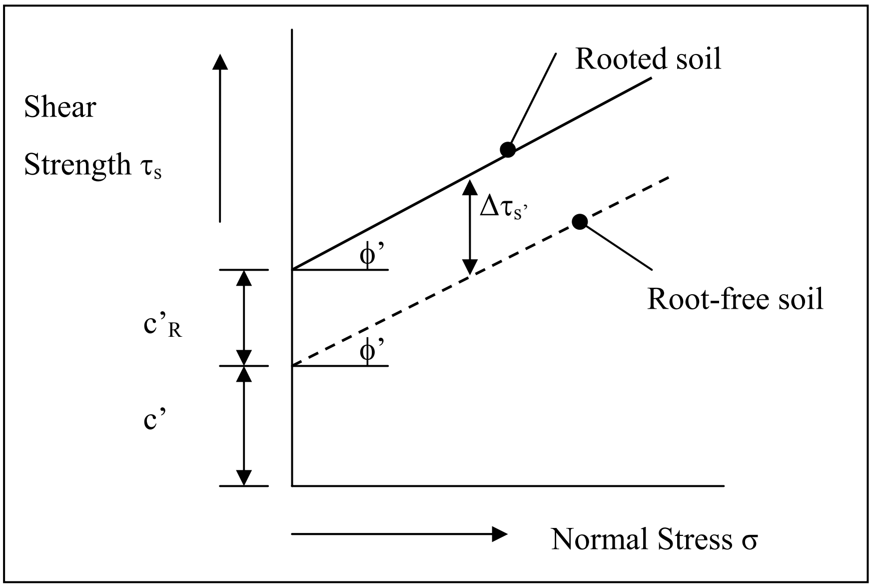


Figure 3.37 The change in shear strength with the addition of roots, adapted from Coppin and Richards (1990)

Figure 3.37 represents the general relationship between shear strength (τ_s) and normal stress (σ), with and without grass, based on the arguments by Styczen and Morgan (1995): The change in shear strength of the soil ($\Delta\tau_s$') is the same as the increase in effective cohesion due to plant roots (c'_R) although it has been discussed that this may not always be the case. The effective angles of internal friction (ϕ) are equal to reinforce this generalisation.

The results of the second phase of experiments demonstrated that the addition of grass roots increased penetration resistance for any given bulk density. Although the differences were not always significant, the additional increase in strength due to grass roots became greater matric potential increased, indicating the complexity of the issue of predicting soil strength were a range of densities exist and where grass roots are within the soil matrix.

Finally, there are two important considerations of this study. The presence of comparably low bulk densities for each soil type would have enabled a greater indication of trends to be established. Although the selection of bulk densities was to represent compact sports pitches, decompaction procedures are often carried out throughout the playing season and the effect of reduced soil densities on the established relationships would have created a clearer understanding of the effects of these ground management options. Secondly, the WG results and subsequent discussion would have benefited from the use of more matric potentials. Three were chosen due to the limited supply of tensiometers, work space and the time involved in sample preparation. However, the results of the relationship between effective stress and matric potential, particularly for the M45 rootzone material (Figure 3.32) would have been clearer had more data been available.

3.2.5 Conclusions

Based on the results of the experiments and the above discussion the following conclusions are apparent:

1. A linear relationship between effective stress and penetration resistance was established for each soil type at each bulk density. This held true with the addition of grass roots, although penetration resistance was significantly increased in most cases. A single model encompassing all soil types, densities and with and without grass was not possible.
2. This presents a contradictory scenario; there is a need to drain soil to add to its strength properties, however, some moisture needs to be retained in soil that is easily accessible to grass roots to ensure they can grow and recover from damage.
3. If the bulk density of a pitch remains relatively stable during a playing season, it is clear that the only method of increasing soil strength is either by improved drainage to increase the matric potential, or through the addition of grass roots; which may be particularly difficult to achieve during winter months. Areas on the pitch repaired with loose sand will be inherently weaker than the surrounding soil as demonstrated by these results, and a player running across established and repaired areas may therefore be exposed to a greater risk of injury, although as highlighted in chapter 2, the link between soil strength and injuries has not been established.
4. The results demonstrate that the effects of density and grass roots are both negated where the matric potential is low i.e. near saturation. It is clear therefore that any attempts to increase density or increase grass cover to contribute to the strength of the soil, particularly to contribute to the degree of

traction available to players, will be wasted if play occurs during periods where the soil is near or at saturation.

5. The results demonstrate that where grass roots are present in the soil, the strength characteristics cannot be described using effective stress alone. It is foreseeable that a correction factor may need to be added to represent the rooting density and more research on this subject is required.
6. Grass roots not only affected the strength of the soil, but also the water release characteristic. At any matric potential, the relative saturation of the soil was greater when grass roots were present. It was argued, with the results of further experiments, that the grass roots are occupying the larger pores and reducing K_{sat} and drainage properties. Therefore, water remaining in the soil is held in smaller pores and to achieve similar moisture contents, greater matric potential is required, possibly indicating the need for deeper drainage schemes.
7. Although the study omitted low bulk densities, the use of effective stress did successfully link soil strength (determined using penetration resistance) to the moisture status of the soil. Further research should aim to link the results of player-surface interaction tests to effective stress.

3.3 Chapter summary

Previous studies have looked to the concept of effective stress to explain the resistance exerted by the soil on plant roots and determine whether crop yields are reduced due to deceased water availability or increased soil strength, inhibiting root exploration.

In bioengineering and the sports turf sector, there is a need to enhance the strength properties of the soil to stabilise slopes or improve the traction properties of a sports field. Extensive drainage will increase the matric potential of the soil and through the concept of effective stress this has been shown to increase its strength. However, the effect of bulk density, particularly on granular material has been shown to affect this relationship and it is also clear that grass roots contribute significantly to soil strength by a factor of 2-3. Effective stress may need a correction factor to account for root density if it is to be used in a sports turf scenario, however, a prediction of soil strength, with and without grass and at three bulk densities was shown to be possible.

The two Performance Quality Standard (PQS) tests which determine the quality of player surface interaction are also measures of soil strength; for the results of this chapter to be of use to a sports turf consultancy firm, and be used in a model to predict the quality of a pitch, the link between effective stress and measures of traction and hardness need to be examined. This is the primary focus of chapter 4

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Chapter 4 PQS and soil physical conditions

In response to the mixed results reported in previous studies and the absence of a clear conclusion regarding how a Groundsman can manage or manipulate a pitch to achieve a desired level of quality, *in situ* tests were conducted. The tests also sought to verify the relationship between effective stress and soil strength, although the principal objectives were;

- To investigate the relationship between Performance Quality Standard test results and a variety of soil physical conditions
- To investigate the possibility of predicting the outcome of Performance Quality Standard tests, using easy-to-measure pitch factors as predictor variables. These regression equations would be used to develop a model for monitoring pitch quality in real-time (chapter 5).

The aim of this chapter is to provide a clear link between measures of player-surface interaction quality and soil physical conditions, in order that pitch management can be targeted and tools selected according to the desired outcome.

4.1 Methodology

Contact was made with a number of football clubs in 2003 to seek permission to access the pitch for testing. The research aimed to test a variety of pitch construction types and therefore visit clubs in the Premiership (or Scottish Premiership), in the lower leagues and private schools. Many clubs refused permission however, a total of 15 clubs gave permission which resulted in a total of 25 pitches. Tests were scheduled to occur within the 2003/4 season. Unforeseen circumstances prevented this and tests actually took place during January / February and May / June 2004 and April / May 2005. Due to the summer renovation work in 2004, three pitches were omitted but the total number of visits was 72, and with five tests being carried out on each pitch a total of 360 data points were produced.

Correlation (section 4.2.3) and regression (section 4.2.4) analyses generated many relationships to investigate. Only those pertinent to accepted theory will be discussed in detail. For the purposes of this study, a minimum of 0.5 for correlation coefficients (r) and regression statistics (R^2) was used to disregard the many statistically significant relationships that fell below this threshold.

4.1.1 The clubs

The clubs that gave permission are detailed in Table 4.1. This table shows the number of pitches visited for each club and a note regarding their identifying features. Those visited only twice, due to summer renovation work, are marked with an *.

Club ref	Pitch ref	Club or school name	Pitch note	Visit (V) date V1	V2	V3
1	a	St Christophers School, Letchworth	One training pitch	F04	M04	A05
2	a	Royal Medical School Ipswich	First team pitch	F04	M04	M05
3	a	Ipswich Town FC	Stadium	F04	M04	M05
3	b	Ipswich Town FC	Training ground	F04	M04	M05
4	a	Charlton Athletic FC	Pitch 1	J04	M04	A05
4	b	Charlton Athletic FC	Pitch 2	J04	M04	A05
4	c	Charlton Athletic FC	Pitch 3	J04	M04	A05
5	a	Hearts FC, Edinburgh, Scotland	Stadium	J04	M04	A05
6	a	Rangers FC, Glasgow, Scotland	Stadium	J04	M04	A05
7	a	Sunderland AFC	Fibresand	J04	M04	A05
7	b	Sunderland AFC	Rootzone	J04	M04	A05
7	c	Sunderland AFC	Soil/sand slit	J04	M04	A05
8	a	York City FC	Stadium	J04	M04	A05
8	b	York City FC	Training ground	J04	M04	A05
9	a	Bolton Wanderers FC	Reebok Stadium	J04	M04	A05
9	b	Bolton Wanderers FC	Training ground	J04	M04	A05
10	a	Manchester City FC	Training ground	J04	M04	A05
11	a	Shrewsbury Town FC*	Stadium	F04	-	M05
12	a	Oswestry School	First team	F04	J04	M05
13	a	Cheltenham Town FC	Stadium	F04	J04	M05
13	b	Cheltenham Town FC	U17/U19's pitch	F04	J04	M05
14	a	Yeovil Town FC*	Stadium	F04	-	M05
14	b	Yeovil Town FC	Training Pitch	F04	J04	M05
15	a	Bristol Rovers FC*	Stadium	F04	-	M05
15	b	Bristol Rovers FC	Training Pitch	F04	J04	M05

Table 4.1 Football clubs visited and the pitches tested. J04, F04, M04 and J04 refer to January, February, May and June 2004 respectively. A05 and M05 refer to April and May 2005.

4.1.2 Pitch testing

The tests

Table 4.2 shows the tests conducted at each location on each pitch and Figure 4.1 shows the location of the test positions. At each test location some tests were replicated three times in order to produce a mean reading for that location and are identified with an *.

PQS Tests	**Soil Physical Tests**
Grass Cover (%)*	Moisture content (%)*
Evenness (mm)*	Matric potential (kPa)
Traction (Nm)	Penetration resistance (kPa)*
Hardness (g)*	Bulk Density (Mg/m^3)
Grass length (mm)	Particle size analysis

Table 4.2 Performance Quality Standard tests and soil physical tests performed *in situ*.

- Grass cover (%)

Using a point quadrat the grass cover percentage was determined. The distinction between grass and weeds was not made, only between vegetated areas and bare soil. The point quadrat features dual pins to ensure the observer is looking directly down onto the surface and the presence, or otherwise, of grass at the end of the pins was recorded.

- Evenness (mm)

Using a 2 m straight edge and a metal wedge, the evenness of the playing surface was assessed three times in each test location. The straight edge was placed on the pitch and a gradated metal wedge pushed between them. The result of the test was a figure in mm which represented the maximum deflection in the surface.

- Traction (Nm)

It was not possible to purchase the necessary equipment to measure traction; instead it was manufactured in the University workshops following the guidelines presented by Canaway (1986). It differed from the design by Canaway in a number of ways; the shaft did not incorporate handles for lifting and the disk attached to the shaft by a square-fit socket. In order to ensure the studs had penetrated the soil surface effectively, the disk was first placed on the surface and stamped on. If this caused the disk to become unsteady, it was repeated. The total applied weights totalled 41 kg, resulting in a total test equipment weight of 45.6 kg. The final difference was in the use of a one handled, rather than two-handled torque wrench. The disk and position of the studs was identical to the design suggested by Canaway and the result was presented in Nm. See appendix X for full specifications.

- Hardness (g_{max})

Hardness was determined using the Clegg hammer. A 0.5 kg hammer was dropped 0.55 m onto the soil surface and the reading (g_{max}) recorded. The method followed STRI and BS7044 (BSi, 1990) guidelines and the one-drop method was performed.

- Grass length (mm)

The grass length was determined once at each test location using a rising-disk apparatus, as advised by BS 7370 (BSi, 1991).

- Moisture content (%)

Volumetric moisture content was determined using a Theta™ probe, however, its operation was unreliable due to the metal probes becoming damaged in hard ground, unable to accurately read moisture content in frozen ground and the hand-held unit broke, preventing its use during further visits. A soil core was taken and the moisture content used during the analysis was the figure derived from the core, not the theta probe.

- Matric Potential (kPa)

In order to determine matric potential, a quick-draw tensiometer was fabricated. Attached to a digital manometer, the output (mbars) was converted into kPa during post test analysis. The tensiometer featured a piston and the ability to raise or lower the piston increased the speed at which equilibrium could be found. In trials it was found that the tensiometer reached equilibrium in 15 minutes on a sandy loam soil, without the need to raise or lower the piston, therefore during testing the piston was used to set the tensiometer to zero, the first 3 or 4 minutes of time v tension data were then recorded, followed by a ten minute period in which all the other tests were conducted. On completion of the tests, the reading after a total period of 15 minutes was noted before the tensiometer was moved to the next test location. For design and calibration details, see appendix XI.

- Penetration resistance (kPa)

To measure penetration resistance over a shallow depth of penetration a Mecmesin Advanced Force Gauge (AFG) was used. The same cone was attached to the device as used in the experiments detailed in section 3.2.3 and penetration depth was 100 mm, after the cone was fully embedded. The device was limited to displaying the maximum force registered (N) over the depth of penetration, rather then the mean penetration used in the previous chapter. The load (N) was converted to a force (kPa) for analysis.

- Bulk density and particle size analysis

A soil core was taken from each test location on each pitch. This core was split into sections representing the top 0 – 50 mm (labelled as ‘upper’) and 50-100 mm (labelled as ‘lower’). Once the cores were split they were weighed before being saturated. Once saturated a ‘wet-end’ water release characteristic was determined using the same tensions detailed in chapter 3 (0, 0.98, 2.94, 5.89 and 9.81 KPa) using tension tables. The air and oven dry moisture contents were also established.

After oven drying at 105°C, bulk densities for both the 'upper' and 'lower' sections were calculated. The pipette method was used to determine the particle size distribution of every 'upper' core section.

Test locations

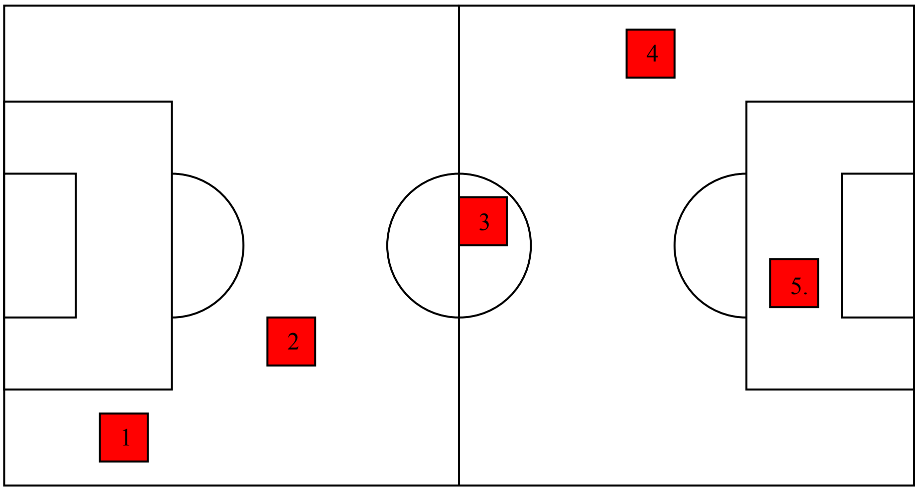


Figure 4.1 Pitch test locations. The numbers indicate a pitch position reference which was adhered to throughout the study enabling differences in the data to be detected depending on where the data was collected.

Figure 4.1 was drawn on the data collection sheets so that reference points could be marked on the map (such as access ramps etc) enabling the same pitch locations to be selected each visit. Test results were recorded under the relevant position number which enabled separation of goal mouth and centre circle results (high wear areas), wings (low wear areas) and a mid-wear region of the pitch (position 2).

The tensiometer test was started first at each location and all the remaining tests occurred within approximately 2 m x 2 m of the tensiometer.

4.1.3 Effective stress and soil strength

Chapter 3 detailed the relationship between the concept of effective stress (σ') and a measure of soil strength, using a penetrometer. *In situ* data was collected in order to examine this relationship further. It was argued that traction and hardness tests measure soil strength; therefore the concept of effective stress was investigated in order to verify whether prediction of pitch traction and hardness was possible.

Penetration resistance data was obtained using the Advanced Force Gauge (detailed in section 4.1.2). To calculate effective stress, relative saturation of the soil cores was determined in the laboratory and multiplied by matric potential, taken as the final reading (after fifteen minutes) from the quick-draw tensiometer. This is also detailed in section 4.1.2.

4.1.4 The effect of weather

Logistically, it was not possible to cancel or rearrange visits due to inclement weather, therefore testing took place regardless. Rainfall was rarely monitored by clubs; therefore a note was made of the pitches that were tested during rainfall or irrigation events or when rainfall or irrigation had occurred the previous day. This was used to separate the data into wet or dry categories used in the analysis.

4.1.5 Statistical analysis

Initial analysis was conducted to ensure pitch data were normally distributed and determine overall trends across the playing surface and between the identified soil textural classes. Spearman rank correlation analysis was used to construct correlation matrices and General Linear Modelling using Statistica was used to generate linear regression models between the factors in order to address the objective of predicting traction and hardness qualities from other pitch measures.

4.2 Results and discussion

Initially, the data were analysed for normality. Data not normally distributed (Clegg hammer reading, penetration resistance, and percentages of; coarse sand, fine sand, silt and clay) were log-transformed and this removed the skewness in the data. Grass cover was heavily skewed in favour of 100% grass cover, although this factor was not transformed and the continuous variable was used. All subsequent analysis used the transformed Clegg, penetration resistance, coarse sand, fine sand, silt and clay data.

4.2.1 Effective stress and soil strength

The results of the investigation reported in chapter 3 were dependent on soil type and bulk density. *In situ* tests utilised a quick draw tensiometer and analysis of soil cores in order to determine matric potential and relative saturation respectively. Pitch tests included three measures of soil strength: traction, penetration resistance and surface hardness. The limitation of the AFG was that the maximum penetration force was recorded, rather than the mean force as measured in the laboratory furthermore it became clear during tests that the tensiometer had not been tested in soils of equal compaction.

It was observed that the tensiometer output was not always relevant to the visible condition of the surface, therefore once all data had been collected; the relationship between volumetric moisture content and the final soil water tension reading obtained from each test location was compared. The range of moisture contents was limited however, the output of the tensiometer varied greatly. The scatter plot in appendix XII shows the lack of relationship between these two variables. During the tests, problems regarding the quality of the connections were encountered and although the tensiometer was primed with distilled water prior to each pitch test and transported with the ceramic cap at saturation, the reliability of the output is questionable. It is likely that due to limited time to equilibrate in the soil, the tensiometer had not done so and the readings are therefore unreliable.

Volumetric moisture content was therefore used as a factor rather than matric potential or effective stress in correlation and regression analysis.

Continued research into the appropriateness of effective stress as a means of predicting soil strength *in situ*, using penetration resistance or traction or hardness, should proceed with caution. The method of determining matric potential needs improving and testing under realistic field conditions, but the laboratory analysis was successful and effective stress may be a suitable method of linking player-surface interaction quality to a measure of soil moisture status. The impact of grass roots and bulk density may further complicate interpretation, while intensive management will prevent sensors for matric potential to be left permanently in the pitch.

4.2.2 Trends in pitch quality data

Determination of soil type followed a method similar to the STRI method outlined by Baker and Gibbs (1989) and McClements and Baker (1994). The results of the 5 particle size range analyses per pitch were averaged and the soil textural type determined per pitch. The single occurrence of sandy clay loam (*) was removed from the data set prior to all subsequent analyses. The physical properties of sand used in sport turf rootzones varies as a result of the total fine (silt and clay: <63µm) particles present. Table 4.3 therefore highlights the percentage of fine particles for each 'sand' textural type.

Club	Pitch	Textural Class (visit 1)	Textural Class (visit 2)	Textural Class (visit 3)
1	a	Clay	Clay	Clay
2	a	Sandy Silt Loam	Sandy Silt Loam	Sandy Silt Loam
3	a	Sand (5.2)	Sand (2.7)	Sand (2.7)
3	b	Sand (2.9)	Loamy sand	Sand
4	a	Loamy Sand	Loamy sand	Loamy sand
4	b	Sandy Loam	Sandy Loam	Sandy Loam
4	c	Sand (11.0)	Sand (7.7)	Sand (8.1)
5	a	Sand (5.6)	Sand (5.6)	Sand (8.9)
6	a	Sand (3.0)	Sand (3.0)	Sand (3.4)
7	a	Sand (2.7)	Sand (2.8)	Sand (5.2)
7	b	Sand (3.3)	Sand (2.1)	Sand (3.6)
7	c	Loamy Sand	Sand (6.3)	Loamy Sand
8	a	Sand (6.6)	Sand (3.7)	Sand (3.7)
8	b	Clay Loam	Sandy Clay Loam*	Clay Loam
9	a	Sand (4.2)	Sand (3.0)	Sand (4.9)
9	b	Sand (4.3)	Sand (2.2)	Sand (5.1)
10	a	Loamy sand	Sand (7.8)	Sand (11.2)
11	a	Sand (11.5)	-	Sand (12.2)
12	a	Clay Loam	Clay Loam	Clay Loam
13	a	Sand (6.5)	Sand (6.6)	Sand (5.5)
13	b	Clay Loam	Clay Loam	Clay Loam
14	a	Sand (8.25)	-	Sand (3.9)
14	b	Clay Loam	Clay Loam	Clay Loam
15	a	Sand (8.0)	-	Sand (5.4)
15	b	Clay	Clay	Clay

Table 4.3 Soil textural types per pitch and per visit determined using soil samples from the upper 50mm of the pitch. Missing data is due to the pitches undergoing summer renovation, preventing testing. The number in parentheses represents the percentage of particles <63µm.

Table 4.4 shows the standard of each pitch visited for the two player-surface interaction tests and its classification per visit. The method of classification followed the approach used by Baker *et al.*, (1988), but adapted to use the categories listed in the current PQS standards (IOG, 2001) of High (H), Standard (S) and Basic (B). The mean values per pitch are also presented with their rating. Where one test fell in the 'high' category and one in the 'basic', the 'standard' category was selected.

		Test conducted and result for each visit								
		Traction (Nm/quality rating)			Hardness (g/quality rating)			Overall rating		
Club	Pitch	1	3	3	1	2	3	1	2	3
1	a	29.6/S	49.2/H	45.6/H	101.5/H	156.7/B	133.5/S	S	S	S
2	a	33.2/S	46.8/H	44.8/H	110.3/H	153/B	110/H	S	S	H
3	a	38.8/S	46.8/H	44/H	125.3/S	98.2/H	130.5/S	S	H	S
3	b	41.6/H	52.8/H	48.8/H	94.3/H	106.3/H	131.3/S	H	H	S
4	a	35.2/S	44/H	43.2/H	124.9/S	115.7/H	120.5/S	S	H	S
4	b	35.6/S	40/H	54.4/H	108.8/H	81.5/H	121.1/S	S	H	S
4	c	32.8/S	46.8/H	50/H	126.7/S	151.7/B	124/S	S	S	S
5	a	36.8/S	38.4/S	38.8/S	92.8/H	133.2/S	134.9/S	S	S	S
6	a	38/S	46/H	37.6/S	100/H	116.5/H	127.8/S	S	H	S
7	a	47.2/H	50.8/H	44.8/H	115.1/H	158.3/B	118.1/H	H	S	H
7	b	52.4/H	49.6/H	52/H	98.3/H	157.8/B	107.8/H	H	S	H
7	c	52/H	57.6/H	43.2/H	128.8/S	186.7/B	122.6/S	S	S	S
8	a	37.6/S	42.8/H	42/H	103.5/H	123.3/S	109.9/H	S	S	H
8	b	22.4/B	31.6/S	34.4/S	86.5/H	105.7/H	106.6/H	S	S	S
9	a	40.4/H	41.6/H	40.4/H	127.9/S	137.3/S	100.1/H	S	S	H
9	b	38.8/S	50/H	54/H	85.3/H	112.9/H	106.2/H	S	H	H
10	a	46.4/H	54.4/H	50.4/H	109.7/H	119.9/H	92.2/H	H	H	H
11	a	25.6/B	-	43.2/H	83.6/H	-	147.9/B	S	-	S
12	a	29.2/B	55.6/H	38/S	70.6/H	192.5/B	101.9/H	S	S	S
13	a	42/H	47.2/H	49.6/H	134.3/S	73.2/H	143.2/B	S	H	S
13	b	37.6/S	40/H	43.2/H	115.4/H	68.2/H	148.7/B	S	H	S
14	a	43.6/H	-	49.2/H	146.3/B	-	120.4/S	S	-	S
14	b	37.2/S	62.8/H	43.2/H	129.6/S	256.7/B	116/H	S	S	H
15	a	33.6/S	-	36.8/S	126.6/S	-	154.9/B	S	-	B
15	b	30/S	50.8/H	39.2/S	116/H	275.2/B	148.7/B	S	S	B

Table 4.4 Performance Quality Standard results for all the pitches tested

In chapter 2, traction and hardness values were shown to vary with pitch position. Although the actual values and significance varied, the trend was clear; with maximum traction values recorded on the wing and minimum traction values recorded in the centre circle and goal mouth. The opposite was true for hardness data. Using the total data set, General Linear Modelling was conducted to establish variations according to pitch position. As detailed in Figure 4.1, numbers 1 and 4 were on the wing, 2 was between the wing and centre circle, 3 was within the centre circle and 5 was adjacent to the penalty spot.

4.2.2.1 Pitch quality tests; results and discussion

Analysis of the total data set demonstrated that there were no differences in traction ($p=0.42$) or hardness ($p=0.11$) values according to pitch position. The percentage grass cover did vary significantly however ($p<0.01$) with positions 3 and 5 having a significantly reduced grass cover compared to positions 1, 2 and 4, which were not significantly different.

Neither moisture content ($p=0.79$), 0-50mm bulk density ($p=0.72$) or 50-100mm bulk density ($p=0.97$) varied according to pitch position, although grass length was shown to differ across the pitch ($p<0.05$) with results as was grass cover.

The effect of textural class

For both traction (Figure 4.2) and hardness (Figure 4.3) there was significant difference in readings depending on the soil type of the pitch ($p<0.05$ and $p<0.001$ respectively).

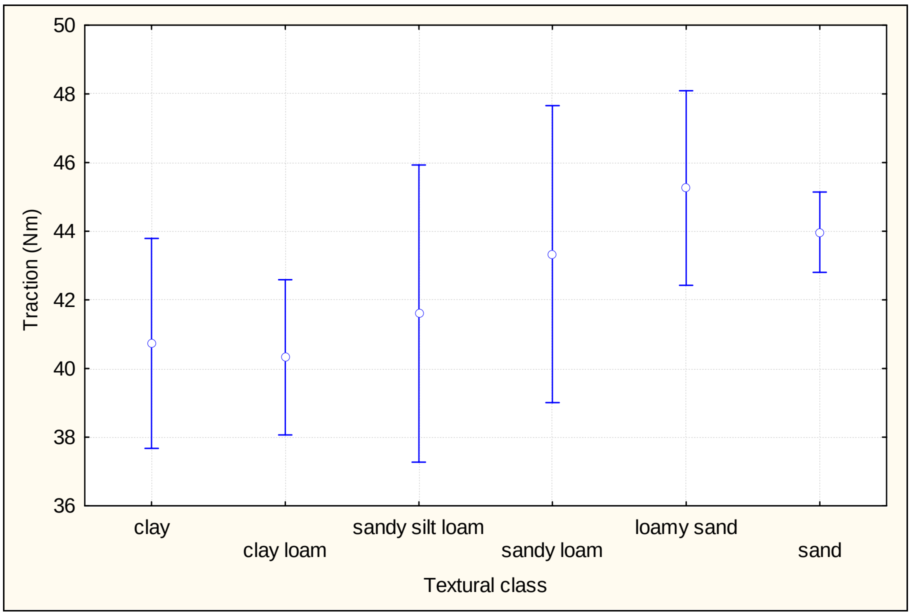


Figure 4.2 Traction readings according to soil textural class. Standard error bars are shown.

The clay loam soil type produced traction results significantly lower than all other soil types. The loamy sand soil type produced the greatest traction readings and the other soil types did not differ significantly.

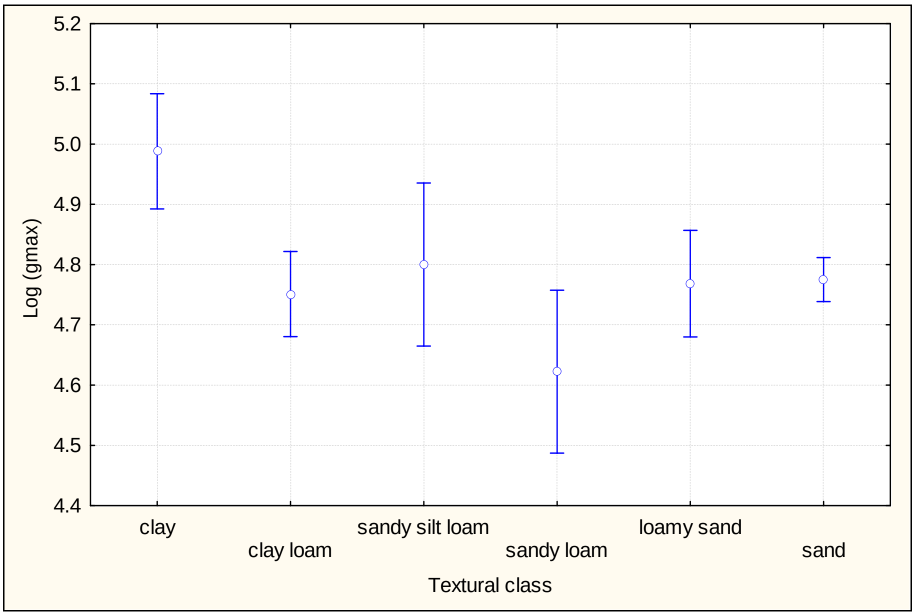


Figure 4.3 Log gmax (hardness) readings by soil type. Standard error bars are shown.

Sandy loam hardness readings were the lowest ($p<0.05$) and the clay soil results were the greatest ($p<0.05$). The rest did not differ significantly from each other.

The results also demonstrated that sand-based pitches varied the least for both traction and hardness.

The effect of textural class and pitch position

In order to determine the existence of differences across the pitch within textural classes, textural class*pitch position interactions were conducted for a variety of parameters. The results demonstrated that although variations existed between textural classes, within each textural class, there was little variation in readings across the playing surface. For both traction and hardness, there were no significant differences in readings across the playing surface within the same soil type (p=1.00 and p=0.99 respectively), but as discussed above, differences between soil types were evident.

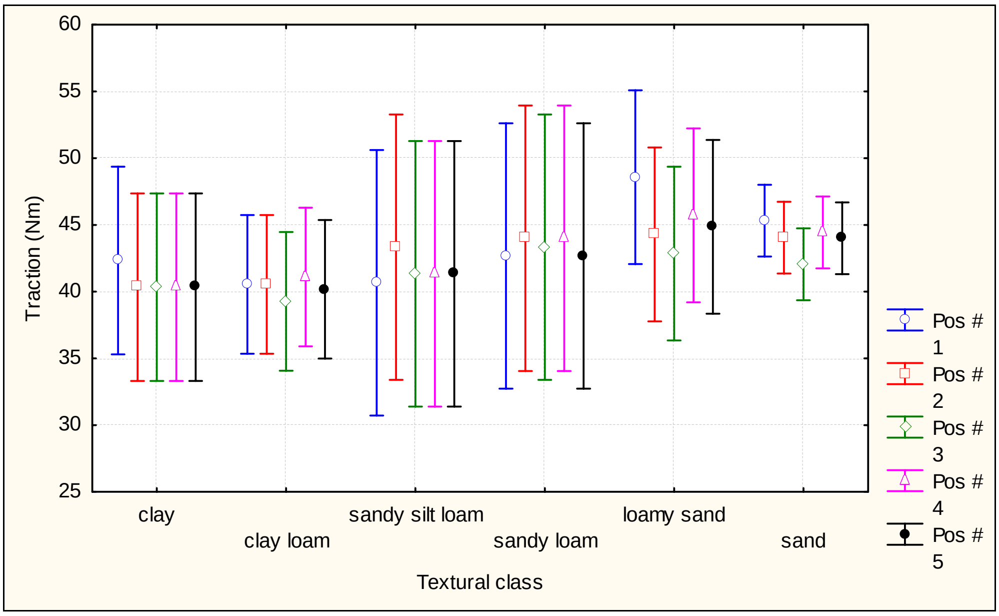


Figure 4.4 Traction readings according to pitch position and soil textual class. Pos # refers to the test positions as shown in Figure 4.1.

Traction readings varied least in the 'sand' category, but this may have been due to the larger number of tests on this type of pitch. The expected trend is that traction would be reduced in positions 3 and 5 as a result of wear. This is poorly evident above, however temporal variations are masked by grouping the data.

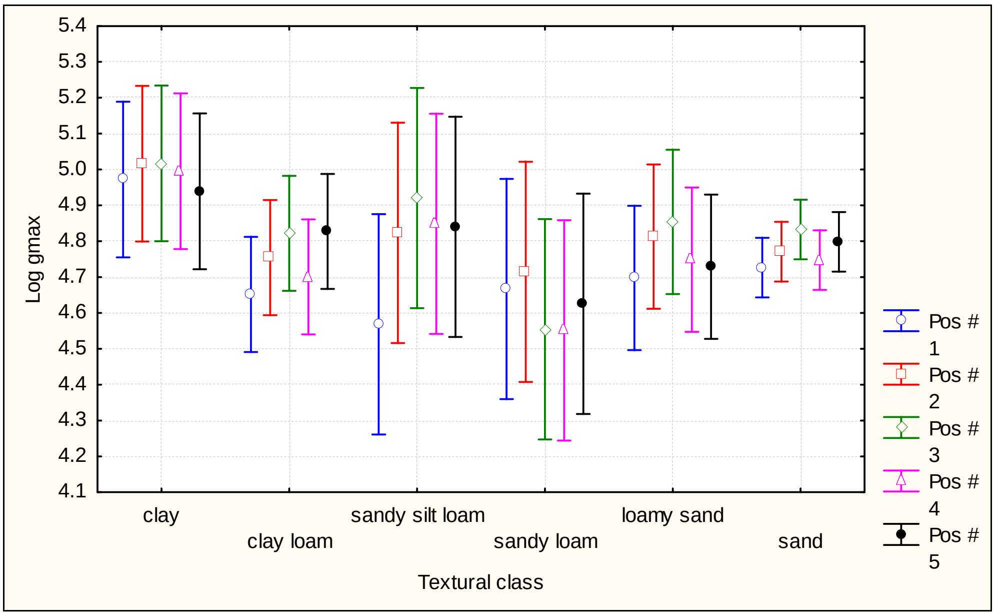


Figure 4.5 Log gmax (hardness) readings according to soil type and test position. Pos # refers to the test position as shown in Figure 4.1.

As with the traction results, 'sand' pitches demonstrated the least variability and previously reported trends were also visible; hardness was greatest at positions 3 and 5 as a result of increased wear and possibly increased bulk density. Again, temporal variations were masked by this analysis.

Variation due to pitch visit

Considering the total data set, the effect of pitch visit date can be highlighted for both traction and hardness using Figure 4.6 and Figure 4.7 below.

Traction readings were significantly lower ($p<0.05$) in the winter than both the summer tests. Hardness varied less between visits but visit one position 1 gave the lowest reading ($p<0.05$) while visit two, position three gave the highest reading ($p<0.05$).

Evident for both traction and hardness is an emerging pattern of variation across the pitch. Traction readings were consistently lowest for position three, while hardness values were consistently greatest at position three.

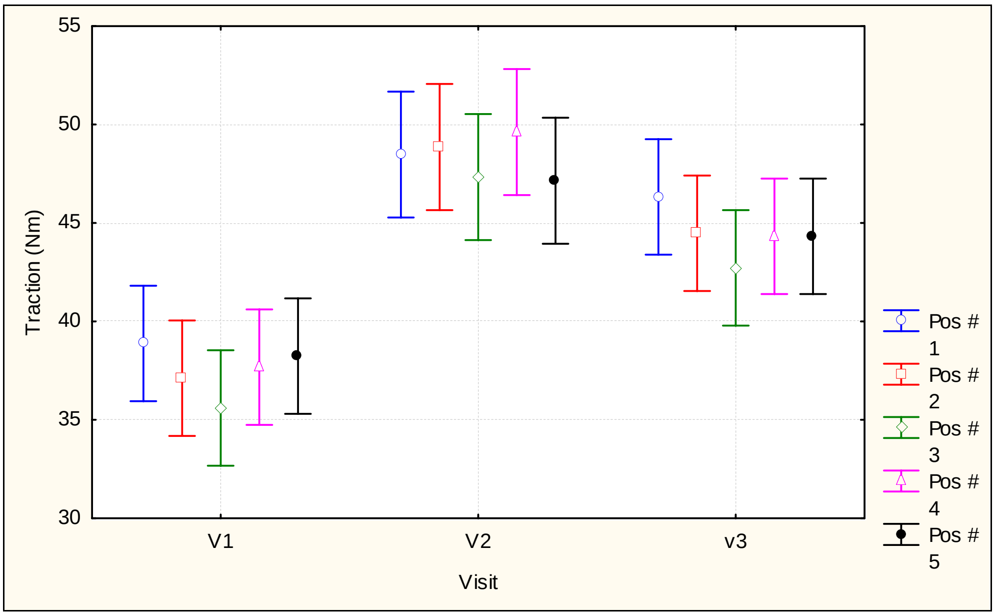


Figure 4.6 Traction variation with pitch visit; all data. Standard error bars are shown.

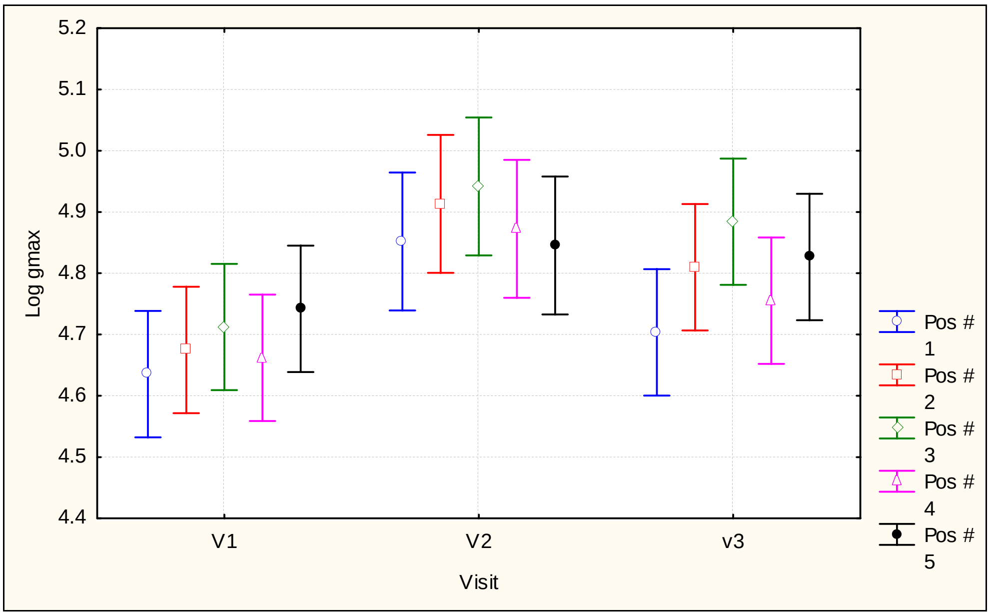


Figure 4.7 Log gmax (hardness) variation with pitch visit; all data. Standard error bars are shown.

The variation between visits was investigated further for two contrasting soil types; clay loam and 'sand'.

- Clay loam

Variation of traction and hardness with pitch position and visit date are demonstrated by Figure 4.8 and Figure 4.9.

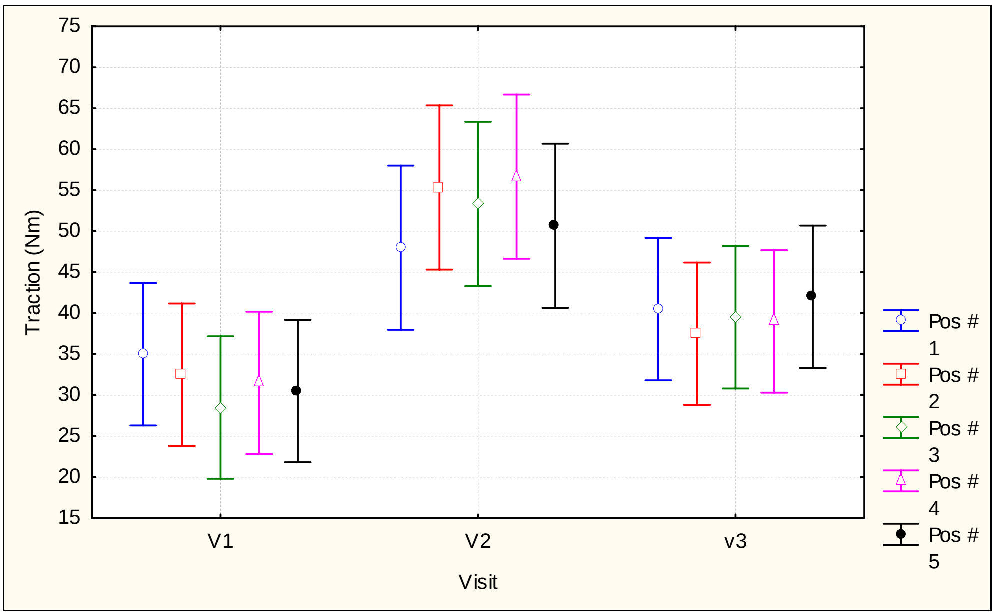


Figure 4.8 Traction variation due to pitch position and visit date; clay loam. Standard error bars are shown.

Traction readings during the winter (visit one) were significantly lower ($p<0.05$) than visit two, but not visit three. It is possible that the very hot and dry conditions observed during visit three resulted in either brittle failure of the soil, or poor stud penetration, which resulted in lower readings. Interestingly, the pattern of variation across the pitch is less clear, particularly during visit three. Improved grass cover observed during visit two may have resulted in the high traction readings.

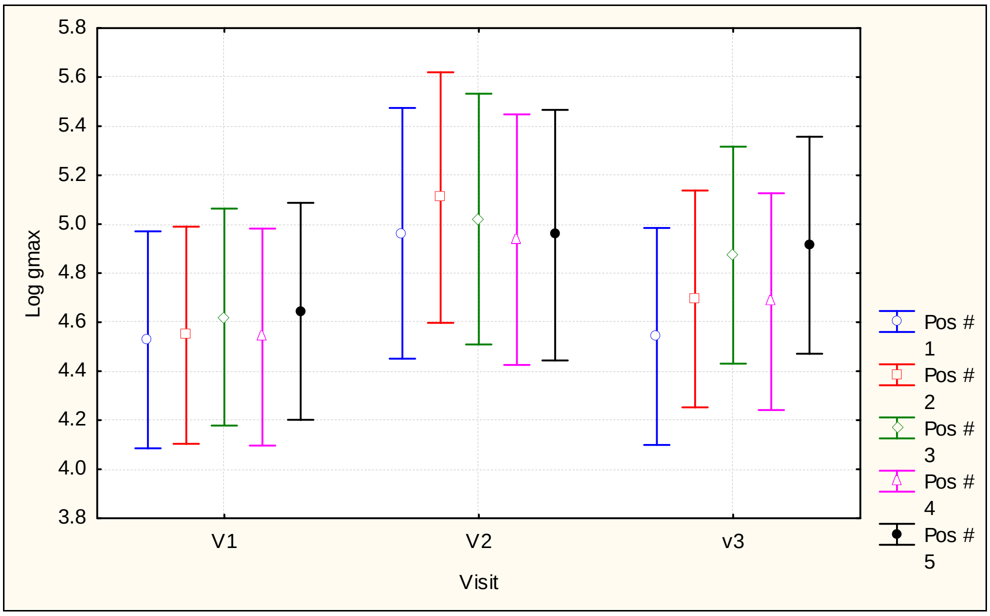


Figure 4.9 Hardness (log gmax) variation due to pitch position on each visit; clay loam pitches. Standard error bars are shown.

As for traction, hardness trends across the pitch were less clear although visit one and three had the highest readings in positions three and five as would be expected. Readings taken during visit two may have been affected by the dense sward present, although the cushioning effect of the grass was not conclusively demonstrated in chapter 2.

- Sand

Sand based pitches are becoming more widespread as a result of their superior drainage properties, as discussed in chapter 2. The effect of temporal variation for traction and hardness is shown in Figure 4.10 and Figure 4.11.

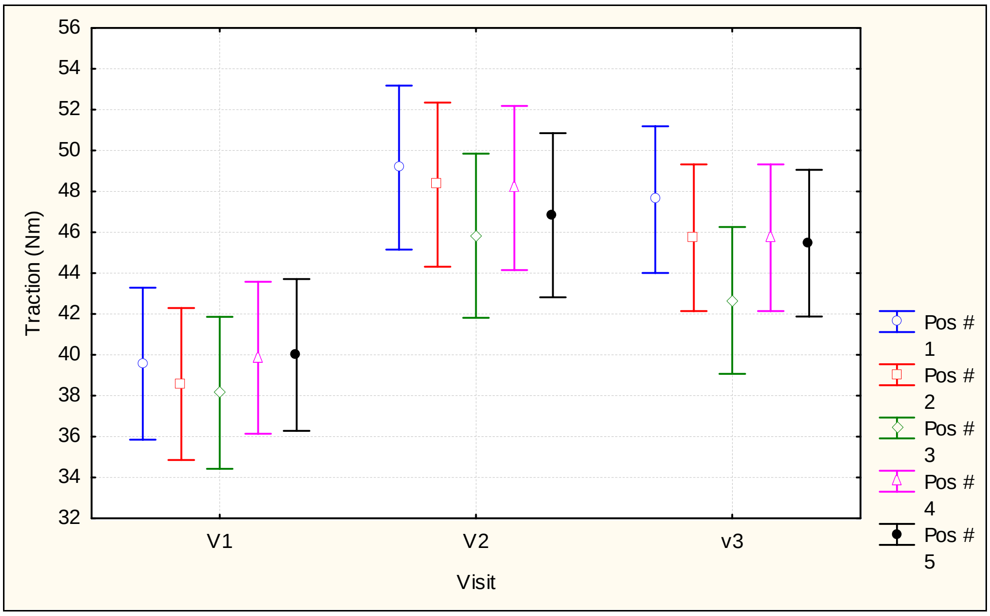


Figure 4.10 Traction variation due to pitch position and visit; 'sand' pitches. Standard error bars are shown.

The trend for traction variation according to pitch position, observed in Figure 4.6, is also evident in Figure 4.10. Although differences between pitch positions were only significant on one occasion (visit three, position three was significantly lower than positions one, two, four and five ($p>0.05$)), the overall trend is clear. Position three (all visits) and five (visits two and three) were the areas of intensive wear and produced the lowest traction readings. Where surface biomasss was reduced, it would be expected that below ground roots would begin to decay and weaken.

Hardness values for ‘sand’ pitches matched the trend observed in Figure 4.7; the positions subject to the most intensive wear (three and five) generated the highest readings, except for visit two.

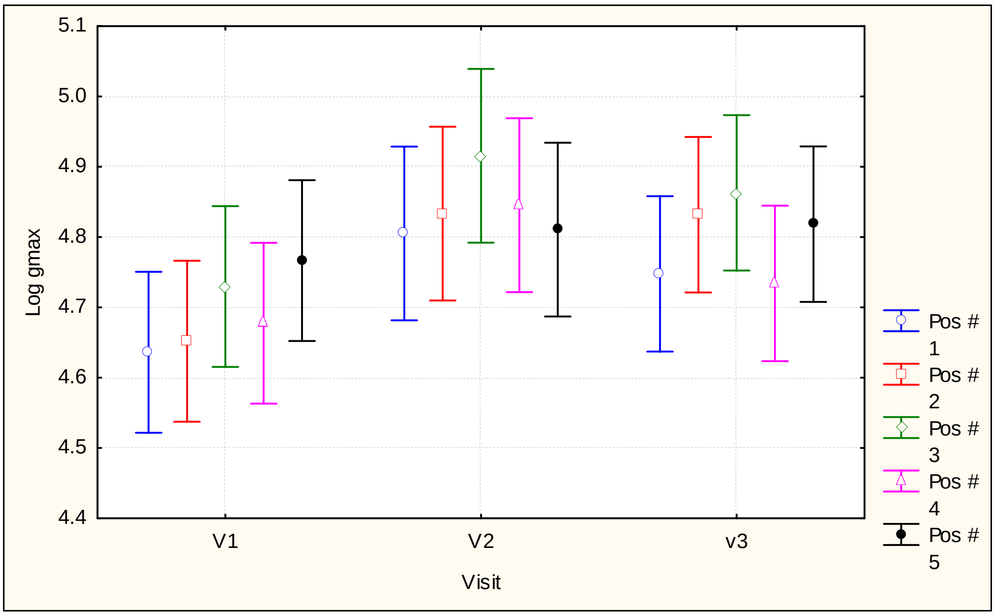


Figure 4.11 Hardness (log gmax) variation due to pitch position and visit; ‘sand’ data. Standard error bars are shown.

The hardness results may support the argument that grass cover cushions the impact of the hammer. Areas of low wear, where grass cover would remain, generally produced the lowest readings while high wear areas, with reduced grass cover, produced higher readings. Furthermore, hardness exhibited less temporal variation than traction results; indicating the reliance of the traction test on sufficient grass roots in the soil to provide additional strength. If the visit two and three results were reduced according to the cushioning effect of grass, it would suggest a heavier hammer would be required to disassociate the effect of grass from the hardness readings.

The effect of wet and dry test conditions

It was discussed in chapter two that the conditions during the test and immediately prior to the tests could have an impact on the result. Overall there was no significant difference between traction readings obtained under wet and dry conditions (p=0.38), although the mean was greater for the dry conditions. For hardness, analysis of the overall data set showed a significant difference between wet and dry conditions (p<0.001) with the greatest readings obtained during dry testing conditions. Separation by soil type enabled a more detailed overview to be gained.

Traction results demonstrated a significant interaction between textural class and wet/dry conditions (p<0.001). Only sand-based pitches produced traction results not significantly different under wet or dry conditions. For the two clay based soil types, higher readings were recorded under dry conditions, while the remaining pitches all exhibited greater traction values under wet test conditions, possibly as a result of increased matric potential, providing additional soil strength.

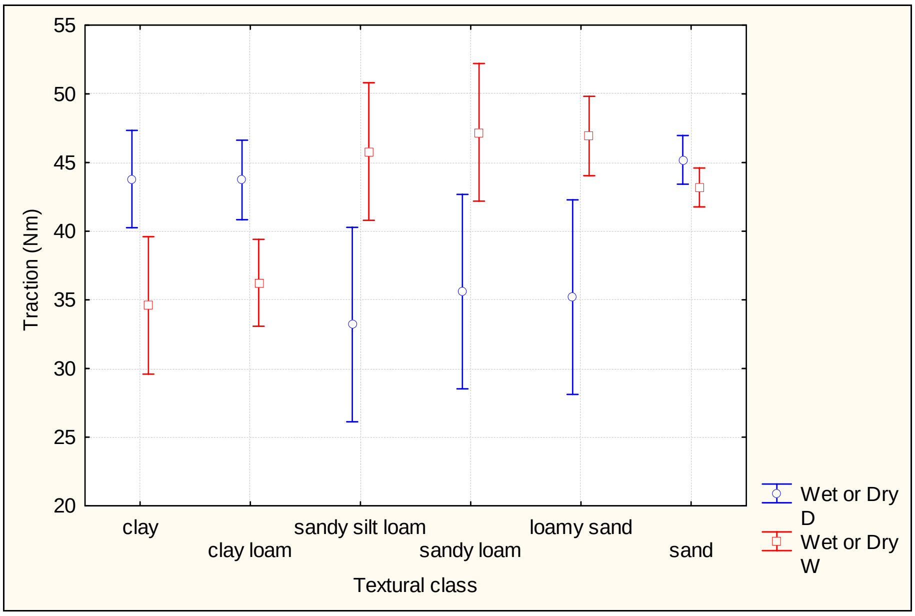


Figure 4.12 Traction readings as affected by textural class and wet (red) and dry (blue) conditions. Standard error bars are shown.

Analysis of the hardness readings also demonstrated a significant interaction between the soil types and wet or dry conditions. The results were the inverse of the traction results; the only pitch type to demonstrate significant differences in hardness when wet or dry was ‘sand’. Significantly higher readings ($p<0.05$) were produced under dry conditions.

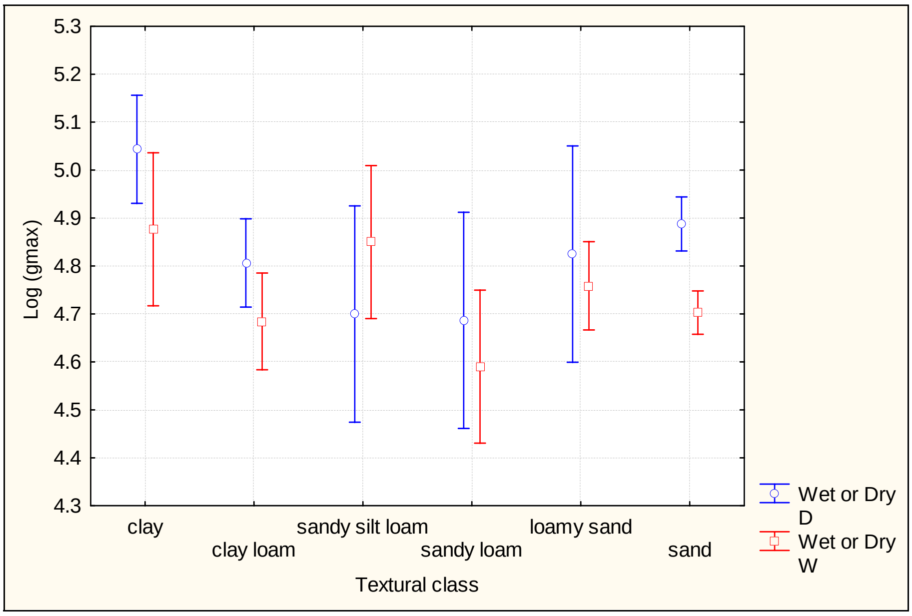


Figure 4.13 Variations in Log gmax (hardness) for each textural class under wet (red) and dry (blue) conditions. Standard error bars are shown.

There was little variation in volumetric moisture content readings between wet and dry conditions. Only for ‘sand’ and ‘clay’ textural class pitches was a significant difference between wet and dry moisture contents observed.

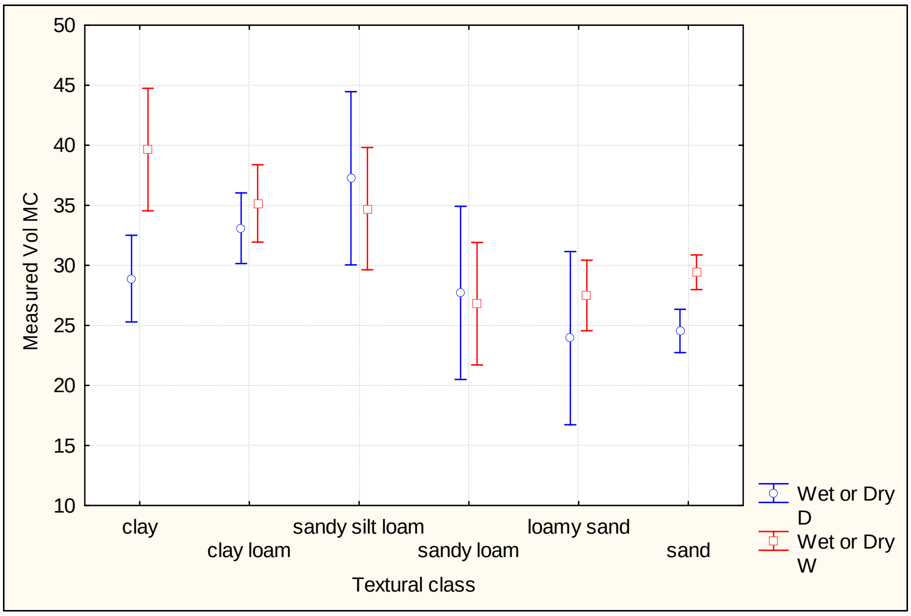


Figure 4.14 Volumetric moisture content (%) under wet (red) and dry (blue) conditions. Standard error bars are shown.

Sand results by bulk density

The investigation into soil strength in chapter 3 demonstrated the need to separate the results by bulk density. The number of samples collected that were classed as sand (205 out of 360; 41 of the 72 pitch tests) enabled the data set to be categorised according to bulk density. Three density categories were selected based on the data available and the number of samples that would be in each category. The categories (and their associated reference number) were ≤1.0 Mg/m^3 (1), >1.0 and ≤1.2 Mg/m^3 (2) and >1.2 Mg/m^3 (3).

Although for each bulk density category the mean traction reading was greater under dry conditions, the differences between the readings for the three densities, whether under wet or dry testing conditions, were not significant ($p=0.99$).

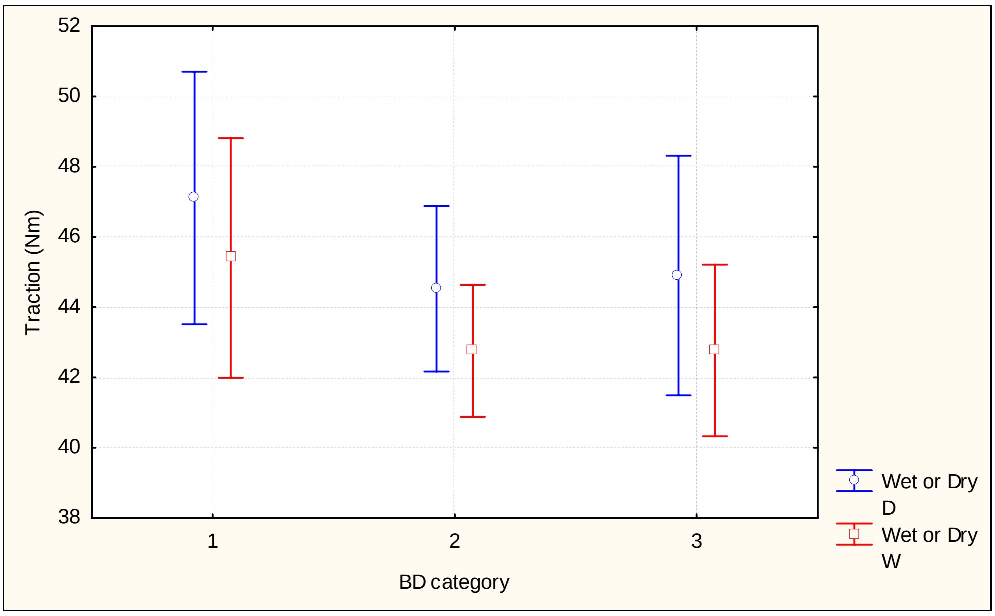


Figure 4.15 Traction results for sand-based pitches as a result of different bulk densities and wet (red) or dry (blue) conditions. BD 1 is ≤1.0Mg/m^3, 2 is >1.0 and ≤1.2Mg/m^3 and 3 is >1.2Mg/m^3.

Analysis of the hardness data demonstrated that there was no significant differences between the results under dry testing conditions for the three bulk densities, but the results from wet conditions were significantly different from the dry results ($p<0.05$) and the results from each bulk density category were significantly different ($p<0.05$).

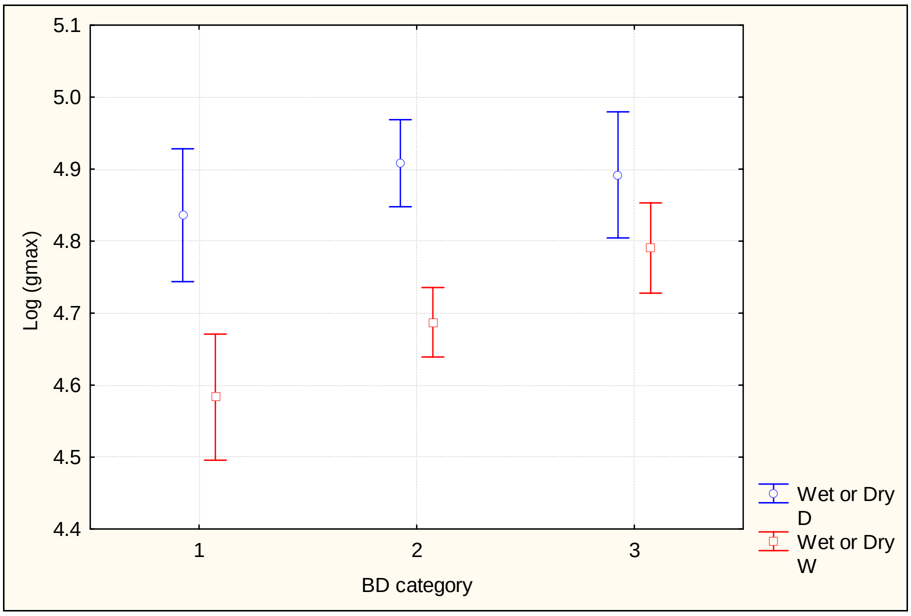


Figure 4.16 Log gmax (hardness) readings as affected by bulk density (BD) and wet (red) or dry (blue) conditions. BD 1 is ≤1.0 Mg/m^3, 2 is >1.0 and ≤1.2 Mg/m^3 and 3 is >1.2 Mg/m^3.

'Sand' results; the effect of fine (<63µm) particles

The specification of the sand used in sports turf rootzones can affect the physical properties of the rootzone and therefore the percentage of fine particles <63µm (the clay and silt fractions) are closely controlled. According the PQS document (IOG, 2001), the combined total must be below 10% of the total rootzone. The effect of fine materials on the outcome of traction and hardness readings, on each visit date was investigated.

The total content of fine particles was categorised for each sample taken and used to produce the following figures. The following ranges (and the corresponding category) were used; ≤ 5% total fines (1), >5 and ≤ 10% fines (2), <10% fines (3).

There was insufficient data for visit 2, >10% fines, but the effect of increasing the quantity of fines was to increase the variability in the data. No significant differences existed between positions one to five for any visits where fine materials were below 5% (category 1). As fine percentage increased the trends became less clear. The effect of wet and dry testing conditions is masked by this analysis and may be causing the high degree of variability in the data where >5% fine particles are present.

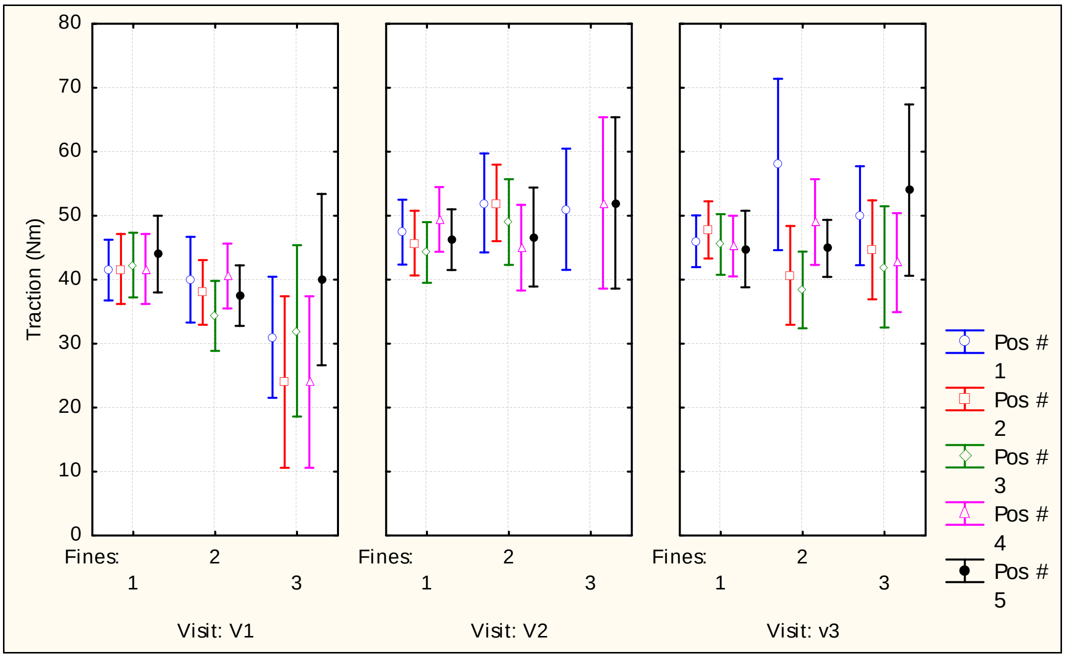


Figure 4.17 Traction variation due to pitch location, fine (<63µm) percentage and visit; sand data. Fine content category 1 is ≤ 5%, 2 is >5% and ≤ 10%. 3 is >10%. Standard error bars are shown. There was insufficient visit 2 data with fine content >10%.

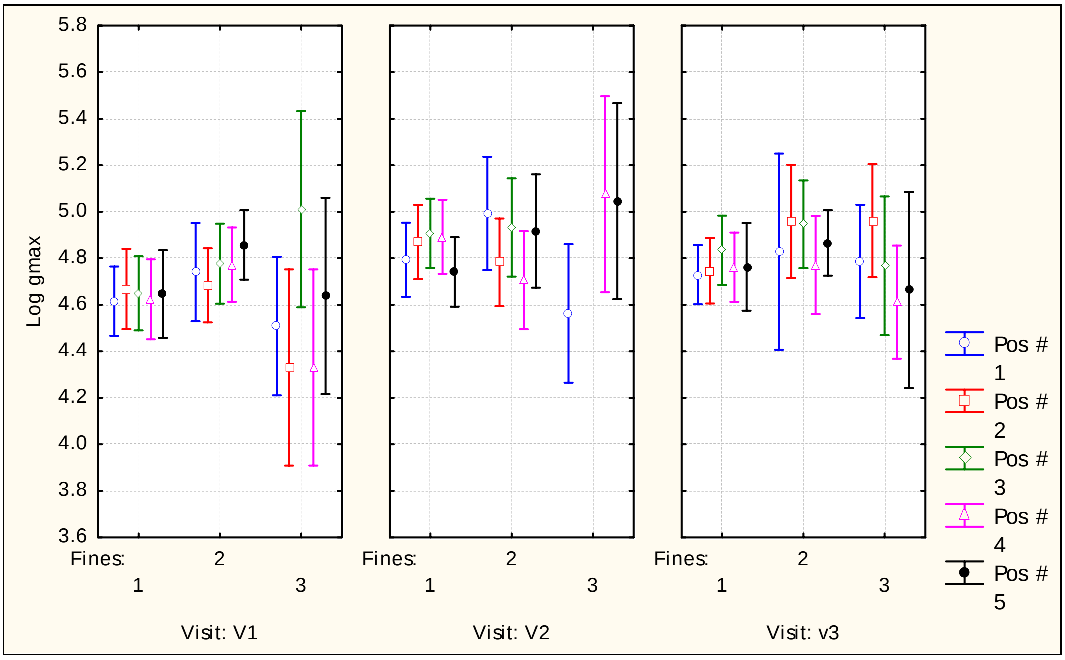


Figure 4.18 Hardness (log gmax) variation according to pitch location, fine (<63µm) percentage and visit; sand data. Fine content category 1 is ≤ 5%, 2 is >5% and ≤ 10%. 3 is >10%. Standard error bars are shown. There was insufficient visit 2 data with fine content >10%.

As with the traction results, separation of the data according to the percentage of fine materials did not result in clear differences between pitch positions. It did demonstrate that the greater the quantity of fine materials, the more variable the outcome. Pitches with the least fine material content (<5% silt and clay) demonstrated limited temporal variation and no significant differences according to pitch location, suggesting that the smaller the fine percentage, the more consistent the pitch in terms of player-surface interaction quality.

4.2.2.2 Pitch quality tests - synopsis

The overall pitch PQS result based on the two player-surface interaction tests was established for each visit and shown in Table 4.4. Of the 72 total pitch tests (25 for visits 1 and 3 and 22 for visit 2), 21 High, 49 Standard and 2 Basic levels of quality were recorded. Between visits one and two, 13 pitches retained their quality rating, 7 improved and 2 worsened. Between visits two and three 8 readings stayed the same, 6 improved and 8 worsened.

It is clear from these results that the Standard level of quality is achievable by the majority of clubs and in most cases, one test result was deemed High while the other was deemed Standard, thus lowering the overall pitch quality to Standard.

The majority of traction tests (96%) remained in either the High (65%) or Standard (31%) categories each visit although on three occasions the level of grip was below the Standard requirement and fell into the Basic category. Interestingly, the hardness readings for the same pitch were classed as high, indicating a difficulty in achieving suitable soil shear strength when the Clegg hammer readings are optimal. Traction results have been shown to be dependent on grass cover and a firm surface may not be conducive to grass development. The mean traction result for all tests was 42.8 (Nm; Standard error 0.90; High classification), with the lowest value being 22.4 Nm and the highest 62.8 Nm.

Overall, 79% of hardness readings fell into the High (50%) and Standard (29%) categories and fell into the Basic category on fifteen (21%) occasions. On all occasions this was due to too hard a pitch rather than too soft, indicating a pitch that could have been hazardous to players. On two of the fifteen occasions, the reading was greater than 200 g which is higher than the Basic level will allow. Failure for studs to penetrate effectively in the soil will reduce the level of grip available and falling on a hard surface would also present a hazard. These conditions should be avoided and three of those four readings were on professional football club training grounds.

The investigation of the effect of textural class, density, fine material content and visit date demonstrated that the accepted trend of reduced traction and increased hardness in high wear areas (centre circle and goal mouth) was evident, although generally not significant. Significant differences did exist as a result of testing date; winter tests exhibited reduced traction and hardness, possibly as a result of increased moisture content and reduced grass cover caused by wear.

The high degree of variability at each test position prevented significant differences between each pitch position from being detected. As a result, future studies should be more intensive (to take advantage of similar climatic conditions) and on fewer pitches of known soil type. It may be necessary to analyse future results on a per-pitch basis.

4.2.3 Correlation analysis

As a result of the above analysis, traction and hardness results were separated by textural class and correlation matrices used to determine the relationship between each test and the various components measured on the pitch. Figure 4.12 demonstrated that only sand based pitches showed no significant differences in traction readings under wet and dry conditions therefore all soil types except sand were separated according to wet or dry. Figure 4.13 for Log g_{max} (hardness) showed that only sand pitches showed significant differences when wet or dry and hence only this textural type was separated by wet or dry conditions.

4.2.3.1 Correlation results

12 correlations were performed for each test; therefore the minimum sample size was 12. Where fewer samples than this were evident, correlations were not investigated and are marked with an * in Table 4.5 and Table 4.6.

Correlation results for traction against measured parameters

	Soil type and test conditions (sample size given)																	
	Clay			Clay loam			Loamy sand			Sand			Sandy loam			Sandy silt loam		
	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All
	10	20	30	25	30	55	30	5	35	135	70	205	10	5	15	10	5	15
Log gmax	*	**0.66**	**0.67**	**0.56**	**0.79**	**0.74**	-0.17	*	-0.30	NS	NS	0.13	*	*	0.42	*	*	0.38
Grass length	*	-0.17	0.03	**-0.68**	0.10	-0.20	**-0.43**	*	-0.09	NS	NS	0.09	*	*	**-0.60**	*	*	0.10
Evenness	*	-0.18	-0.28	0.37	-0.19	-0.03	-0.01	*	0.14	NS	NS	**-0.16**	*	*	**-0.68**	*	*	0.45
Grass cover	*	**0.79**	**0.81**	**0.52**	**0.48**	**0.46**	**0.37**	*	**0.67**	NS	NS	**0.66**	*	*	**0.56**	*	*	**0.93**
Bulk density (U)	*	**0.54**	0.01	0.21	0.05	0.03	0.05	*	0.06	NS	NS	-0.09	*	*	0.37	*	*	0.28
Bulk density (L)	*	0.04	0.24	0.09	-0.07	-0.06	0.25	*	0.29	NS	NS	0.04	*	*	0.46	*	*	0.16
Moisture content	*	**-0.62**	**-0.62**	0.03	**-0.83**	**-0.51**	-0.15	*	0.03	NS	NS	-0.20	*	*	-0.23	*	*	-0.30
Log coarse sand	*	**0.46**	-0.04	-0.19	-0.30	-0.15	**-0.45**	*	**-0.38**	NS	NS	-0.12	*	*	-0.35	*	*	-0.36
Medium sand	*	-0.20	-0.26	-0.11	-0.34	**-0.28**	0.14	*	0.24	NS	NS	0.12	*	*	0.37	*	*	-0.49
Log fine sand	*	**-0.58**	-0.06	-0.12	0.18	0.05	-0.02	*	-0.18	NS	NS	0.03	*	*	0.01	*	*	0.43
Log silt	*	**0.51**	0.35	0.15	0.32	0.24	-0.24	*	-0.27	NS	NS	-0.05	*	*	-0.02	*	*	-0.02
Log clay	*	-0.12	-0.11	**-0.50**	**-0.37**	**-0.37**	0.12	*	0.08	NS	NS	**-0.21**	*	*	-0.11	*	*	0.44

Table 4.5 Correlation coefficients for traction against measured variables. Coefficients in red are significant (p<0.05).

Correlation results for Log g_{max} (hardness) against measured parameters

	Soil type and test conditions (sample size given)																	
	Clay			Clay loam			Loamy sand			Sand			Sandy loam			Sandy silt loam		
	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All	Wet	Dry	All
	10	20	30	25	30	55	30	5	35	135	70	205	10	5	15	10	5	15
Traction	NS	NS	**0.67**	NS	NS	**0.74**	NS	NS	-0.30	-0.04	**0.39**	0.13	NS	NS	0.42	NS	NS	0.38
Grass length	NS	NS	0.03	NS	NS	-0.21	NS	NS	-0.09	-0.04	0.07	-0.08	NS	NS	-0.17	NS	NS	0.05
Evenness	NS	NS	-0.26	NS	NS	0.17	NS	NS	0.23	0.12	0.13	**0.19**	NS	NS	-0.04	NS	NS	**0.68**
Grass cover	NS	NS	**0.51**	NS	NS	0.02	NS	NS	-0.31	**-0.25**	0.07	-0.12	NS	NS	-0.14	NS	NS	0.29
Bulk density (U)	NS	NS	0.33	NS	NS	0.24	NS	NS	**0.39**	**0.33**	0.16	**0.24**	NS	NS	0.15	NS	NS	0.20
Bulk density (L)	NS	NS	0.09	NS	NS	-0.06	NS	NS	0.13	-0.07	0.16	0.03	NS	NS	0.28	NS	NS	0.12
Moisture content	NS	NS	**-0.67**	NS	NS	**-0.62**	NS	NS	-0.26	**-0.22**	**-0.61**	**-0.43**	NS	NS	-0.47	NS	NS	**-0.52**
Log coarse sand	NS	NS	0.19	NS	NS	-0.16	NS	NS	**0.39**	**0.29**	0.03	**0.28**	NS	NS	0.30	NS	NS	0.36
Medium sand	NS	NS	0.06	NS	NS	**-0.38**	NS	NS	0.06	-0.07	0.04	-0.08	NS	NS	0.26	NS	NS	0.24
Log fine sand	NS	NS	**-0.38**	NS	NS	0.10	NS	NS	-0.13	-0.18	-0.14	-0.14	NS	NS	-0.13	NS	NS	**0.57**
Log silt	NS	NS	0.27	NS	NS	**0.41**	NS	NS	-0.19	0.06	0.04	0.05	NS	NS	-0.18	NS	NS	**-0.79**
Log clay	NS	NS	-0.07	NS	NS	**0.34**	NS	NS	-0.02	0.06	-0.01	0.02	NS	NS	-0.33	NS	NS	0.34

Table 4.6 Correlation coefficients for Log gmax (hardness) against measured variables. Coefficients in red are significant ($p<0.05$)

Correlation results by bulk density – Sand

Figure 4.15 demonstrated that traction readings did not vary significantly according to bulk density, or due wet or dry conditions therefore, the overall correlations will suffice (labelled 'all' in Table 4.5). For hardness data Figure 4.16 showed that no significant difference existed under dry test conditions but significant differences existed under wet test conditions, therefore Table 4.7 details the correlations between factors at different bulk densities, only under wet conditions.

	Sand		
	≤1.0 Mg/m^3	1.0-1.2Mg/m^3	>1.2 Mg/m^3
	Wet	Wet	Wet
n	19	58	39
Traction	**0.56**	-0.04	-0.19
Grass length	-0.20	0.09	0.02
Evenness	-0.38	0.08	0.26
Grass cover	**0.52**	-0.21	-0.33
Bulk density (U)	-0.05	**0.38**	-0.01
Bulk density (L)	-0.39	-0.03	-0.34
Moisture content	0.06	**-0.27**	-0.06
Log coarse sand	0.12	0.08	031
Medium sand	-0.13	0.01	-0.31
Log fine sand	0.29	-0.07	-0.11
Log silt	-0.02	0.05	0.12
Log clay	-0.22	-0.02	0.26

Table 4.7 Correlation coefficients for Log gmax (hardness) at each bulk density category under wet test conditions only. Under dry test conditions no significant differences between hardness readings were observed between bulk density categories. Correlations in red are significant (p<0.05)

4.2.3.2 Discussion of correlation analysis

PQS and soil physical tests – correlation analysis all results

There were 61 significant correlations between the measured factors out of a total of 77 possible correlations (79%), however, the strength of these correlations varied and only eight of those 61 (13%) were greater than or equal to 0.50. The size of the data set resulted in even the weaker correlations being significant ($p<0.05$) but an r value of 0.50 would be the minimum preferred strength of relationship for the proposed analysis. Of those eight correlations ($r>0.50$), traction was significantly correlated with grass cover (0.63) while log g_{max} (hardness) was not correlated to any factor where $r>0.50$. Upper and lower bulk densities were correlated (0.62) indicating that as the bulk density of the upper 50mm increased, so did the 50-100 mm bulk density. Upper bulk density increased with increasing medium sand content (0.55) and decreased with increasing clay content (-0.50). Lower bulk density decreased as silt and clay content increased (-0.60 and -0.69 respectively) and increased with increasing medium sand content (0.72). This resulted in a greater range of particles which enabled inter packing and hence a greater volume of solids was possible in a given volume.

Separating the data set into either wet (rain on the day of test of the day before) or dry (no rain on either the day of the test or the day before) the number of significant correlations decreased to 50 with 15 (30%) exhibiting an r value > 0.50 under dry conditions and the total number of significant correlations under wet conditions was 56 of which eight (14%) had r coefficients >0.50. 7 relationships were the same (between the same factors) for both situations, leaving only one unique relationship under wet conditions. This was a negative relationship between moisture content and upper bulk density indicating that as density reduced, the water holding capacity of the soil increased as a result of the a more porous structure. Under dry conditions, increases in upper bulk density resulted in limited grass height, possibly due to poor root exploration, or maybe due to the height of grass cut during the drier testing periods. Grass was cut more frequently during the summer months and may have resulted in localised compaction in the upper surface of the soil. Also under dry conditions, both traction and hardness values decreased with increased moisture content which demonstrated that at reduced moisture contents, when the remaining water was held under tension, increased soil strength was measured. As the moisture content increased, the strength of the water bonds were reduced and soil strength was reduced.

In wet and dry conditions the significant relationship between grass cover and traction remained (0.70; wet and 0.55; dry). Hardness was correlated with moisture content under dry conditions (-0.67) which demonstrates a need to irrigate in the summer to reduce hardness values that are too great and to ensure adequate drainage in the winter to remove excess moisture. This also demonstrates the link between measures of playing quality and the soil conditions; the soil component must be adequately managed by a Groundsman in order to achieve the desired level of quality.

PQS and soil physical tests – correlation analysis by soil type

Figure 4.12 and Figure 4.13 demonstrated a need to separate the data set according to soil type. Sandy clay loam was removed due to the limited sample size (a single occurrence), resulting in 6 soil types being identified. These were; clay (n=30), clay loam (n=55), loamy sand (n=35), sand (n=205), sandy loam (n=15) and sandy silt loam (n=15). Correlation matrices for traction results were produced for wet and dry conditions for each textural class except sand. When hardness data were analysed, Figure 4.13 showed no significant difference between wet and dry conditions for each soil textural class apart from sand, therefore only the sand data for hardness was separated according to test condition.

- Clay

Under dry test conditions, Traction was significantly correlated ($p<0.05$) with grass cover (0.79) upper 50 mm bulk density (0.54) volumetric moisture content (-0.62) log fine sand (-0.58) and log silt (0.51). These provide a target for pitch management on clay based pitches. The link between traction and grass cover supports previous literature in terms of the overall trend, of a reduction in grass cover would result in a reduction in traction. The correlation with moisture content indicates a need to adequately drain clay based pitches. Under wet testing conditions, the data set was reduced (n=10) and with this being less than the list of factors, correlation analysis was not possible.

Overall, hardness data was positively correlated with grass cover (0.51) which is contrary to the argument that increased grass cover reduces hardness data due to a cushioning effect. The correlation with moisture content (-0.62) however supports the theory that under wet conditions, the surface becomes softer. This would be useful during the summer months when the pitch may become too hard but also indicates that drainage would be required in the winter to prevent damage to the surface as a result of wet conditions being unable to support play.

- Clay Loam

In dry conditions, traction was only correlated with moisture content (-0.83) indicating a strong relationship between the soil drying and the strength increasing. This is likely to be due to the increased matric potential and additional strength this provides to the soil. Under wet testing conditions, more factors were significant and exhibited an r >0.50, although the data set was reduced. Increasing grass length reduced traction values (-0.68) possibly as a result of the studs being unable to penetrate the soil surface. This would suggest pitches supporting play during wet conditions would benefit from having shorter grass as greater traction will be on offer. Increased grass cover would also offer increased traction (0.52) and this indicates a need for pitch management to ensure adequate grass cover at all times of the playing season.

The correlation between traction and log clay content (-0.50) would suggest that minimising the clay content may enhance the degree of traction available, a result also observed in Figure 4.17.

- Loamy Sand

Only one loamy sand pitch was tested under dry test conditions therefore the production of correlation matrices was not possible. Under wet conditions, traction did not correlate with any factor with an r statistic >0.50. Hardness was not correlated with any factors. This is likely to be the result of limited data points.

- Sand

205 samples were classed as ‘sand’ in textural analysis (14/25 in visit 1, 12/22 in visit 2 and 15/25 in visit 3). The cause of this may have been the bountiful use of topdressing to repair areas, correct levels and possibly an attempt to adjust the soil physical properties, such as drainage. It is possible that particle size analysis of the top 50mm failed to determine the actual profile textural class, instead the final classification was influenced by topdressing; this argument is supported by the changing numbers of sand pitches tested per visit.

Traction results were not significantly different under wet and dry testing conditions; therefore, the entire data set could be used to address relationships. Although four factors demonstrated significant correlations with traction, only one had an r value >0.50; grass cover (0.66) This suggests that on sand based pitches, grass cover must be maintained in order to generate suitable levels of grip. Although it is unclear whether zero percent grass cover would result in readings below the recommended minimum of 20 Nm (basic quality).

Hardness readings were significantly different between wet and dry testing conditions and the correlation matrices in appendix XIV demonstrated that under dry conditions, hardness reduced with increasing moisture content (-0.61) indicating that hardness could be manipulated by a Groundsman using water application. Under wet conditions, no significant factors (r>0.50) were present.

- Sandy Loam

Sandy Loam samples were only collected on three occasions, which limited the number of data points to 10 for wet and 5 for dry conditions. This was too few to enable separation of the data set therefore both traction and hardness correlations used all 15 values. With limited data, strong conclusions can not be made, however traction reading were strongly correlated with grass length (-0.60), evenness (-0.68) and grass cover (0.56). These would suggest that increased grass length and degree of unevenness would both reduce traction, possibly through poor stud penetration. The relationship with grass cover once again indicates a need to encourage grass growth to ensure optimum traction. Hardness data were not correlated with any factors and would suggest that more data would be required from pitches of this soil type.

- Sandy Silt loam

As with the sandy loam textural class, a limited number of tests were conducted on the sandy silt loam soil type, therefore only one correlation matrix encompassing all data was constructed. Traction test results were correlated with grass cover (0.93) which highlighted the need for pitch management to concentrate on providing an optimum root environment to encourage grass growth. Hardness was shown to correlate with a number of factors; evenness (0.68), moisture content (-0.52), log fine sand (0.57) and log silt (-0.79). The relationship with evenness is unusual; it suggests that as the pitch becomes more uneven, hardness would increase. It is possible that unevenness is a result of intensive use and localised compaction which would cause the uneven surface and higher hardness values in places. Typically, hardness would reduce as moisture content increased, again highlighting the need for appropriate water management. The effect of top dressing with sand may have the combined effect of increasing the fine sand percentage and proportionately decreasing the silt content which would both result in a harder surface via inter-packing.

PQS and soil physical tests – effect of bulk density on correlation analysis

Categorisation of the data according to three bulk density classes demonstrated that traction results (Figure 4.15) did not vary between categories, or within categories under wet or dry conditions. Therefore, the general correlation analysis presented in Table 4.5 would be acceptable. Hardness data did differ according to bulk density classification. When dry, the data was not significantly different and therefore the correlations presented in Table 4.6 would be acceptable. When wet however, the hardness values were significantly different and correlation matrices constructed for each bulk density classification.

BD1 (≤ 1.0 Mg/m^3) hardness values were influenced by increasing coarse sand content (0.55) possibly due to increased packing densities and particle rearrangement. Coarse sand was also correlated with traction (0.56); traction readings may increase due to increased friction between the coarse sand particles. BD2 (>1.0 and ≤1.2 Mg/m^3) and BD3 (>1.2 mg/m^3) hardness analysis produced no significant correlations. Increasing bulk density in sand therefore reduces the number of factors that the hardness values are correlated with and this reduces informed management options. On sand-based pitches decompaction work is vital and efforts to encourage grass cover and maintain rapid drainage are also essential. Furthermore, management practices should be carefully selected to reflect the state of the pitch and not produce further compaction.

4.2.4 Regression analysis

The second objective of this chapter was to investigate the potential to predict the quality rating of a pitch in terms of its traction and hardness readings. This would use other pitch parameters which could be either measured easily by a Groundsman or include soil factors that would vary little over time, except for specific events such as topdressing or decompaction methods. Multiple regression equations for traction and hardness were produced by soil type. These provide empirical models to produce an approximation of the true relationship. Each parameter was linear therefore linear regression was permissible and coarse sand was omitted due to all the soil constituent factors totalling 100%. The factors entered into the backward stepwise analysis as possible predictors were (and their identifying labels):

- Grass cover (%; GC)
- Grass length (mm; GL)
- Evenness (mm; E)
- Moisture content (MC)
- Upper (0-50 mm) bulk density (UBD)
- Lower (50-100 mm) bulk density (LBD)
- Log clay content (LCC)
- Log silt content (LSC)
- Medium sand content (%; MS)
- Log fine sand content (LFSC)

Although initial analysis demonstrated the presence or absence of significant differences between the outcome of the tests under wet or dry conditions, and for sand according to bulk density, the regression equations were not separated as before.

Instead, it was accepted that prediction under different climate conditions may be different, even though the result is the same, therefore regression equations for each test under wet and dry conditions was produced.

4.2.4.1 Regression analysis results

To fulfil the regression equation for traction (Eqn 4.1) and Log g_{max} (Eqn 4.2), the values for a to k for each soil type under 'wet', 'dry' and 'all' test conditions are shown in Table 4.8 and Table 4.9 respectively. Regression for 'all' conditions is shown either where there was sufficient wet and dry data, or where regression equations for wet and dry could not be generated due to insufficient data. Regression analyses for sand results according to bulk density are shown in Table 4.10 and Table 4.11 for traction and hardness respectively.

$$\text{Traction (Nm)} = a + b(GC) + c(GL) + d(E) + e(MC) + f(UBD) + g(LBD) + h(LCC) + i(LSC) + j(MS) + k(LFSC) \quad \textbf{(Eqn 4.1)}$$

		a	b	c	d	e	f	g	h	i	j	k	St Err	Adj R^2	P value
Clay	Wet	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Dry	53.64	0.39	-0.67	0	0	0	0	0	0	0	-8.84	4.65	0.78	$p<0.001$
Clay	All	92.68	0.16	-0.60	0	-0.60	-26.50	0	0	0	0	0	8.22	0.49	$p<0.001$
loam	Wet	31.66	0.17	-0.54	0.86	0	0	0	0	0	0	0	4.56	0.69	$p<0.001$
	Dry	74.68	0	0	0	-0.94	0	0	0	0	0	0	7.19	0.68	$p<0.001$
Sandy	All	19.68	0.26	0	0	0	0	0	0	0	0	0	2.38	0.86	$p<0.001$
silt	Wet	-	-	-	-	-	-	-	-	-	-	-	-	-	-
loam	Dry	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sandy	All	-34	0.96	-1.19	-0.89	0	0	0	-40.59	44.32	0	0	2.40	0.92	$p<0.001$
loam	Wet	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Dry	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Loamy	Wet	18.83	0.48	-0.57	0	0	0	0	0	0	0	0	4.36	0.35	$p<0.01$
sand	Dry	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sand	All	18.12	0.26	0	0	-0.17	0	0	0	0	0	2.67	5.76	0.46	$p<0.01$
	Wet	37.80	0.31	-0.29	0		0	-9.43	0	0	0	0	5.57	0.55	$p<0.01$
	Dry	28.79	0.23	0	0	-0.22	0	0	0	1.98	0	0	5.64	0.38	$p<0.01$

Table 4.8 Traction regression coefficient values for 'wet' and 'dry' conditions. A regression for 'all' conditions is shown where both wet and dry data existed (clay loam and sand) or where there was insufficient data to generate a regression for both wet and dry (sandy silt loam and sandy loam). Insufficient data is marked with an (-), where no significant factors existed and a regression equation could not be established (NS) is displayed. Zero indicates the factor was not significant.

$$\mathrm{Log}\ (g_{max}) = a + b(GC) + c(GL) + d(E) + e(MC) + f(UBD) + g(LBD) + h(LCC) + i(LSC) + j(MS) + k(LFSC) \qquad \textbf{(Eqn 4.2)}$$

		a	b	c	d	e	f	g	h	i	j	k	St Err	Adj R^2	P value
Clay	Wet	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Dry	5.88	0	0	0	0	0	1.24	0	0	0.02	-0.89	0.15	0.84	$p<0.001$
Clay loam	All	5.33	0	0	0.03	-0.02	0	0	0	0	-0.01	0	0.29	0.54	$p<0.001$
	Wet	8.64	0	-0.01	0.04	0	0.71	0	-0.98	0	-0.03	-0.27	0.13	0.76	$p<0.001$
	Dry	6.58	-0.004	0	0	-0.04	0	0	0	0	-0.01	0	0.16	0.91	$p<0.001$
Sandy silt loam	All	21.29	0	0	0.04	0	0	0	0	-4.02	0	0	0.11	0.74	$p<0.001$
	Wet	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Dry	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sandy loam	All	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Wet	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Dry	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Loamy sand	Wet	4.38	0	0	0	0	0.34	0	0	0	0	0	0.10	0.13	$p<0.05$
	Dry	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sand	All	5.87	0	0	0.11	-0.01	0	0	0	0	-0.006	-0.16	0.20	0.22	$p<0.01$
	Wet	4.34	-0.002	0	0	0	0.46	0	0	0	0	0	0.21	0.13	$p<0.01$
	Dry	4.95	0	0	0	-0.01	0	0.23	0	0	0	0	0.15	0.39	$p<0.01$

Table 4.9 Log (gmax) regression coefficient values for 'wet' and 'dry' conditions. A regression for 'all' conditions is shown where both wet and dry data existed (clay loam and sand) or where there was insufficient data to generate a regression for both wet and dry (sandy silt loam and sandy loam). Insufficient data is marked with an (-), where no significant factors existed and a regression equation could not be established (NS) is displayed. Zero indicates the factor was not significant.

$$\text{Traction (Nm)} = a + b(GC) + c(GL) + d(E) + e(MC) + f(UBD) + g(LBD) + h(LCC) + i(LSC) + j(MS) + k(LFSC)$$

		a	b	c	d	e	f	g	h	i	j	k	St Err	Adj R^2	P value
BD1	Wet	-89.52	0.35	-0.55	0	0	0	-17.90	0	0	0.84	27.01	4.84	0.61	$p<0.01$
	Dry	22.08	0.27	0	0	0	0	0	0	0	0	0	5.67	0.37	$p<0.01$
BD2	Wet	34.63	0.26	0	0	-0.47	0	0	0	0	0	0	5.80	0.56	$p<0.001$
	Dry	29.27	0.25	0	0	-0.29	0	0	0	0	0	0	6.02	0.42	$p<0.001$
BD3	Wet	19.24	0.29	0	0	0	0	0	0	0	0	0	4.53	0.65	$p<0.001$
	Dry	27.37	0.13	0	0	0	0	0	0	4.19	0	0	3.82	0.32	$p<0.05$

Table 4.10 Traction regression coefficient values for sand results, separated into three bulk density categories. Insufficient data is marked with an (-), where no significant factors existed and a regression equation could not be established (NS) is displayed. Zero indicates the factor was not significant.

$$\text{Log}(g_{max}) = a + b(GC) + c(GL) + d(E) + e(MC) + f(UBD) + g(LBD) + h(LCC) + i(LSC) + j(MS) + k(LFSC)$$

		a	b	c	d	e	f	g	h	i	j	k	St Err	Adj R^2	P value
BD1	Wet	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Dry	3.09	0	0	0.10	0	2.67	0	0	-0.56	0	0	0.18	0.57	$p<0.01$
BD2	Wet	3.14	0	0	0	0	1.38	0	0	0	0	0	0.20	0.12	$p<0.001$
	Dry	3.99	0	0		-0.01	1.10	0	0	0	0	0	0.12	0.50	$p<0.001$
BD3	Wet	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Dry	3.87	-0.008	0	-0.02	0	0	0	0	0	0.02	0.22	0.08	0.66	$p<0.01$

Table 4.11 Log (gmax) regression coefficient values for sand results, separated into three bulk density categories. Insufficient data is marked with an (-), where no significant factors existed and a regression equation could not be established (NS) is displayed. Zero indicates the factor was not significant.

4.2.4.2 Predicted versus actual

Figure 4.19 and Figure 4.20 demonstrate the relationship between predicted and actual traction and hardness readings; two graphs for each represent a good (high R^2) and poor (low R^2) ability to predict quality test outcome for sand based pitches under wet and dry conditions. 1:1 lines are displayed on each figure.

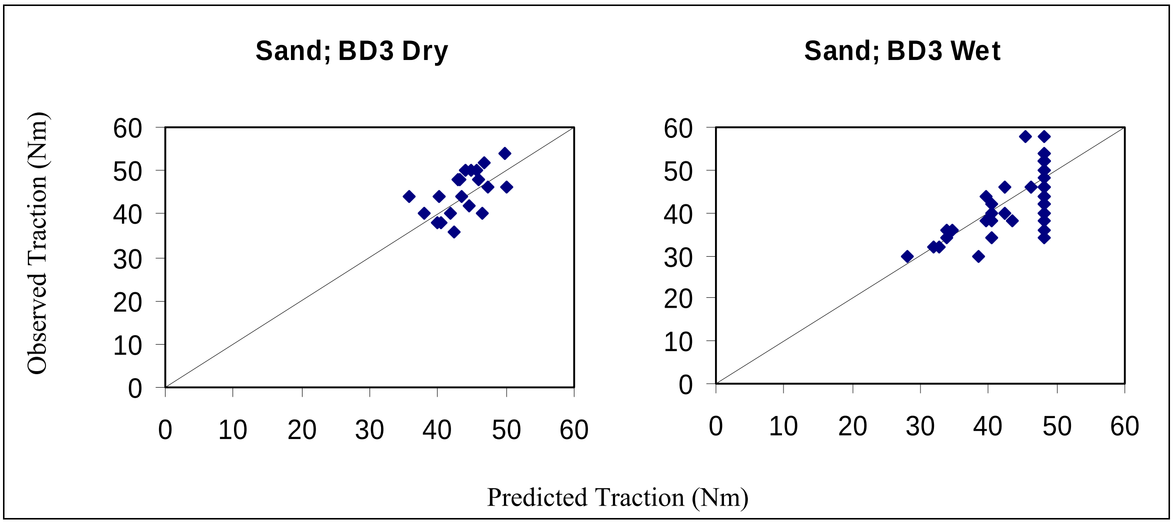


Figure 4.19 Actual v predicted Traction (Nm) for sand based pitches, BD3. The 'dry' prediction equation has an R^2 of 0.32 and the data has a narrow spread and not close to the 1:1 line. The regression equation for the 'wet' prediction is stronger (R^2 = 0.65) but the prediction is only based on one predictor variable; grass cover. This has a maximum of 100% therefore at the predicted maximum there was a large range of observed readings.

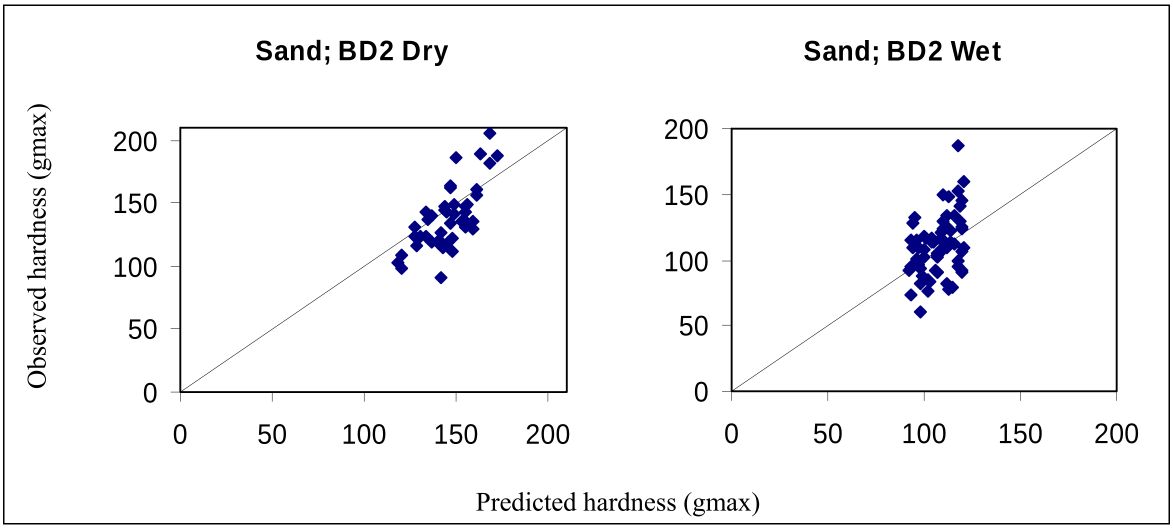


Figure 4.20 Actual v predicted hardness (gmax) readings for sand based pitches, BD2. The 'dry' prediction equation has an R^2 of 0.50 and the data is poorly spaced around the1:1 line. The regression equation for the 'wet' prediction was weaker (R^2 = 0.12) due to a narrow range of predicted values compared to a greater number of observed values, not following the 1:1 line.

4.2.4.3 Discussion of regression analysis

Traction

On six occasions there were insufficient data available to generate a regression equation but where sufficient data were present, significant regression equations were established. The R^2 value of the equations differed and was a function of the soil type and number of observations. The general trend was for an increase in the R^2 value as the number of observations reduced, limiting confidence in the outcome of the regression analysis. Ten regression equations were completed for traction by soil type (regressions according to bulk density for sand are discussed further below), and of those ten, six had an R^2 value greater than 0.50 and lowest was 0.35. Generally, traction was a function of grass cover, although a link emerged between other soil physical conditions, and the results of the tests for quality. The individual equations also demonstrated that the relationships were not straight forward, as a simple correlation analysis would suggest; eight regression models used more than one variable, with grass cover predicting traction as a single factor only once, despite the simple assumption expressed in the industry that greater grass cover equals greater traction. The presence of bulk density demonstrates that detailed knowledge of the below ground elements of the pitch is required by Groundsmen in order to monitor quality. What is also required is an understanding of how bulk density changes as a result of the various pitch management tools in use. Pitch management and density could be empirically linked so that a model could account for pitch management by altering the density parameter. Sporadic laboratory analysis throughout a playing season could confirm this.

The reduced R^2 values on sand-based pitches would suggest that either the measured parameters excluded other parameters that may have proved to be more significant, or that these tests are inappropriate for use on such granular material. Another possibility is that pitches labelled as sand were only sand in the upper horizon as a result of top-dressing. Had sampling deeper in the profile occurred and particle size analysis used samples from a range of depths in the profile, the actual textural classes may have been established. It is also possible that sand-based pitches varied little in their quality rating, without this variation, regression equations would be difficult to generate.

Hardness

As with the traction results, R^2 values greater than 0.50 were established indicating that a link between easily measurable pitch parameters and a measure of playing quality is emerging. Generally, the regression results were based on upper bulk density, but other factors were present. Interestingly, as sand content increased, the R^2 value fell. Clay, clay loam and sandy silt loam data generated regression equations which could predict pitch hardness and achieve the objective of this aspect of the study. Loamy sand, sand and sandy loam data produced poor regression results, with no R^2 value above 0.4 and no significant factors being present for sandy loam soils, possibly due to limited sample size.

It is possible that soils labelled as sand were a different textural class beneath the concentrated layer where top dressing was evident. This may have jeopardised the regression equations due to the variety of soil types being grouped together. Also, sand samples were dominated by organic material in the upper layers, with concentrated root patterns being observed. Where this was present, there may have been a degree of sponginess in the pitch surface, impacting on the results. Where rooting density was reduced and density of solids in a proportional volume increased, as a result of wear, this sponginess was not evident and hence the readings would have been greater. It is perhaps this that caused the reduction in hardness readings caused by increased grass cover, as reported in the literature, rather than the above ground biomass cushioning the blow of the hammer.

As with the traction results, the presence of a range of factors in the regression equations, particularly soil parameters such as the results of particle size analysis suggests that changes in soil constituents, by actions such as topdressing and hollow tining followed by topdressing, may have a profound impact on the overall quality of the surface. Again, the impact of pitch management on measures of quality needs to be researched.

Importantly for traction and hardness results, the sampling dates used in this study may not have been representative of conditions typical of an entire football playing season. A more frequent schedule of testing would have been beneficial.

4.3 Chapter Discussion

The aim of this chapter was to develop the link between effective stress and measures of soil strength that had been successfully completed in chapter 3. In addition, the chapter aimed to establish the existence of a link between the player-surface interaction tests of traction and hardness, and a range of soil physical parameters. The purpose of establishing this link was to provide a guide for Groundsmen that would aid them achieve the desired level of playing quality through appropriate soil management.

4.3.1 Test equipment

The Clegg hammer, straight edge, point quadrat and rising disk equipment used during this study was loaned from TurfTrax. The traction equipment required fabrication. It was cumbersome and difficult to transport and its poor use in clubs is understandable. Furthermore, the manufacturing process used prevented the weighted unit from being lifted and dropped in accordance with the operational guidelines; therefore the studded disk was manually forced into the ground via stamping, and then loaded with weights. This action may have caused soil disturbance around each stud, lowering the traction readings, however, this method was used at every test location on each pitch, minimising its overall effect. The biggest drawback was on hard soils encountered during May 2004 and June 2005. Many of the pitches were about to enter a period of renovation work and were particularly hard. Adequate stud penetration was difficult to achieve, again reducing the reliability of the results.

The Clegg hammer was not robust enough given its importance to the testing procedure. The delicate data cable was used to lift and drop the hammer while the readings often became erratic (indicating low battery power) before the low battery warning appeared. Where pitches were clearly not as hard as the numbers suggested, batteries were replaced and the tests re-run. This added to time but also reduced confidence in the test equipment. American researchers use a heavier 2.25 kg hammer. British literature has highlighted the potential cushioning effect of grass, therefore preventing the Clegg hammer from isolating the soil conditions from the overall system, and yet the 0.5 kg hammer continues to be used. The lightweight 0.5 kg hammer is also susceptible to the frictional effect within the guide tube. A heavier hammer may not be as susceptible and should perhaps replace the lighter hammer. Importantly, the tests should also provide evidence of an injury risk and it is unclear from the literature, at what values injuries become an issue, and what type of injuries they are likely to be.

The difficulties with the tensiometer have been discussed and although penetration resistance had been used in chapter three as the measure of soil strength and regressions equations had been established, it proved to be difficult to achieve *in situ*. A penetrometer that was sensitive enough to measure and record data from shallow (100 mm) penetration depths was difficult to locate, therefore the advanced force gauge was chosen. This was limited to recording a maximum rather than mean value and perhaps a very detailed geological penetrometer with continuous logging would have yielded the required results. The results were not put to use however for future *in situ* investigations into effective stress, penetration resistance should be measured, but must utilise sophisticated equipment that is capable of logging penetration data over the entire depth of penetration.

4.3.2 Relationship between traction and measured parameters

Every significant correlation between traction and moisture content was negative, i.e. traction reduced as moisture content increased. Although in agreement with the data presented by Baker (1991) this was in opposition to the results of Bell and Holmes (1988), although their positive correlation was weak (0.16). Grass species were not identified during the visits, therefore the work of Canaway (1975) and (1983) cannot be used for comparison, however, other studies demonstrated positive correlations between traction and ground cover (varying r values, all significant), mirroring the results found in this chapter. Every significant correlation between ground cover and traction was positive, although the actual r value varied according to soil type and wet or dry conditions which may explain the variety of r values presented in STRI papers; separation by textural class occurred infrequently. Grass length was infrequently a significant factor in this chapter, however every significant correlation that did exist was negative i.e. traction reduced as grass increased, possibly due to the extra above ground biomass preventing adequate stud penetration into the pitch surface or reducing the amount of friction between the base of the plate and the soil surface.

The relationship between traction and soil constituents had previously been considered very little in terms of percent of the various materials, but the results presented in this chapter provide evidence that soil constituents have a significant effect. For each soil type, the correlations varied and these have been discussed in section 4.2.3.2.

Regression equations have been suggested by previous authors (Holmes and Bell, 1986), although their relevance was not made clear. The aim of this chapter was to determine whether the quality of the pitch could be predicted from simple-to-measure pitch parameters and feed into a grounds management model to enable the Groundsman to adjust management techniques in real-time to continually affect quality.

The regression equations presented in section 4.2.4 suggested that this may be possible. Although limited in sample size, many of the regression equations exhibited R^2 values greater than 0.5, indicating that a clear link between pitch parameters and quality can be established. This has not been clearly presented before, and their continued development may encourage more Groundsmen to adopt PQS as a means of assessing quality and selection of appropriate pitch management tools. It was also clear from the regression equations that traction was a function of more than just the degree of grass cover; and is influenced by moisture content, density, grass length, evenness of the surface and the relative proportions of the soil constituents.

4.3.3 Relationship between hardness and measured parameters

In agreement with past studies, Clegg hammer readings were shown to decrease with increasing moisture content on every occasion a significant correlation existed. The actual r value varied with soil type, and wet or dry conditions, and may have been the result of the narrow range of moisture contents available for analysis under wet conditions.

It was discussed in chapter 2 how the relationship between hardness and grass cover parameters had been infrequently considered. Correlation matrices presented in appendix XIV show that the Clegg hammer readings were both negatively correlated (sand; wet conditions) and positively correlated (clay; wet conditions) with grass cover. The argument in previous papers suggested that grass cushioned the impact of the hammer and this may have been the case, although the positive correlations may also suggest that the density of the sward, organic material accumulation and grass tillering would be the cushion, rather then simply the percentage of shoots. It was also suggested that high rooting density in low wear areas may create a softer surface than high wear areas where root density is reduced. In high wear areas, there would be a greater volume of solids in a proportionate volume of soil, increasing bulk density.

The regression equations for hardness generally utilised soil factors such as moisture content, density and results of the particle size analysis. Out of twelve possible equations, insufficient data prevented equations to be established twice, and once no significant equation was possible. It was also shown that increasing sand content reduced the R^2 value. This may have been the result of an interaction between rooting density and the softening effect of sand. Managers of pure sand pitches regularly perform decompaction work and encourage root density through fertiliser applications, complicating an explanation regarding why this was the case. It is also possible that under dry conditions, particle rearrangement on impact was occurring on sand-based pitches, especially where grass cover was low, and may have reduced readings.

Like traction test results, the regression equations demonstrate that pitch hardness is a function of the below ground properties of a pitch and although a link between these factors and a measure of quality is emerging, greater research is required to determine how the different management options impact on the root zone or soil properties.

4.3.4 Overall

Traction test equipment used in STRI papers was bespoke and not available commercially, therefore the equipment was manufactured and a slight deviation from the recommended construction method was made. This deviation should have had little bearing on the reliability of the results and through consistent application of a standard test method, results between pitches were comparable.

In situ tests attempted to determine which factors influenced the results of traction and hardness tests. This would also serve to corroborate or oppose past research. Chapter 2 highlighted that a range of different correlations between traction or hardness and other factors had been previously reported and the *in situ* test results reported in this chapter also reported a wide range of coefficients. It was clear that different soil types, and whether the pitch was in a wet or dry state, generated different correlation equations, and in some cases produced no correlations. Furthermore, some pitch data were not normally distributed and required log transformation.

Contrary to the previous studies, no variation was detected in traction or hardness readings according to test location. The variation in test results was attributed to soil textural class but no difference was detected as a result of pitch position. This may be due to only three test times and the dominance of summer tests, but the test session in January/February 2004 was during the winter months and wear effects would have been detected. The high degree of variation for each test position meant that differences between them were rarely established. It was clear though that high-wear areas were generally harder and generated less traction. Pitches of the textural class sand that had <5% fines did not vary across the pitch, nor temporally, illustrating one of the reasons why sand-based pitches are popular choices for maintaining consistent playing surfaces.

The regression models generated in section 4.2.4 present for the first time detailed links between measures of playing quality and easy-to-measure pitch factors which can be manipulated by a Groundsman. Where it was not possible to generate regression models, it was due to insufficient data. The presence of high R^2 values suggests that soils currently found on local authority pitches (such as heavier textured clay and silt dominated soils) would be suitably modelled using the regression equations. This would help ensure the limited resources used to manage these areas are targeted by being able to monitor quality in real-time and select appropriate management techniques.

What is still to be established is the link between the various management options (scarification, aeration, topdressing, rolling, irrigation) on measures of quality. This knowledge would aid in the selection of the appropriate tool for a desired result, while also delay the use of some equipment until there was sufficient time for quality to recover after its use in time for the next game.

The regression equations presented in section 4.2.4 can be used to generate a model that will achieve the aim of producing a suitable interface for the Groundsman to use to monitor pitch quality. In its current form, its application would benefit managers of local authority and amateur pitches, however, pitches intended for professional games (which are usually sand-based) would not be adequately catered for. Dury (Pers. Comm.) argued that PQS tests should only be used annually and a drop in quality should be expected of pitches under Local Authority management during the winter months. The application of improved regression models would enable quality to be targeted directly and ensure appropriate use of finances. Professional league clubs who have a duty of care to limit the hazard presented by the pitch in training or matches could use a model to ensure that player-surface interactions are always within the range suitable for the standard of the game being played.

Finally, the users of the pitch should also have been considered and tests must reflect their requirements. A drawback of this study was a lack of player feedback in order to correlate the test results with player perception, although there may be little correlation between player perception and the standard of pitch that will minimise injury potential. The tests themselves must be clearly linked to sports injuries and studies that investigate a relationship between test results and injury incidence will accelerate the use of PQS. Future experimentation of this nature may prove to be more fruitful with a smaller selection of pitches which are tested more frequently and coupled with a detailed investigation into the incidence, type and severity of sports injuries among users of the surface.

4.4 Conclusions

1. The concept of effective stress was not able to be utilised but the results of chapter 3 suggest that its use may produce significant prediction between soil moisture status and soil strength. In order to achieve this through *in situ* experiments, a more reliable, robust tensiometer is required; with sufficient testing time available to enable the tensiometer to equilibrate. The use of sensors in the pitch may not be suitable as they are likely to become damaged as a result of pitch management practices.
2. 'Standard' pitch quality was the most common result when the results of both traction and hardness tests were combined. This accounted for 68% of the results, 'high' standard 29% and 'basic' standard only was recorded on 3% of the total number of tests. Between tests one and two and two and three the number of pitches that retained their quality reading was 13 and 8 respectively, while 7 and 6 pitches improved and 2 and 8 worsened.
3. The soil textural classes did not remain stable, possibly due to the effects of top dressing and hollow tining which seeks to add sand into the rootzone. The most common soil type discovered was 'sand' but this was in opposition to the opinion of the Groundsman who stated that the majority of pitches were built on the natural soil type.
4. Considering all the data together, regardless of weather conditions, traction was strongly correlated with grass cover (0.63) although traction and hardness results required separation according to soil type. Traction data was affected by wet and dry test conditions except for sand, while hardness data only needed separating according to wet or dry conditions for sand. In general both demonstrated a reduction as soil moisture content increased.
5. Regression models generally exhibited a range of R^2 values. Although the data set for some soil textural classes were limited, it suggests for the first time that a clear link between pitch conditions and surface quality exists, and that by combining a selection of the factors together in specific regression equation, a reliable prediction of pitch quality can be made. Arguably, the desired R^2 value would be greater than 0.7.

6. This suggests that a model could be produced, incorporating the regression equations established in this chapter to provide a tool for use by groundsmen in order that pitch quality can be monitored in real-time.
7. Also highlighted was the need for further research in order to determine the effect on surface quality of the various management tools used in the production and maintenance of sports pitches. This will further aid in the selection of appropriate tools to maintain or improve on pitch quality.
8. Future studies should incorporate pure-sand or sand-dominated rootzones in order to establish whether prediction equations can be improved upon. It will also facilitate the collection of data under similar climatic conditions and possibly support the suggestion that regression models would need to be bespoke for each pitch. Heavy textured soils should also be addressed in order to determine the minimum management inputs required to achieve the desired quality. This would be beneficial to Local Authorities and schools where pitches were on heavy soils and budgets limited.

4.5 Chapter summary

It has been argued in chapter two that the uptake of Performance Quality Standards has been slow and this may be due to the absence of guidelines regarding how to achieve the desired outcome. It was the aim of this chapter to extend the sporadic use of correlation and regression in past papers, which attempted to link measures of quality with a variety of other factors, and generate a clearer understanding of what pitch and soil factors influenced traction and hardness on a variety of soil types and, where possible, at different bulk densities. The concept of effective stress was also investigated in order to ratify the results of chapter three with *in situ* analysis, but tensiometer difficulties rendered analysis impossible.

The regression equations established significant equations from which to predict player-surface interaction quality although the R^2 varied in strength, according to soil type. This may have been the result of too few data points, unmeasured factors in the field, the testing strategy, and date of testing or inappropriate tests whose results cannot be achieved through pitch management.

However, chapter 5 will utilise these results in order to develop a model that could easily be used by groundsmen to determine the equality of a pitch on a real-time basis. Only sand results will be used in the model due to the separation by bulk density being possible, however the low R^2 values of the regression equations reduces the model to a demonstration of how the results of this (and future) work could be applied.

Chapter 5 Decision support model

Chapter 4 developed prediction equations which utilised a range of pitch variables (percentage grass cover, grass length and evenness) and soil variables (0-50 mm and 50-100 mm depth bulk density, moisture content, and the percentage proportions of soil constituents) to predict pitch traction and hardness. The equations that were produced provided a clear link between the soil conditions and pitch quality. The six soil types were separated according to wet or dry test conditions and due to limited data, regression equations could not be established in every case. Furthermore, only the 'sand' data were separated according to bulk density and it was the sand regression used in the production of this model.

The limited data sets and varied R^2 values for the sand regressions suggest that further research is required before this model could fulfil the aim of providing a pitch management tool for Groundsmen. However, the regression models that were determined were used to produce a model that demonstrated how more reliable prediction equations, developed using further research, could form the basis of a model. This model is called *PitchQual*. The maintenance and monitoring of pitches, with a focus on player-surface interaction quality should ensure that rising sports participation will not be mirrored by an equivalent rise in lower-limb injury, particularly in the amateur game where sports injuries are a cost to industry through missed work days.

5.1 PitchQual

The model was implemented in Microsoft Excel (appended on the CD-Rom) and is applicable to sand-based pitches; only this textural class had sufficient data to enable separation by bulk density and wet and dry test conditions. It is foreseeable that a football club, local authority or school will have a model tailored to their pitch, or pitches, and be available as web-based software, housed on the website of the company responsible for marketing the final version. The R^2 values were of mixed strength however a standard error for each equation was calculated and this should reduce as further research confirms the relationships discovered.

5.1.1 Predicted v actual

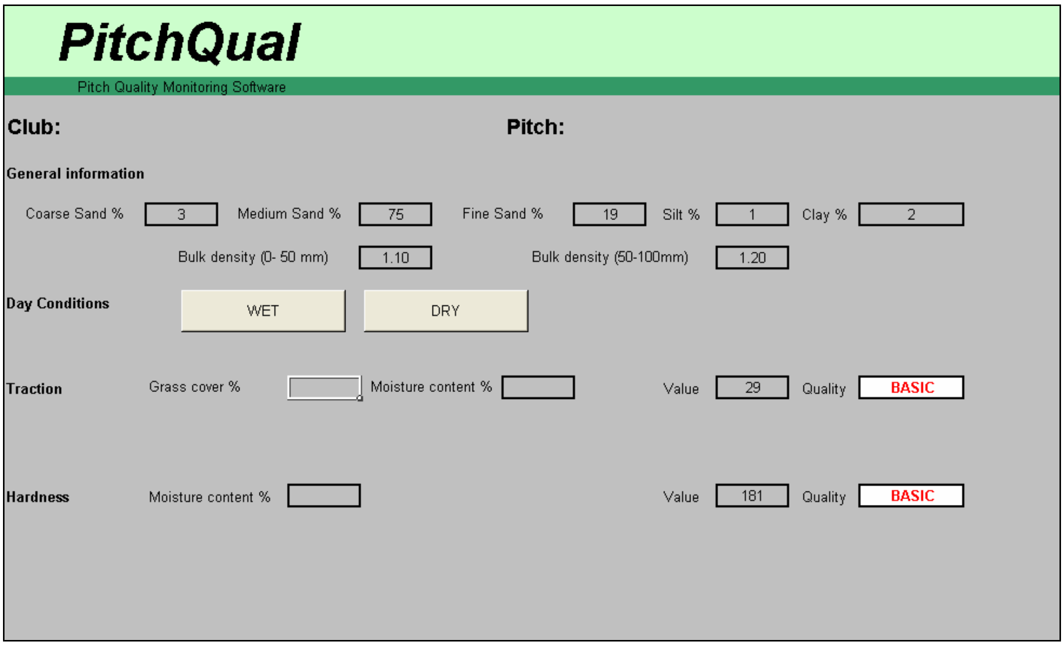
Discussed in section 4.2.4.2, the R^2 values varied in strength. Each equation was detailed in Table 4.8 to 4.11 which highlighted a range of significant predictor variables, which varied according to bulk density and wet or dry testing conditions. Figure 4.11 and Figure 4.12 demonstrated the relationship between predicted and observed data and a 1:1 line was shown. Where a high R^2 value existed, the data were spread around the 1:1 line but were parallel; where the R^2 value was low, the data were spread around the line with no discernible pattern evident.

5.1.2 Statement of quality

In order to produce a statement of quality based on the calculated value, IF statements were used and the output in red (see Figure 5.1) depends on the value in the cell on the left of the quality statement. Four possible statements exist: high, standard, basic and poor. The limits for each quality rating are based on the current PQS guidelines (Table 2.4).

5.1.3 *PitchQual* interface

The interface shown in Figure 5.1 is in two halves. The upper part of the screen (below the title bar) incorporates club information such as name and the pitch this model is for. It is foreseeable that a club with training pitches established on different soil types, may have a model for each. Soil data required in the regression models is also listed here and where the data requires log transformation this occurs within the regression equation based on the untransformed data entered. It is assumed that soil data will remain relatively stable throughout a season, but topdressing applications and management tools may impact on the particle size distribution and the bulk density, therefore the firm marketing and supporting this model would include within its fee, periodic testing of the soil surface in order to update this information throughout the season. Figure 5.1 gives an overview of the interface and its general layout:



Club:

Pitch:

General information

Coarse Sand % 3
Medium Sand % 75
Fine Sand % 19
Silt % 1
Clay % 2
Bulk density (0- 50 mm) 1.10
Bulk density (50-100mm) 1.20

Day Conditions

Traction
Grass cover %
Moisture content %
Value 29
Quality BASIC

Hardness
Moisture content %
Value 181
Quality BASIC

Figure 5.1 'PitchQual' pitch quality monitoring software interface

The two buttons labelled 'wet' and 'dry' are to select the conditions on the day of the test. The criteria for a dry pitch is that it is dry (no rainfall or irrigation) on the day of the test, or the day before. Rainfall or irrigation in that period will result in the 'wet' option being selected. Operating as a result of the selection of either option is a macro that alters the required inputs for either wet or dry, but also responds to the bulk density figure supplied for the upper 50 mm of the rootzone (see appendix XV for wet and dry macros).

It is assumed that upper bulk density will vary little throughout a playing season; therefore this figure would be updated periodically. Therefore, on each day the pitch is monitored, selection of the wet or dry button will indicate which factors require determination. The factors required under wet conditions and dry conditions with an upper bulk density of 1.10[1] Mg/m^3 are shown in Figure 5.2 and Figure 5.3 respectively.

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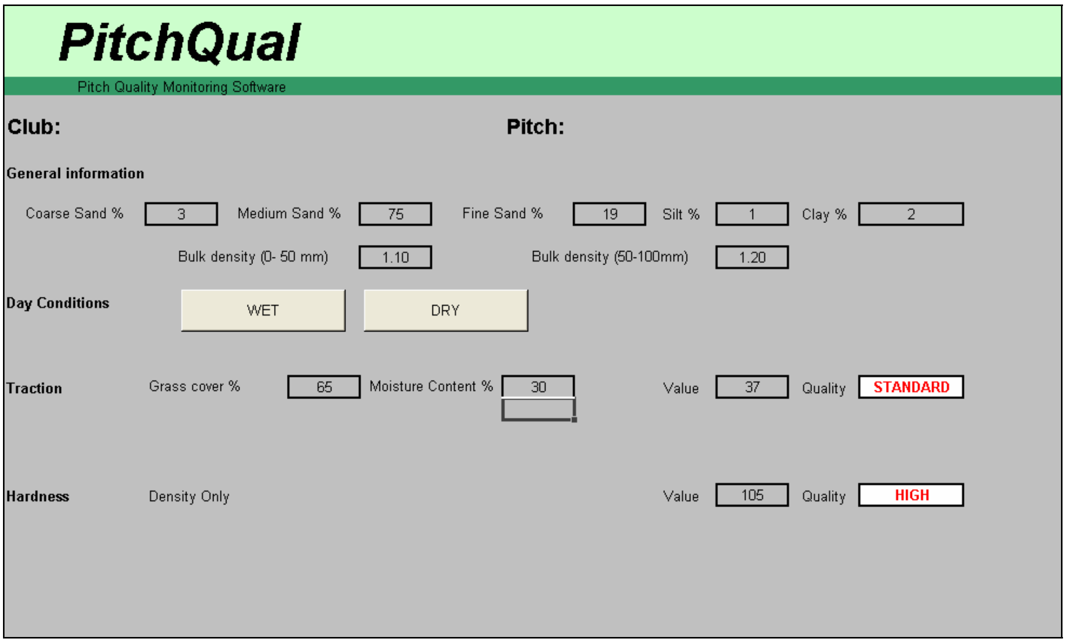
[1] Although 1.10 Mg/m^3 is low, grass roots reduce the volume of soil solids in the upper layer.



Club:

Pitch:

General information

Coarse Sand % 3 Medium Sand % 75 Fine Sand % 19 Silt % 1 Clay % 2

Bulk density (0- 50 mm) 1.10 Bulk density (50-100mm) 1.20

Day Conditions

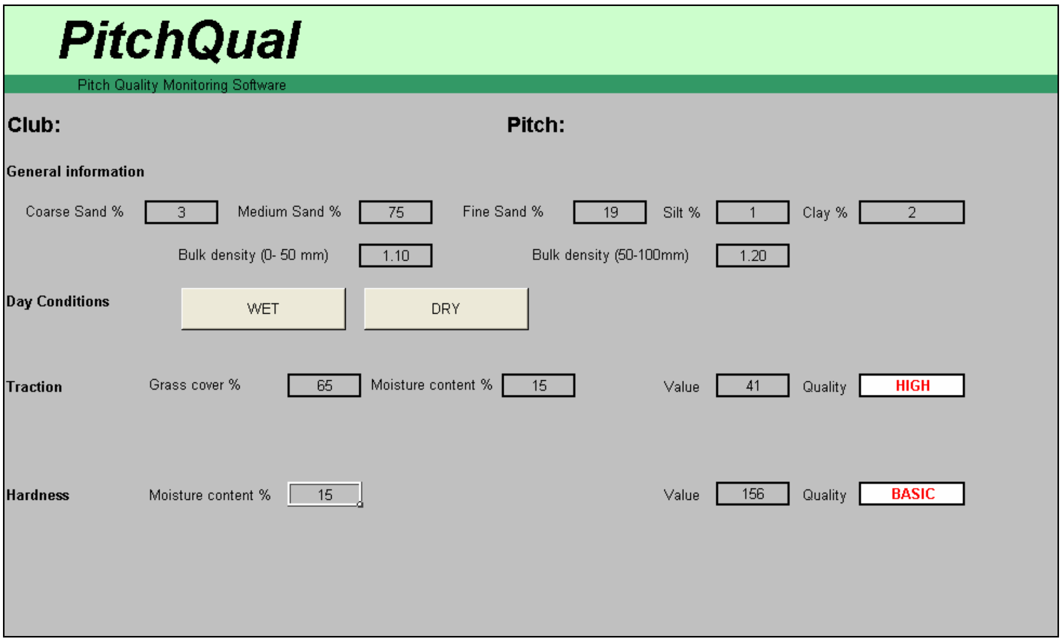
Traction Grass cover % 65 Moisture Content % 30 Value 37 Quality STANDARD

Hardness Density Only Value 105 Quality HIGH

Figure 5.2 PitchQual interface and the factors that need inputting when upper 50mm bulk density is 1.10 Mg/m^3 and the conditions are 'wet'.

When 'wet' is selected, the lower half of the screen alters to display the parameters that must be measured by the Groundsman and inputted into the model. Figure 5.2 shows this is grass cover (%) and grass length (mm), both simple to determine. Under the same conditions, hardness prediction only utilises the bulk density in the upper 50 mm of the pitch. This message is relayed to the Groundsman and may ensure that pitch management decisions are not to the detriment of this, and increase the density further. Example figures have been inputted; increasing moisture content reduces traction while increasing grass cover negates this. Although this suggests that play could continue on a wet surface, as long as adequate grass cover existed; players may be at a low risk to injury but the pitch will be susceptible to further damage.

Under dry testing conditions, at the same bulk density (Figure 5.3) traction is a function of grass cover and moisture content (in the example the figures are lower to represent dry conditions) although the readings are still categorised as high quality. Under the same conditions, hardness is classed as basic due to the surface being too hard, the reading of 156 g reduced with the application of water. This is to the detriment of traction which demonstrates the difficult balance required for pitch management to successfully achieve the desired standard in both tests.



Club:

Pitch:

General information

Coarse Sand % 3
Medium Sand % 75
Fine Sand % 19
Silt % 1
Clay % 2
Bulk density (0- 50 mm) 1.10
Bulk density (50-100mm) 1.20

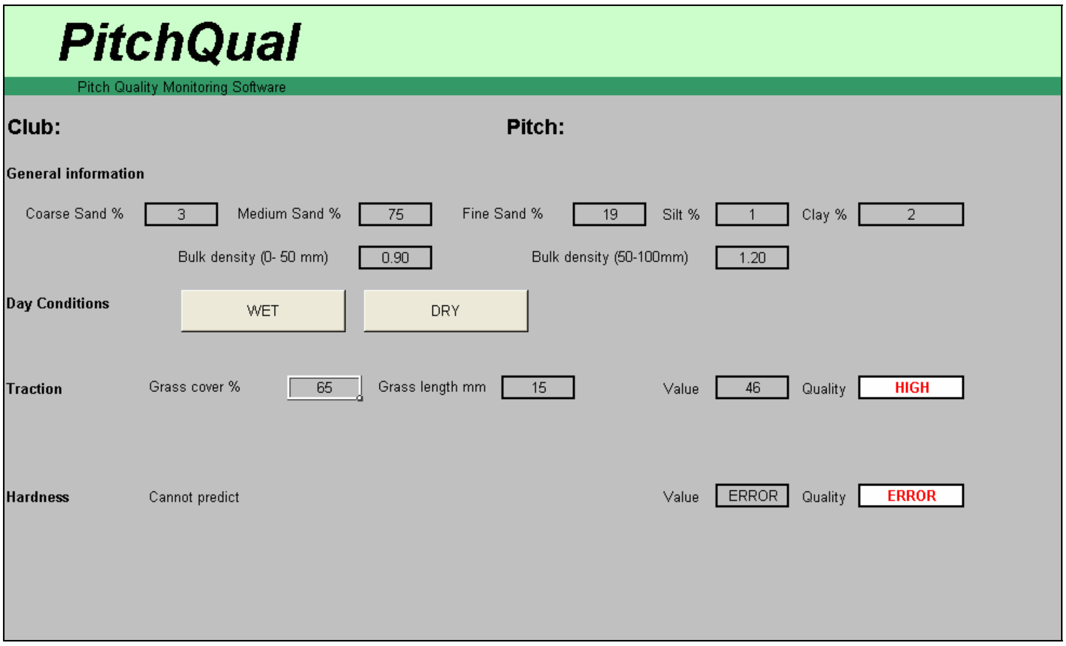
Day Conditions

Traction
Grass cover % 65
Moisture content % 15
Value 41
Quality HIGH

Hardness
Moisture content % 15
Value 156
Quality BASIC

Figure 5.3 PitchQual interface and the factors that need inputting when upper 50 mm bulk density is 1.10 Mg/m^3 and the conditions are 'dry'.

It was not possible to predict the outcome of the every hardness test and the model incorporates this, as demonstrated in Figure 5.4:



Club:

Pitch:

General information

Coarse Sand % 3
Medium Sand % 75
Fine Sand % 19
Silt % 1
Clay % 2
Bulk density (0- 50 mm) 0.90
Bulk density (50-100mm) 1.20

Day Conditions

Traction
Grass cover % 65
Grass length mm 15
Value 46
Quality HIGH

Hardness
Cannot predict
Value ERROR
Quality ERROR

Figure 5.4 Error reading for hardness to demonstrate that prediction cannot be made.

5.1.4 Testing with climate data

One pitch variable that was retrospectively entered into the model was moisture content. To achieve this, the water release data obtained from the soil cores from club 7 pitch b (Sunderland AFC; ‘rootzone’ pure sand pitch) after visit three was required; by modelling the water release characteristic a number of parameters were established which were then entered into the HYDRUS 1-D (Simunek *et al.*, 2005) soil moisture status modelling software.

The model is based on the water release equation established by van Genuchten and therefore the data obtained from the pitch required modelling in order to ascertain the relevant parameters. A spreadsheet was produced to achieve this (see appendix XVI) and the actual data and modelled data are shown in Figure 5.5:

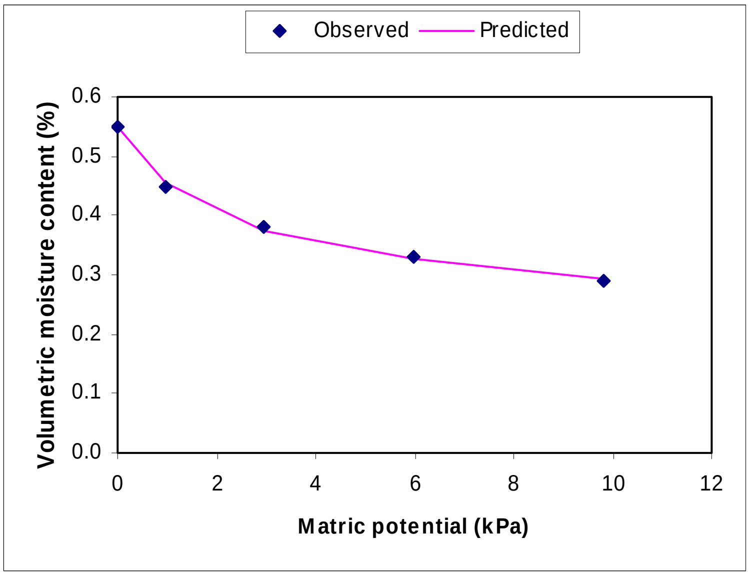


Figure 5.5 Sunderland AFC actual water release data and modelled data. The results of the modelling were inputted into the HYDRUS 1-D model to model soil moisture changes within the profile of a sports pitch rootzone.

The parameters entered into HYDRUS 1-D as a result of the model presented in Figure 5.5 were:

Variable	Value
Rootzone depth (mm)	600
θ saturation	0.55
θ residual	0.01
Alpha (mm^{-1})	0.012
N	1.22
Ksat (mm/d)	12000

Table 5.1 van Genuchten factors entered into HYDRUS 1-D as a result of modelling a sand-based rootzone material.

The boundary conditions for the model were entered as a rootzone depth of 600 mm, over lying a gravel layer (seepage phase) with real climate data entered for 1997 and then 1998. The climate data was for Rosewarne in the west of England and represented a relatively dry year (1997) and wet year (1998):

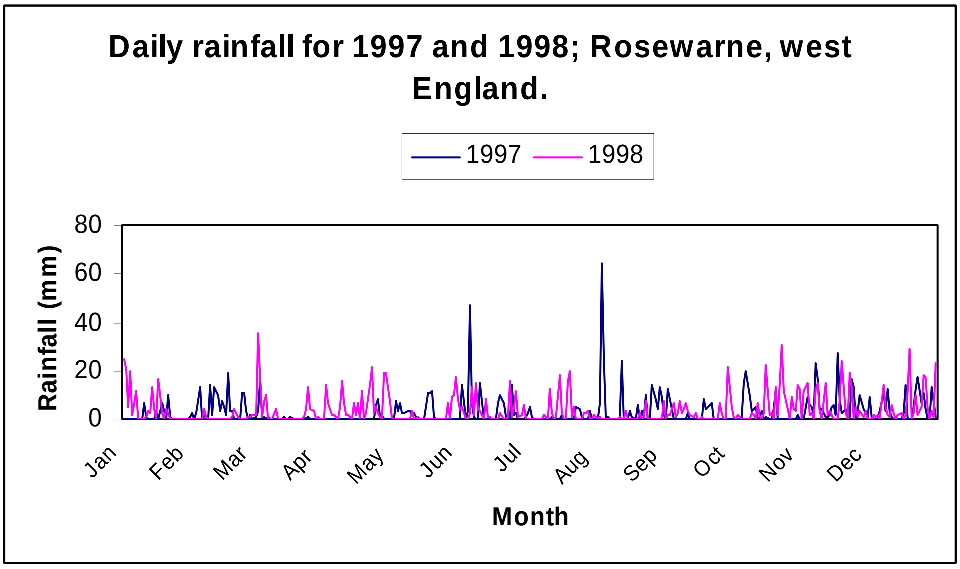


Figure 5.6 Daily rainfall for 1997 and 1998; Rosewarne, west England.

The output produced moisture content values at regular intervals down the profile; therefore the mean of all the data within the top 50 mm was used as this represented the depth at which a Theta™ probe would determine moisture content. The results were as follows:

	Volumetric moisture content (%)	
	1997	1998
Mean	36	36
Minimum	23	23
Maximum	56	48

Table 5.2 Mean, minimum and maximum moisture contents recorded for the top 50 mm of sports pitch sand-based rootzone in 1997 and 1998.

5.1.5 Model sensitivity

Completion of the model enabled the sensitivity of the regression equations to each factor to be established. If the soil factors are assumed to remain stable, the model will be more sensitive to the factors that a Groundsman must input on a daily basis. Using the scenarios in Figure 5.2 and Figure 5.3 the sensitivity of the model to changes in pitch conditions can be established. BD2 will be selected so that the sensitivity for both hardness and traction can be established; regression equations were not determined for hardness BD1 or BD3 under wet conditions, and three of the four BD2 regression models require moisture content as an input.

5.1.5.1 Traction

BD1

Under wet conditions, the two factors to be inputted by the groundsman are grass cover (%) and grass length (mm). The model demonstrates that to increase traction using changes in grass length, the grass must become very short, for any given grass cover percentage. As discussed in chapter 4, this may be due to the studs penetrating the surface better with reduced above ground biomass. However, this also indicates that with a grass cover of only 50% traction quality can be ranked as high if the grass is cut to just 10 mm, (although this would not be done in practice). Conversely, traction readings are much more sensitive to changes in grass cover percentage, due to changes in rooting density, rather than the effect of the grass shoots. At 25 mm length, traction will be classed as high at 65% grass cover, standard at 37% to 65% basic at 8-37% and poor below this. Although the data presented in chapter 4 did not suggest that a difference between test locations was evident, high wear areas such as goal mouths may suffer from poor levels of traction once grass cover begins to thin. Improving quality by adjusting grass length, particularly during the summer months would have a more immediate effect on traction than grass cover changes.

Under dry conditions, only grass cover can be used to predict traction. From 0-26% grass cover the surface is classed as basic; possibly due to the dry sand exhibiting greater inter particle friction than wet sand. From 26%-63% the surface is classed as standard and 64% and above; high quality. To achieve high levels of traction, grass cover is an important target for pitch management and tools should be selected to minimise the potential of producing unfavourable pitch conditions for grass growth.

BD2

At an increased bulk density, moisture content influences the traction readings; excess moisture would effectively lubricate soil particles while insufficient soil water would cause the sand to become loose, losing strength. Between these two extremes, water held under tension would contribute to soil strength. Grass cover is also a significant predictor variable. Both of these variables are required for wet and dry conditions, and no soil factors. Table 5.2 demonstrated that the mean moisture content in 1997 and 1998 was 36 percent. At this moisture content, to achieve a high quality traction rating, grass cover percentage needs to be greater than 86%. At the maximum moisture content of 56%, even 100% grass cover would result in only a standard quality ranking. This indicates the need for adequate drainage to remove as much soil moisture as possible, especially where rainfall events occur just before a game or during play.

Under dry conditions, the lowest moisture content of 23% would enable a traction rating of high to be achieved with 70% grass cover; this assumes however, that 23% moisture content is sufficient for optimum grass growth. And perhaps irrigation would be required to enable the grass to grow, but this would reduce the traction rating of the pitch.

BD3

Traction is only a function of grass cover under wet conditions. The model suggests that at grass cover percentages greater than 63%, a high traction rating would be achieved. However, to achieve this in such dense soil-surface conditions management to maintain a sward at 63% or more would be difficult. The primary aim should be to reduce the density, producing a more open surface structure, more conducive to grass growth and development.

Under dry conditions, traction is a function of both silt content and grass cover. It is assumed that soil constituents remain stable throughout a season (except for specific top-dressing events); therefore the silt figure obtained from the Sunderland United FC pitch will remain unchanged, at 1%. Its involvement is likely to be the result of cohesion and its ability to retain moisture under tension as it dries, contributing to soil strength. The result of this is that even with grass cover reduced to as low as 43%, traction was classed as high; this is under dry conditions however and it is foreseeable that moisture would be added to aid grass growth which would be to the detriment of the traction value.

5.1.5.2 Hardness

BD1

Under wet conditions the hardness of the soil cannot be predicted. A wide range of values were observed during the pitch tests, when the soil was wet; this may have been due to localised compaction, high and low wear areas and the position of the test relative to the drainage layout.

In dry conditions, hardness is a function of bulk density, fine sand content (both of which are assumed to remain stable over time), but also evenness. A small change in evenness results in a large change in the hardness value, and to achieve a high rating, flat surface with deviations no more than 10 mm must be produced. It was discussed in chapter 4 that this may be due to localised compaction causing the unevenness, therefore the greater the unevenness, the higher the hardness reading.

BD2

In wet conditions, the hardness readings are only based on the soil density. Although the BD2 category ranges from 1.00 to 1.19 Mg/m^3, this degree of variation makes little difference. If density increased to the limit for the BD2 category, the hardness rating would remain in the high category.

Moisture content determines the hardness reading under dry conditions. The minimum moisture content was 23% which results in a rating of basic due to the pitch being too hard. The mean moisture content was 36% which increases the rating to standard but to achieve a pitch that is not too hard, and not a threat to player safety, pitch irrigation will be required. At this bulk density, a moisture content of 52% or more is required to achieve a high level of hardness, which is close to saturation, and would not be a suitable option, especially where irrigation occurs via mains water supply.

BD3

Under wet conditions, the hardness rating of the surface could not be predicted with the data collected, at this bulk density category. This may be due to the factors discussed for BD1, but also due to a limited data set at this bulk density.

In dry conditions, the hardness is affected by the evenness of the surface and the grass cover percentage. With evenness kept to a minimum to limit the pitch from impacting on the interaction between the ball and the surface, a figure of 10 mm was inputted into the model. At 10 mm, maximum grass cover still cannot improve on a hardness rating of basic and therefore the aim of pitch management must be to reduce bulk density.

5.1.6 Discussion

For this model to successfully provide an indication of traction and hardness, both soil physical parameters are required, and pitch variables that can be easily measured each day. This would suggest that the model is more sensitive to changes in pitch factors (such as grass cover and moisture content) but in fact operation of the model assumes that the pitch variables remain stable over time; changing only in response to specific events (such as top dressing) and density may increase due to particular management practices, but the action of tining and other soil loosening operations may reverse this.

It is foreseeable that a consultancy firm that supports a model such as this and markets it may also offer a support service which regularly tests the pitch to establish changes periodically throughout the playing season. This could be included as part of an overall fee for the model. Failure to do this may result in the model prediction and the actual values of traction and hardness differing greatly.

This also suggests the need for further research to understand how pitch management impacts on playing quality. This was discussed at the end of chapter 4 but is highlighted further by these results; given the quality statement that this model generates, a Groundsman may have to either improve or maintain pitch quality. What is lacking is any guidelines on how to achieve this, in terms of the machinery available. Where the only factor that can be adjusted to manage traction is grass cover (sand; wet BD3 and dry BD1), pitch management must seek to maximise ground cover but the response of the grass would be too slow if the improvement was required quickly, and difficult to achieve during the winter months.

Where a number of factors are involved in the prediction, particularly soil factors, pitch management must ensure that the condition is not made worse by inappropriate machinery selection, particularly with regard to bulk density changes. Therefore, future research needs to establish how each operation available to a Groundsman alters pitch quality, or bulk density, and this could be incorporated into future versions of the model.

Similarly to the conclusions of the previous chapter, a more intensive study on few pitches of known soil type would produce more data from which stronger conclusions and regression models could be generated from. These pitches could be monitored much more frequently, and, with permission, irrigation could produce wet conditions, removing the need to rely on climatic conditions to produce variability in pitch condition. A greater spread of data, such a wider range of soil moisture contents, may aid the production of more reliable regression models.

Model sensitivity is a function of the reliability of the regression equations, which in some cases was less than 0.50, resulting in a quality rank that may not be accurate enough. However, accepting this limitation, the model demonstrated that for traction, increased grass cover increased the value and hence quality rank, but under wet conditions, this positive effect was negated. This demonstrated a clear need for adequate drainage; less of a problem on sand-based sports pitches, but difficult to achieve on heavy-textured soils, characteristic of local authority controlled pitches. Hardness values under wet conditions were either not predicted (twice) or poorly predicted, indicating the variability in surface conditions when wet and the inability of the lightweight hammer to provide data of sufficient quality to enable prediction. It highlights the need for further research into the effect of different hammer weights, adequate drainage to prevent surface conditions becoming too wet and perhaps prevention of play (at elite level at least) when conditions are too variable to be predicted and injury potential may be high.

5.1.7 Conclusions

1. Prediction equations to monitor pitch quality in real-time can be incorporated into a water and turf management model for use by Groundsmen.
2. The model may improve the current industry uptake of Performance Quality Standards by making the results easier to monitor while also beginning to highlight the factors that have the greatest effect.
3. The results highlight that further research is required to understand the impact of pitch management options on quality. This would enable the pitch quality to be more accurately modelled, and the effect on bulk density also linked to pitch management (possibly empirically) and incorporated into future versions of the model.
4. The results of chapter 4 and five have for the first time provided a clear link between pitch quality and soil conditions and presented in a way that is meaningful to those charged with managing natural turf winter sports pitches.
5. Maximising player-surface interaction quality is only one aspect of sports pitch management and these results need to be incorporated into an overall pitch maintenance regime.

6. The model demonstrated that as a result of investment into R&D, a consultancy firm could gain more than an increase in knowledge; although further research is required, the development of a marketable product is possible.

5.2 Chapter summary

Using the regression equations established in chapter 4, pitch quality monitoring software was developed to highlight how the regression results could be utilised. The software is not currently marketable due to limited sample sizes, narrow spread of data and poor R^2 values, particularly for sand-based pitches however it gives an indication of how pitch management could be linked directly to measures of playing quality.

Chapter 6 will consider the nature of the football pitch consultancy industry, to discover the opportunities and threats and the strategic options that must be considered if investment in R&D is to result in greater profitability.

Chapter 6 Commercial Investigation

Chapters two, three and four investigated the appropriateness of soil as a support system for football, determined the soil physical issues involved in football pitch management and developed a system of predicting how the quality of a surface can be monitored (and potentially altered) using a day-to-day log of surface conditions. This chapter will focus on the business application of the conducted research and address objective two set out in chapter one. The objective and key deliverables of this chapter are:

To detail appropriate strategic considerations that must be understood in order for a small consultancy to gain market share using the results of out-sourced research by:

a. Identifying the driving forces in the market place and producing a detailed overview of the industry structure and its dynamics.
b. Reviewing appropriate strategic options and highlighting which should be focussed on to increase competitive advantage and affect market share.

An investigation into the structure of the sports turf industry will enable the dynamics in the industry to be understood and visualise the sources of competitive rivalry. Recent changes in the industry have resulted in a range of opportunities and threats which need to be addressed if a small consultancy is to remain competitive.

TurfTrax will not be used explicitly in this chapter; instead reference will be made to a hypothetical ‘small consultancy company’ although key requirements and learning points may be relevant to TurfTrax. The chapter will be split into two distinct sections. The first section will consider the industry structure and through various diagrams, the dynamics of the football sports turf consultancy industry will be mapped. The diagrams will present flows of money, work, solutions, targets and regulation, and through a progression of figures, will highlight how the industry has evolved and the driving forces behind this evolution will be discussed.

The second section will review the strategic options available to the small consultancy company to successfully respond to the changes being witnessed in order to build on existing competencies or obtain new ones, to take advantage of new opportunities. Mintzberg *et al.,* (1998) detailed ten schools of strategic thinking and although this chapter will use tools developed by more than one school, a review of all ten schools will not be performed. Instead, this section will assess the different elements of strategy using ideas primarily from the three descriptive schools described by Mintzberg *et al.*, while acknowledging that emergent strategies i.e. ones that evolve in response to unexpected scenarios, should not be ignored simply because they do not fit in with the original ‘plan’. In a dynamic industry it will be necessary for a company to also be dynamic and responsive to external influences.

6.1 Football sports turf consultancy sector description

This section will show the stakeholders in the industry, and detail the flow of money, work, regulation, targets and solutions that exist to keep the industry functioning. Further figures will highlight how the industry has changed. Once these flows have been established, a PESTEL analysis, as described by Johnson and Scholes (2002) will be used to determine the changing macro-environment by analysing 6 macro-environment factors that can influence a company. Then the five forces model, first developed by Porter (1980) will enable a more detailed focus on a company. Each element of both models will be discussed to establish their relevance, implications and possible origins of change within this industry.

6.1.1 An overview

The football sports turf consultancy industry has witnessed rapid growth in recent years. There is little information available regarding the financial strength of the industry and the turnover generated; however, it seems the intervention of the British Government through a variety of initiatives such as ‘Green Spaces’ and ‘Best Value’ and funding via the National Lottery increased flows of money into the industry, altering the dynamic. Money from these initiatives was (and still is) aimed at improving sports surfaces in order to increase sports participation amongst the general public. A snap shot of the primary flows that occur within the football sports turf industry are shown in Figure 6.1.

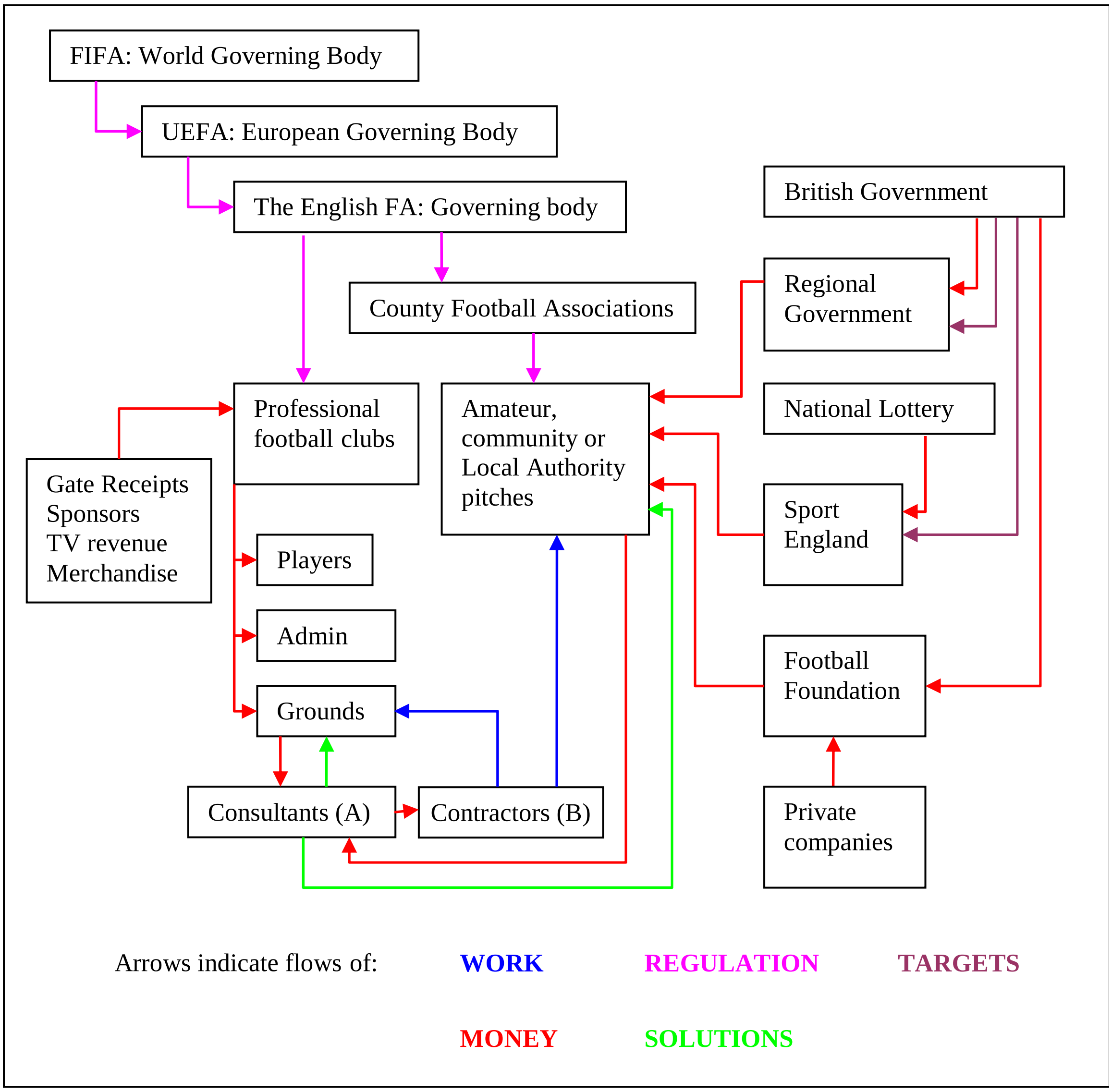


Figure 6.1 The English football sports turf industry and flows of money, work, regulation, targets and solutions. Source: author.

Figure 6.1 assumes a separate consultancy (A) and contractor (B). Where the two are the same company, the two boxes would merge but the general flows would be identical. Internally however, money would flow from one business unit to another. General practice is for the advice of a consultancy company to be put out to tender, in which case the contractor would be paid directly by the club. To investigate the flows in detail, the following sections detail different scenarios and how the flows have been altered in each case.

Premiership and professional league clubs

Figure 6.2 highlights a situation that has remained unchanged over time: cash-rich football clubs are capable of generating a large amount of income and while an ever increasing proportion is being spent on player wages (Mintel, 2004), the provision of high-quality training pitches and stadia, requires adequate investment. Solutions to pitch problems offered by the consultancy are therefore of the highest quality, rooted in scientific research and proportionately expensive.

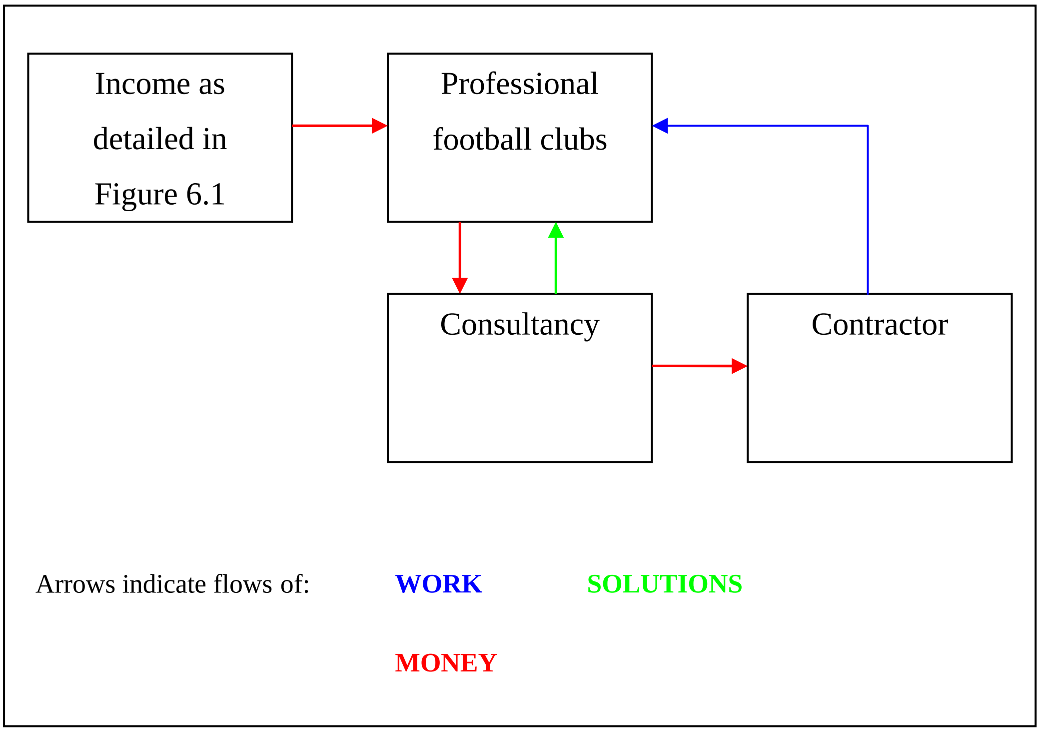


Figure 6.2 Flow of money, solutions and work in the professional game.

Pre 'Green Spaces' initiative

Historically, non-league football clubs, schools and Local Authority pitches had a limited supply of funds with which to upgrade facilities. These funds would have been raised through small local events and other activities and would be a small fraction of the total amount available to a Premiership or professional league club. The result of this was that any work conducted on the pitch was limited in its effectiveness and sophistication, as Figure 6.3 suggests:

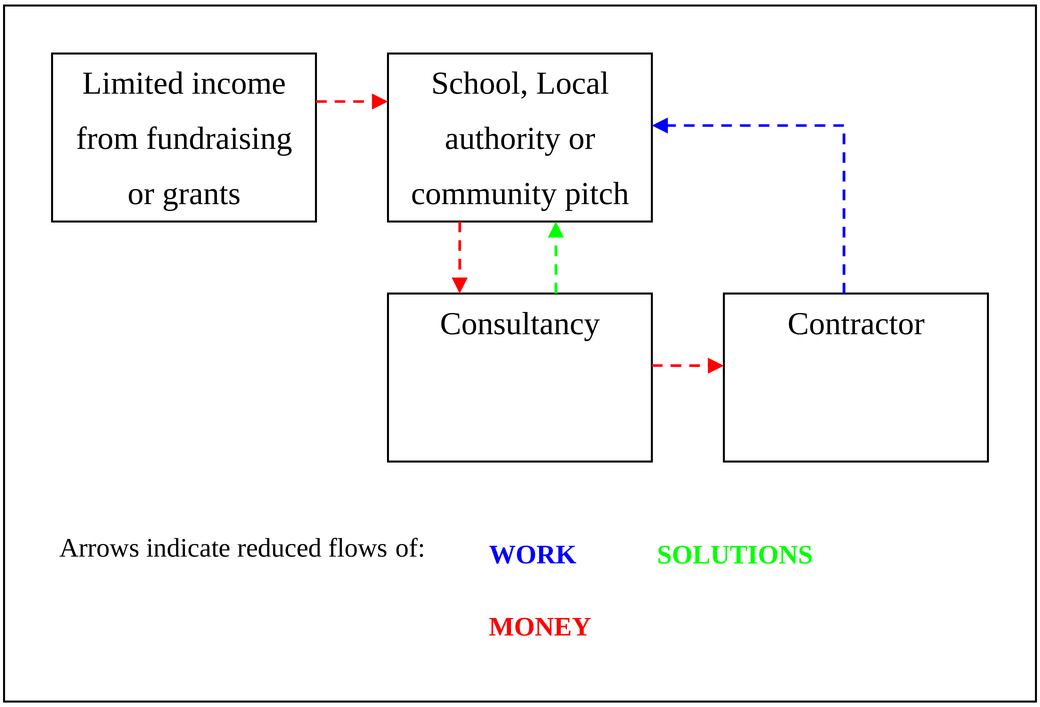


Figure 6.3 Flows of money, work and solutions available to schools, LA or community pitches, pre 'Green Spaces' initiative. Lines are dashed to indicate a limited offering, relative to professional football clubs.

The dashed lines indicate a 'cut-price' or limited offering. In the example above, the reduced flow of money would result in a cheaper solution being offered and therefore the contractor would be performing limited on-site work.

Post 'Green Spaces' initiative

Figure 6.4 represents the situation today, for non-league football clubs. The 'Green Spaces' initiative aimed to channel funds through the National Lottery in order to improve sports facilities and was established during the first year of the new Labour Government (1997-1998). Although criticised for failing to deliver (NUT, 13th March 2002), its financial effects and the effects of subsequent reports such as DCMS (2002) have sustained an increased flow of money into the sports surface industry with the joint aims of increasing sport participation in children and adults, to alleviate the burden on the NHS. The result is as follows:

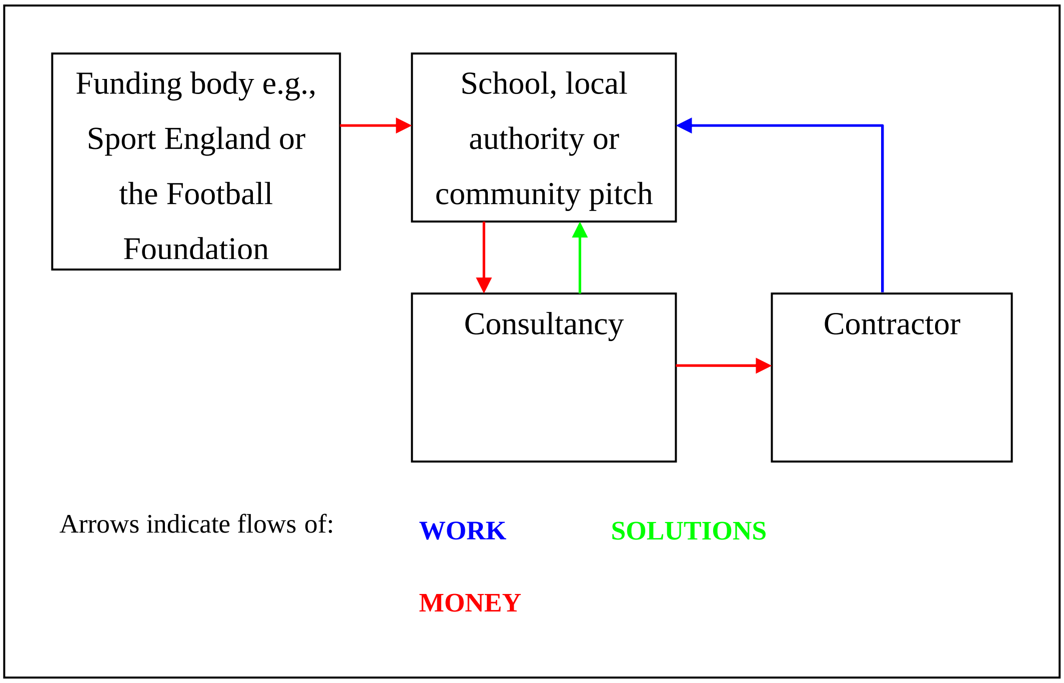


Figure 6.4 Flow of money, work and solutions available to schools, LA or community pitches, post 'Green Spaces' initiative.

Figure 6.4 used solid arrows to represent flows comparable to those in Figure 6.2. Traditionally poorer clubs became able to afford expensive and elaborate solutions to specific pitch problems normally only available to clubs in the professional game, due to their larger overall budget. However, Earl (Pers. Comm.) suggested that the new funding schemes would ensure equivalent finances to a non-league club aiming to perform the same task as a Premiership club. For example, the amount of money available for a slit drain drainage scheme on a single pitch would be equal for a Premiership club or community playing field.

6.2 The external environment

Managers dealing with an uncertain business world are dealing with three fundamental issues: diversity, speed of change and complexity (Johnson and Scholes, 2002). Each of these factors has presented problems to managers who tried to understand the position of their company and how to take it forward. For many organisations, this will take on a global perspective and add to the complexity of analysis (Rosen, 1995).

Difficulties have been overcome by viewing the industry as a series of layers encapsulating the company (Johnson and Scholes, 2002) however, this approach could lead to the view that each component is nested within a larger component. Rosen (1995) argued instead that each component provided different points from which to view the environment the organisation was operating in. The industry layers, adapted from Johnson and Scholes (2002) are presented in Figure 6.5:

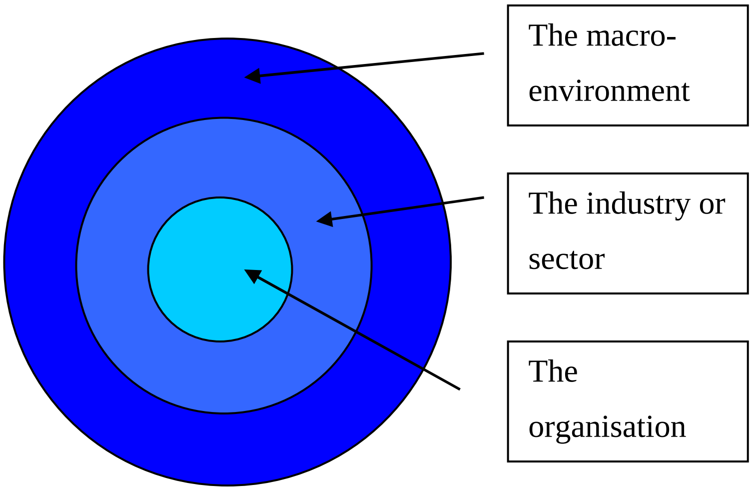


Figure 6.5 The layers surrounding an organisation. Adapted from Johnson and Scholes (2002).

6.2.1 PESTEL

The PEST framework (Politico-legal, Economic, Social and Technological) (Rosen, 1995) or a more up-to-date version; PESTEL (Political, Economic, Sociocultural, Technological, Environmental and Legal) (Johnson and Scholes, 2002) can be used to assess the macro-environment. It should be used to identify the impact on the business of future changes in any of the listed factors.

Political

The impact of Government intervention into the football sports turf industry has been identified in section 6.1.1, Figure 6.3 and Figure 6.4 and the future will most likely remain stable while this forms a priority of the Government. The use of participation in sport to reduce the incidence of obesity, coronary disease, diabetes and crime (DCMS/Strategy Unit, 2002) is a long-term objective, however, should a change of

Government occur at the next election, it is unknown whether a new Government will have the same priorities. The DCMS report also suggested that by 2020 the rate of sport participation should be 70% of the population from its current position of approximately 30%. Although the funding structure is due for renewal in order to easily track the flow of money into sport and measure its benefits, the theme of the reports is that of sustainability and a move from ‘hand-outs’ to investments. This would require facilities to sustain the required usage levels and consultancy firms that provide solutions that do this, will be in a position to capitalise on the change.

Economic factors

The supply of money into the amateur game is expected to continue because of government targets, while the professional game is cash-rich and historically unaffected by recession (Mintel, 2000). While consumer debt in the United Kingdom has reached new heights, having broken through the £1 trillion barrier in 2004 (BBC, 29th July 2004) expenditure on sport and leisure is increasing and is forecast to continue (Mintel, 2004).

Socio-cultural factors

Based on the targets for the government, it is foreseeable that lifestyle changes will occur and attitudes towards health and leisure will change to the benefit of a consultancy operating in the sports turf industry through the addition of increased pressure on facilities and hence a requirement for appropriate solutions, benefiting those firms which are up-to-date with scientific research.

The level of education within the sports turf sector, and with Groundsmen in particular, is an important factor. This could pose a threat as clubs take some of the knowledge of soil science ‘in-house’ resulting in a reduced need for consultancy firms. However, the converse is also possible; that the higher level of education amongst Groundsmen will help to ensure the science-based complex solutions on offer from the better consultancy firms are understood and their maintenance is appropriate for the intended volume of use. The outcome of this increase in education will be witnessed over the coming few years.

Technological factors

It is considered that the input of technological advances into the UK football sports turf industry are slow to be realised compared to overseas sports turf industries (Casimaty, Pers. Comm.). Attitudes towards products, grass species selection and machinery choices can vary rapidly due to the work of bodies such as the Sports Turf Research Institute (STRI), the marketing efforts of companies, personal experience and preferences and budget. New discoveries and developments are likely as research continues, however as this is funded directly by companies and other organisations in the industry (such as The Jockey Club and England and Wales Cricket Board), the benefits should filter through to those responsible for maintaining sport facilities.

Environmental factors

Changes to legislation concerning environmental issues will present further opportunities and difficulties for a consultancy. Legislation regarding the amount of pesticide, herbicide and fertiliser leaching are already in place and are only likely to become more stringent. In Denmark, the government is funding research into min-till style systems where ground management is kept to a minimum and almost zero inputs, such as fertiliser and herbicides, are added (Larson and Fischer, 2005). The results of this study and others around the world should be monitored closely. Furthermore, the volume of water used by sports clubs for irrigation purposes may come under increasing pressure. Clubs that use mains water are placed under greater financial pressure, while others who cannot irrigate could be left with unusable facilities; pitch constructions that allow rapid water loss during the winter for drainage will not retain enough moisture over the summer and additions will be necessary.

Solutions must balance the requirement for excess water removal from the pitch during the winter months, while being capable of sustaining appropriate conditions for play during the summer, without creating environmental pressures or a dangerous surface.

Legal

The Health and Safety at Work Act (HMSO, 1974) has not been applied to sports surfaces in professional clubs effectively and in studies considering the hazards to a football player, the pitch was not identified (Fuller and Hawkins, 1997; Hawkins and

Fuller, 1999). Arguably, this legislation will filter through to the football pitch and employers will have a duty of care to provide employees (the players) with a pitch that does not present any danger of injury.

In amateur football, this legislation could be used against negligent councils who fail to supply pitches of a suitable quality. It has been argued that the widespread introduction of artificial football pitches, despite the current G3 pitches offering a highly consistent playing surface, is unfeasible; therefore, there is a clear need to identify the minimum amount of work necessary to improve the quality of natural turf pitches (Gale, Pers. Comm.). Gale also argued that the development of Local Authority pitches and the understanding of the minimum maintenance requirement will be key to ensuring that future football stars are not being threatened by injuries before they have had time to mature.

6.2.2 Porters five forces

First presented by Porter (1985), this model allows the forces of competition within an industry to be identified, representing the next layer in from the macro-environment shown in Figure 6.5. Analysis determines the extent of ‘threats’ to a company, which provided a basis for the development of strategies to act as counter measures. The framework highlights key points for each threat which will then be discussed in greater detail. Although Porter (1985) does not present room for emergent strategies, instead suggesting a ‘plan’ be stuck to, he does concede that the broader expectations of society need to be taken into account.

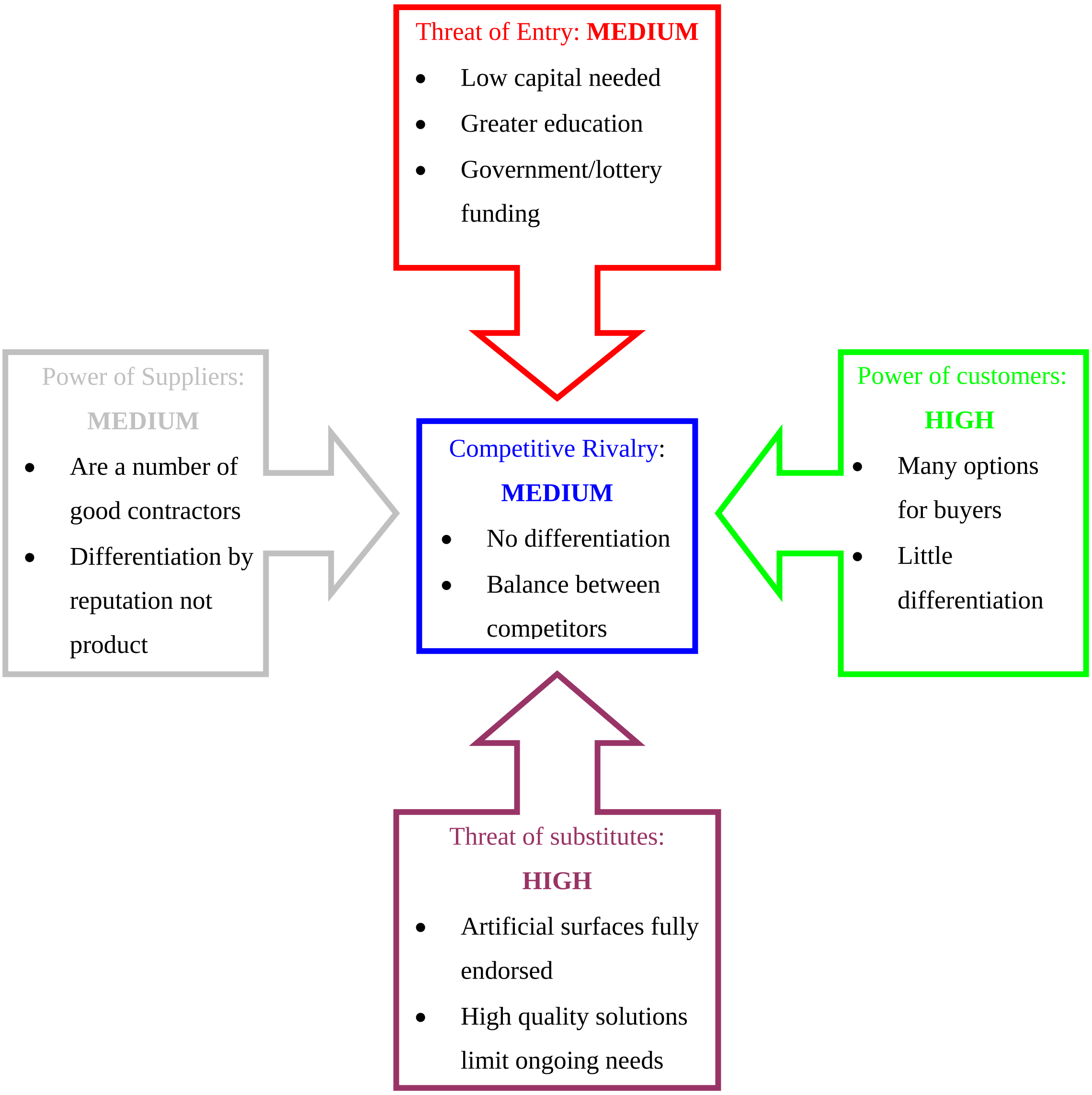


Figure 6.6 Porters five forces framework for a consultancy in the football sports turf industry

Importantly, Porter (Porter, 1980) argued that the strength of these forces will determine the profitability of an industry; where the 'high' threats exist, profitability will be hard to achieve. Figure 6.6 demonstrates three high threats and 2 medium; this would indicate that the outlook is not positive. The justification for the scores for each of the forces is discussed further under the appropriate heading:

Threat of Entry (MEDIUM)

In order to offer a consultancy service, it is foreseeable that a single Groundsman-turned consultant with experience and credibility among Groundsmen would require only a telephone and a mode of transport. Although this may act as a barrier towards other potential entrants, it could serve the new entrant well. This would be a threat to the firms already in the market as the new incumbent could poach market share.

Secondly, there is a threat to the consultants from the increased knowledge gained by Groundsmen working directly for football clubs who are now capable of diagnosing an issue, and then turn directly to a contractor, avoiding the need for a consultant to become involved. To prevent this there are a number of options. Contractors and consultants could collaborate, or potentially merge so that the business would maintain an income from at least one division. Alternatively, a consultancy could market itself as a market leader and provider of unique solutions that the Groundsmen may not have considered, thus sustaining demand. A strong brand identity through appropriate associations and marketing would underpin the quality of the brand (Keller, 2003). Increased education may work in the favour of a consultancy as the increasingly complex solutions and highly technical designs could be understood and implemented correctly by the Groundsman.

Finally, the action of the Government is generating a significant threat of entry. By offering financial assistance to clubs, schools and Local Authorities, the industry is being viewed as profitable and cash-rich. In order to create a barrier, a company needs to establish a benchmark against which new entrants will be judged. If the consultancy relies heavily on staff with post-graduate qualifications for example, these need to be emphasised, ensuring that those who seek solutions understand the value of a particular consultant, creating a barrier that potential entrants would need to overcome.

Offsetting these threats are a number of factors, which empower consultants already working in the football sports turf sector. BASIS is an independent registration, standards and certification scheme for anyone who advises on the use and application of chemical fertilisers and pesticides. RIPTA is a register of consultants that have gained relevant qualifications and experience, meeting the criteria required to register. The membership of either or both of these bodies creates a barrier to entry for new incumbents and thus strengthens the position of existing consultants. However the membership of RIPTA in particular is not a barrier to general entry as such, since it is an organisation that is only recognised within small sections of the sports turf industry itself. Funding bodies such as Sport England only stipulate that a consultant have a minimum of a degree level qualification in a relevant science or engineering subject (i.e. they do not have to be a member of RIPTA).

Threat of substitutes (HIGH)

The threat of substitution in the sports turf consultancy industry hinges around two concepts; the threat of product for product substitution and the threat of substitution of need.

The threat of product for product substitution is significant. In 2002 FIFA, the world governing body of football sanctioned the use of artificial sports surfaces in all major domestic leagues and for most cup competitions, excluding finals and world cup events. Furthermore, the introduction of artificial surfaces was supported with the offer of financial assistance amounting to 50% of the cost of installation and a contribution towards maintenance, both from FIFA. The installation of artificial surfaces will occur, especially where finances are not available to support grounds care staff and in urban communities where space is limited. To limit this threat, a small consultancy should consider taking on a specialist in artificial surfaces to ensure they can bid for contracts that are both natural and artificial turf projects. By incorporating this into the business model, it will become less of a threat.

The substitution of need is a function of the success of the company. As the solutions being offered become more technically advanced and are capable of resolving the issues they were designed to, the on-going need for consultancy may diminish. While there may always be a need for consultants to offer solutions, the danger is that new business will be constantly required to provide a steady income to the organisation. In order to minimise this threat, a consultancy should attempt to ring-fence a customer and ensure that in a given time period, they are contractually obliged to the consultancy for all of their problem solving work, and, where there has been on-site installation, the company has a monitoring and evaluation contract lasting for a period of years. This would also provide the customer with peace of mind and offer security in the event of further problems.

Power of buyers (HIGH)

Buyers are the football clubs, whether the professional leagues, or schools, LA or community clubs that have the finances available to improve facilities as a result of a successful grant application.

The power of the buyers is deemed to be high. Growth in the number of consultants able to offer a solution, especially since the introduction of the MSc Course in Sports Technology at Cranfield University at Silsoe, in 2002 and the lack of differentiation in the market has resulted in greater choice for buyers. To counter this threat a company needs to market itself into a position where it is perceived to offer the ‘best’ solution, generating brand recognition and reputation perhaps justifying higher prices which in turn would lead to greater profitability. This would need to be supported with solutions that are of a high quality and profit should be invested in research and to ensure members of staff are kept up-to-date with current and future ideas via attendance at conferences and further education and training.

Power of suppliers (MEDIUM)

In this example, the suppliers are deemed to be the contractors; those that carry out the work and implement the solutions proposed by the consultancy. The threat is classed as medium for a number of reasons:

Contractors are scattered across the UK, and while many will work in regions far from their head office, this adds to the cost of a job and may render them too expensive. Because of this, geographical constraints on companies ensure that consultancy firms have an ability to pick whichever contractor they require. However, once in a particular region, the choice may be limited, returning some power to the contractor.

Contractors are rated by the quality of their work; therefore, firms are differentiated by their reputation rather than by offering a particular service that another contractor cannot match. The result is that the company can choose which contractor to work with offering them more power.

In order to further reduce the power of buyers, backwards integration would be an option, especially if this could be achieved with a company that has a strong reputation. This would offer the company economies of scale and ensure they had more control over the quality of work and the day-today on-site issues and decision making that occurs.

Competitive rivalry (MEDIUM)

Competitive rivalry exists where there are a number of firms offering similar products or services. A medium threat represents the degree of balance of in the industry; firms range from a small business where a single consultant can work with minimal overheads, to larger organisations, boasting expensive cars, workshop and analytical facilities, new offices and paying high-calibre members of staff. This degree of imbalance will ensure that there are contracts that the larger organisation will avoid from a profitability perspective and the small organisation will avoid due to a lack of capacity.

Where there is a high competitive rivalry, it is due to a factor already discussed: differentiation. In order to reduce the threat of competition while simultaneously erecting a barrier to entry and reducing the power of buyers, the offering made by a consultancy must be differentiated from its rivals. Marketing alone may generate a perceived differentiation and still achieve this objective.

Both the macro-environment (PESTEL) and micro-environment (Porters Five Forces) have been discussed in the context of a consultancy operating in the sports turf industry. Discussions have highlighted a range of issues and these should be brought together succinctly in order that they can be used to formulate a strategic plan, based on which the company can move forwards and further establish itself as the market leader. In order to bring the key elements together for this purpose a SWOT analysis is required.

6.2.3 SWOT

The PESTEL and Five Forces models both highlighted a range of issues, both future and current that must be addressed by a consultancy operating in this industry and aiming to be profitable. The results of the analysis enable a SWOT (Strengths, Weaknesses, Opportunities and Threats) matrix to be used to compare the highlighted issues against the competencies of a company. This model aims to produce a fit between the internal capabilities (Strengths and Weaknesses) of the organisation and the external opportunities (Opportunities and Threats).

The use of a hypothetical small consultancy company limits the production of targeted strengths and weaknesses, therefore, a checklist of desirable competences a company requires to counter the threats discussed, will be presented. The competencies deemed necessary based on the discussion of the Porters five forces model and the analysis of the macro-environment, are:

1. Knowledge of the health and safety legislation and how it can be applied to sports surfaces
2. Detailed soil physical understanding and successful application to sports pitch solutions
3. Knowledge of artificial surfaces in order to take advantage of the situations where they may be the preferred option
4. Employment of high-calibre staff, qualified in turf grass science, to create a barrier to potential competitors, as long as they could not be poached. Suitably qualified staff will also enable diversification into other sports
5. Successful HR provision to ensure retention of valued key staff and staff that are removed from the business are done so in a sensitive manner to prevent them damaging the brand after they have left
6. A simple organisational structure to encourage freedom of discussion to generate new ideas and concepts that could be easily shared among staff
7. A flexible view of strategy in order to take advantage of new opportunities as they arise
8. A dedicated marketing department in order to ensure the company is constantly reinforcing its place in the industry; perhaps through a company newsletter, features and adverts in industry magazines and presence at conferences and trade shows.

9. Close working relationship with a single contractor, or a limited number of contractors in different geographic regions, to ensure a reputation for high quality work could be established.
10. An organisational structure to encourage continued learning by staff to ensure their knowledge is up to date.

The SWOT model also considers the industry opportunities and threats and these must be acknowledged and competencies developed accordingly. From the previous models, the opportunities that have been identified are:

1. Continued investment into facilities, encouraged by Government targets, will ensure continued opportunities for consultancy work to be profitable.
2. This investment has skewed the market such that small projects, such as Local Authority pitch improvements are as profitable (in the short-term) as projects with professional football clubs.
3. Increased legislation will favour the firms that have invested in R&D and basic research to discover the means of producing safe surfaces within the stricter guidelines.
4. The divide between the poorer and richer clubs is not narrowing (Mintel, 2004) therefore an opportunity exists to focus on the wealthier clubs and segment the market, establishing the company as synonymous with high-calibre sports clubs.

The identified threats are:

1. Increased cost of water and legislation regarding its use; vital for softening hard pitches during the summer months of the year and aiding the recovery of the grass.
2. Increased legislation on environmental pollutants and their use and leaching allowances.
3. Increased knowledge of Groundsmen and contractors through further education limiting the need for consultants

4. The continued threat of new entrants into the market due to the extent of funding available and the potential profitability of the industry.
5. The lack of clear differentiation between firms will further encourage new entrants and provide buyers with more power.

6.3 Strategic management

"With the wave of global change that is continually breaking over us, only a foolish organisation would turn its back on the many ways it might improve its efficiency, competitiveness and morale. The future is a dangerous place, and we are already living in it" (Robbins and Finley, 1997).

Strategy is an extensive area of work, both in theory and application; therefore this chapter will address the elements of strategy directly relevant to the issues highlighted by the PESTEL, Five Forces and SWOT analyses. This section will begin with a definition of strategy (although its exact definition will depend on which of the ten schools identified by Mintzberg *et al.,* (1998) is being followed), before the elements of strategic management are addressed, how they are different from conventional management and why firms, particularly technically focussed firms, may fail to generate effective strategies. Once the current strategic position has been discussed and choices for the future identified, methods of achieving and maintaining competitive advantage will be discussed. The idea that an alliance or backwards integration may be an option was presented in section 6.2.2 and strategic considerations for this will be presented, concluding with a discussion on how R&D results can be used to generate a competitive advantage.

6.3.1 Strategy explained

Rosen (1995) suggests that one view of strategy is the notion that it is a long-term plan, where details have been scrutinised and each possible outcome detailed before a final decision is made. This notion of planning for the future is disliked by Mintzberg (1994) who argues that planning prevents the occurrence of emergent strategies and the best strategies, he argues, stem from deliberate outlines, whose details are allowed to emerge, giving rise the idea of strategy *formatio*n rather than strategy *formulation*.

This provides a necessary balance; if all strategies were emergent it would suggest there is no control, but if all strategies were pre-planned it would suggest no flexibility. These ideas stem from the planning school of strategy, with the addition of emergent ideas. Alternatively, Porter (1980), grounded in the positioning school of strategy, considered not only how strategies should come to fruition but also their content. He presented three generic strategies which focussed on what a company hoped to achieve; cost leadership, differentiation or focus (a combination of the first two). Mintzberg *et al.*, (1998) criticised Porter for inflexibility and a failure to incorporate learning into strategy and for such a theoretical, abstract approach.

Stacey (2003) accepted that learning would provide a rich addition to strategic choices but there was a limit on what could actually be achieved by members of an organisation and this was determined by the organisational culture. Overall Mintzberg *et al.*, (1998) argued that strategy must combine all these various elements; including mental, environmental, leadership and organisational demands. The strategy cannot plan for every eventuality; however, it cannot be entirely emergent either.

6.3.2 Elements of strategic management

Strategic management is not just the management of strategic decision making. This definition, according to Johnson and Scholes (2002) fails to clearly differentiate between this and other forms of management. To highlight these differences, the following table is presented;

Strategic Management	Operational Management
Ambiguous/Uncertain	Routinised
Complex	
Organisation wide	Operationally specific
Fundamental	
Long-term implications	Short-term implications

Table 6.1 Characteristics of strategic and operational management, adapted from (Johnson and Scholes, 2002)

These differences may cause difficulties to managers in a sports turf consultancy who view issues with the bias of their particular expertise. This is accentuated by strategic management being concerned with understanding the issues and concepts relevant for forming the analysis and action regarding the strategy; many managers will be used to taking action or planning or analysis. Finally strategic management must also include action; strategy has to be put into effect, utilising all the necessary resources to achieve this. The organisational structure within the consultancy needs to support this view of understanding the core issues and underlines the necessity that a small consultancy must keep up to date with current issues, in order to respond effectively to changes in the industry or customer requirements.

6.3.2.1 Understanding the strategic position of the organisation

The use of tools such as PESTEL and Five Forces is a simple but important means of identifying the strategic position of the company (Johnson and Scholes, 2002). For a consultancy to remain competitive its choice of strategy will be determined by these outputs; the generation of the contents of each of these concepts will aid a manager involved in strategy formation to understand where their company fits into the overall industry and wider business environment. Bowman (1998) also suggests that the generation of these models on an individual basis, before being brought together, may highlight different perceptions. Mintzberg (1994) argued that a company must consider where the customer and company meet and look into the market place for future and current requirements.

6.3.2.2 Understanding the strategic choices for the future

The choices for the future are dependent on the perspective of the company (Mintzberg, 1994); a consultancy would need to consider its grand aims and desires for the future, before action can be taken. The preference may be to service Premiership or upper league professional clubs only, thereby being associated with ultimate solutions and being in a position to integrate that into their marketing.

6.3.3 Turning strategy into action

The intervention of the British Government has skewed the nature of the sports turf industry; formerly a clear-cut divide between the rich and the poor clubs has become confused though the ability of poorer clubs to apply for grants to improve facilities. Prior to this, market segmentation would have dealt with the amateur and professional league clubs independently and differently, whereas the current situation renders this distinction almost obsolete.

However, this distinction is still valuable and the selection of servicing the wealthier clubs (almost exclusively) as a strategy will give the entire organisation focus and drive towards a particular goal. The methods of achieving and sustaining competitive advantage with this strategy will be discussed below and the potential impact on market share and profitability discussed.

Mintzberg (1994) argued that to outsmart competitors and place the company in a niche position that is secure, strategy needs to be a creative phenomenon. He argued the only way to achieve this was for management to consider shifts in consumer habits, changes in products mixes and the action of competitors. This is in contrast to the earlier work by Porter (1980) who argued that a company could choose one of three generic strategies; cost leadership, differentiation and focus, to achieve the same outcome. Actually putting a strategy into practice has been traditionally very difficult. Stirling (2003) argued that nearly 70% of strategies are never successfully implemented and he highlights how small factors such as communication, strong leadership setting examples and targeting pre-identified customer needs will produce more likelihood of success.

Porters’ focus strategy will be selected for the consultancy to pursue but based on the argument by Minztberg *et al.,* (1998) the ability to adapt to changes in the macro-environment (identified in the PESTEL model) will be added. The main approach will be to target Premiership or upper professional league football clubs.

6.3.3.1 Achieving competitive advantage

Rosen (1995) argues that competitive advantage, particularly in the context of strategic management has a definite meaning; “Long-term profitability which is above average for the industry”. This, he argues, will enable a company to reinvest in training and further product or service development; perpetuating the advantage initially gained. For this advantage to be realised, there are further issues to be faced when selecting a strategy.

The strategy clock

The focus strategy highlights a need for the consultancy to differentiate its offering. Wealthy football clubs are each different, with football pitches specially constructed for their stadium, and training grounds. This presents a difficulty in applying the same advice to each customer and therefore the approach must be through product differentiation. The service offered will be tailored to each club, while maintaining the focus on the optimum solution to problems. In order to generate barriers to entry into this segment, the company would require long-term contracts for either maintenance or further advice. This would also provide sustained income for the company. To visualise the effect of the chosen strategy, Faulkner and Bowman (1995), presented the ‘Strategy Clock’. Although based on broad generalisations (Johnson and Scholes, 2002) competitive advantage can become clear. The clock is presented below.

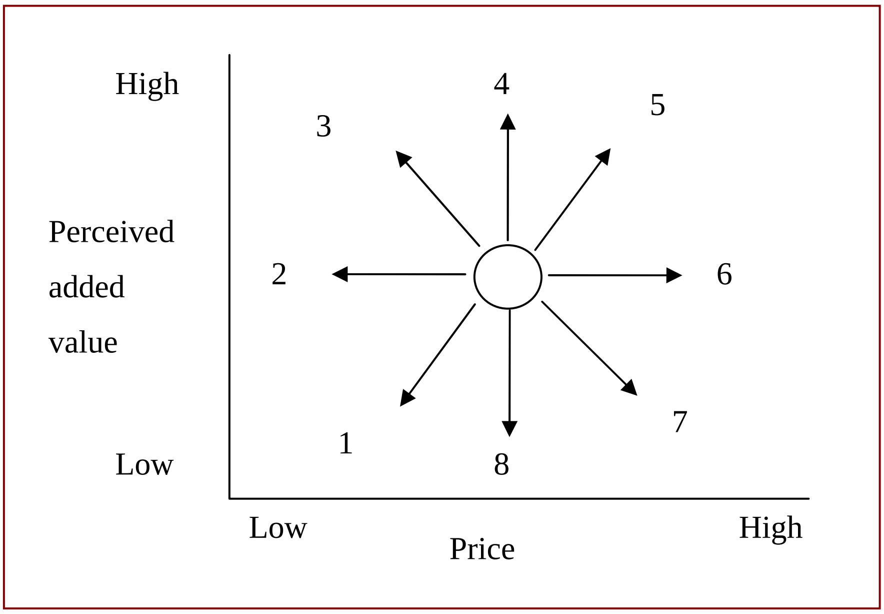


Figure 6.7 The Strategy clock, adapted from Johnson and Scholes (2002)

Experience gained over time would create further barriers to entry to potential competitors as it could help reduce costs while still supplying the same quality of product or service. Using the strategy clock, the focus strategy would be attempting to move the company into position 5; the achievable price would increase due to the time investment required to service these customers effectively, while the perceived added value would also increase through the tailoring of services specifically to that club, while also being accessible to discuss future issues. Increased price should also lead to increase profit which could be re-invested in research and marketing to associate the type of customer and the company.

Small scale projects, such as those at schools and Local Community pitches could still be conducted where they were profitable and used to market the company. They would be used to demonstrate that although the company generally focuses on specific customers, offering the most complex solutions, they also appreciate the need to provide safe pitches for all and wish to be involved with community groups. This would build the concept of brand breadth, presented by Keller (2003).

The disadvantage of this strategy would be trying to overcome the inherent difficulties in managing sports surfaces situated within a stadium. Furthermore, should a problem occur and an injury be directly attributable to the surface, wealthy football clubs will have the financial resources for litigation.

6.3.4 Maintaining competitive advantage

The changing business environment Rosen (1995) and the changing needs of the customer, may impact on the potential to achieve long-lived competitive advantage (Johnson and Scholes, 2002) therefore the aim must be to achieve a superior and lasting position on the strategy clock (Bowman, 1998). The product differentiation strategy being suggested for the consultancy will be imitated by competitors and therefore Porter (1985) suggests a ‘moving target’ needs to be presented to competitors, achieved through re-investment and continually understanding the needs of the customer to stay ahead of the competition. He also argued that failed differentiation strategies did so due to an underestimation of the costs of differentiation and in some cases firms became different, rather than differentiated. The following elements are necessary to achieve sustained competitive advantage:

6.3.4.1 Knowledge management

Knowledge in this context is not just about the ideal depth of a drainage system or which grass species mix should be sown; instead the concept of knowledge management refers to the industry and a company’s competitors. The notion of segmenting a market through product differentiation assumes that competitors operating a blanket approach in the same industry, do not serve the identified segment well enough (Porter, 1980) but knowledge must be continually gained regarding competitors in order to know which of them may offer a similar service based on their available resources, objectives, culture and comparative market strength (Bowman, 1998).

Johnson and Scholes (2002) argued that knowledge is a function of learning and this will also generate unique resources, which may lower costs, creating a barrier to entry or generate distinct competencies within the organisation which other consultancy firms cannot match.

6.3.4.2 Core competencies

A manager in a technically driven business may have difficulties identifying core competencies, instead, highlighting critical success factors (CSF), such as reliability or on-time delivery of solutions to clients (Johnson and Scholes, 2002). However, understanding the company’s core competencies will be pivotal to the success of a differentiation strategy.

Core competencies must be robust i.e. difficult to imitate. An example of core competence could be the structure and culture of the organisation; if supportive of feedback providing an open platform for discussion an advantage could be gained over a competitor. This method has been successfully used by Hewlett Packard (Kowalczyk and Giusti, 1998). The significance of organisational culture should not be overlooked; Schnelder (2000) demonstrated through research that there were four different control mechanisms for strategy and those that were successful had aligned core organisational culture with their strategy and leadership practices. Therefore, the consultancy must develop competencies the customer values in order to prevent imitation, such as an ability to be flexible, or through good personal relations with the clients to build a degree of trust. This must however become part of the organisational culture, rather than an *ad hoc* approach, inconsistent in its application.

Tucker (2001) argued that to maintain competitive advantage, the notion of innovation, of continual service offering and constantly being noticeably superior to ones rival, have become core competencies and must permeate though the entire organisation. Additionally, recent research (Cho and Pucik, 2005) identified that a focus on innovation alone is insufficient; strategy must focus on quality and innovation and the intangible resources to manage these elements are a source of value to a company.

Johnson and Scholes (2002) suggest that an advantage gained from a new marketing campaign may be short-lived. However, investment into brand association, through presence at trade shows, conferences and by providing articles for industry magazines may increase brand depth (Keller, 2003). This would help develop the perception that the consultancy is a key player in the industry and may assist in sustaining advantage.

6.3.4.3 Competitive alliances

Another means of competitive advantage is through the application of scale (Johnson and Scholes, 2002). It was argued that the consultancy many require a strong relationship with its preferred contractor (regarded as a supplier for the purposes of the Five Forces model; Figure 6.1) in order to minimise their power, to ensure the quality of work they produce is to the required standard and to generate a synergy between the two firms. The disadvantage of an alliance is that the contractor may decide to leave the relationship and take with it information regarding how the consultancy operates, leaving it vulnerable. To minimise this threat, the consultancy could merge with a contractor. The advantage of this approach is in the company’s ability to maintain quality and guarantee work schedules to clients that are paying a price premium; this may not be possible when using external contractors. The joint effort, if successful, would generate another barrier to entry for this segment. However, even if collaboration rather than a full merger was the preferred option, this may still be the driver required for successful innovation, which in turn would drive profitability and sustainability (von Stamm, 2004).

6.3.5 Investment in research and development

Research and development will be discussed in the context of generating new technology or technological changes to existing products or services that could result in a shift in competitive advantage or changes in the sports turf industry. The research presented in chapters 2-4 fulfil that criteria; the results have provided for the first time a link between the playing quality of a surface (from a player-surface interaction perspective) and measures of surface and soil parameters. Through the use of the model (chapter 4) Groundsmen are now able to monitor the quality of their pitch or pitches in real-time. Although further research is required to determine the effect on quality of the various management options have, this research has the potential to provide a company with an advantage; both through the application of this model and with the increase in knowledge that chapters 2 and 3 provide.

Burgelman *et al.,* (2003) argue that investing in basic research and development benefits a company, not just via the results but because it helps develop a capacity to assimilate new knowledge which could be used to exploit future developments. The benefit from research should be more than simply the gains in tacit knowledge. Using the terminology of Argyres (1996) this research would seek to deepen a consultancy firms' existing capabilities, rather than extend capabilities to address new markets or opportunities, but the need to understand how to benefit from the research remains.

Porter (1985) argued that technological change was a key driver for competition. His background was in manufacturing rather than the service industry, although this does not detract from the usefulness of his arguments. He suggested that pioneering technological change gives the company a first-mover advantage. It had been argued in (chapter 2) that health and safety regulation and the duty of care employers face in the provision of work place facilities may extend to the football pitch for professional football players. This will generate a greater need for high quality safe football pitches that can be managed appropriately to sustain quality throughout the season. The research outlined in previous chapters addressed this requirement, enabling the consultancy to take the next step; to alter the industry themselves, prior to legislation taking effect. By promoting the results of the research and utilising them in their service offerings they are differentiating their product while simultaneously creating a barrier to entry for that segment. The price premium can be justified in two ways; being the only company to be forward thinking enough to have supported this research, and through the added value to a football club of being able to select a team from a full squad of available players, rather than a squad limited by injuries.

Abraham (2005) asked the question "is outsourcing R&D worth the cost?" He concluded that it was, if the results made the company a better competitor.

6.4 Discussion

Section 6.1 reviewed the current nature of the football sports turf industry, from the perspective of a small consultancy. The review highlighted how the increased supply of funds into the industry through the involvement of the British Government has had important ramifications. Most significant has been the change in the financial status of small non-league football clubs (including community pitches in small towns and villages and pitches managed by Local Authorities) who are now able to afford the same quality of solution to a problem as a professional football club. A PESTEL analysis demonstrated that changes in the macro-environment are not expected to be extensive and a period of stability can be assumed, at least until the next general election; the government targets for sport participation extend to 2020 and the opposition parties have not advocated the removal of these suggestions. Perhaps the biggest change will be in the form of legislative changes; both towards environmental issues such as water use and pollution from pesticides and fertilisers, but also in terms of the health safety of players.

In the amateur game, the cost of injuries to British industry in 1991 was £996m and the drive for increased participation in sport should not be met by an equal increase in sports injuries (DCMS/Strategy Unit, 2002). For professional football clubs, the financial losses from finishing lower down the league table at the end of a season continues to grow and failure to qualify for various European cup competitions or relegation from the Premiership has the same effect. The finishing position or failure to qualify for a competition should not be due to a decreased squad of players caused by injuries. It is foreseeable that health and safety legislation will be extended to football pitches to ensure they do not present a hazard to the participants.

The use of the Five Forces model (Porter, 1980) enabled analysis of the industry which the company is operating in. It was shown to present high or medium threats from all angles, including the threat of rivalry from other firms. From this model, the two key areas a company must consider as priorities are: the formation of barriers to entry to prevent new incumbents from entering the market and secondly to mitigate against the power of the buyers, preferably through a differentiation strategy to simultaneously limit their power and increase their competitive rivalry.

The SWOT analysis (section 6.2.3) detailed the key competencies a consultancy requires to achieve the above while it also highlighted the key threats and opportunities. The potential emphasis on player safety is deemed to be the key opportunity and therefore the investment in research to further explore the relationships between the soil physical conditions and measures of pitch quality should be used appropriately towards a particular market segment in order to sustain competitive advantage and achieve above-average industry profitability.

Section 6.3 considered the primary strategic considerations that must be addressed by a company embarking on a focus strategy; segmenting the market and targeting the wealthy football clubs, justifying a price premium by tailoring their service offering to incorporate the results of outsourced R&D into the playing quality of services. Moving towards point 5 on the strategy clock (Figure 6.7) the price premium can be charged on the basis that their competitors will not have this knowledge and this knowledge will be used to limit player injuries, providing as much as possible, full strength squads in order to ensure every opportunity to succeed in matches.

This focus strategy does not seek to maximise market share, rather it is a definite step taken to segment the market and target a limited number of customers and maximise profitability, as the red lines on the return on investment (ROI) versus market share curve demonstrate (Porter, 1980). Figure 6.8 shows that concentration on a limited number of customers will limit market share but maximise ROI, unless the market share held by the company is large:

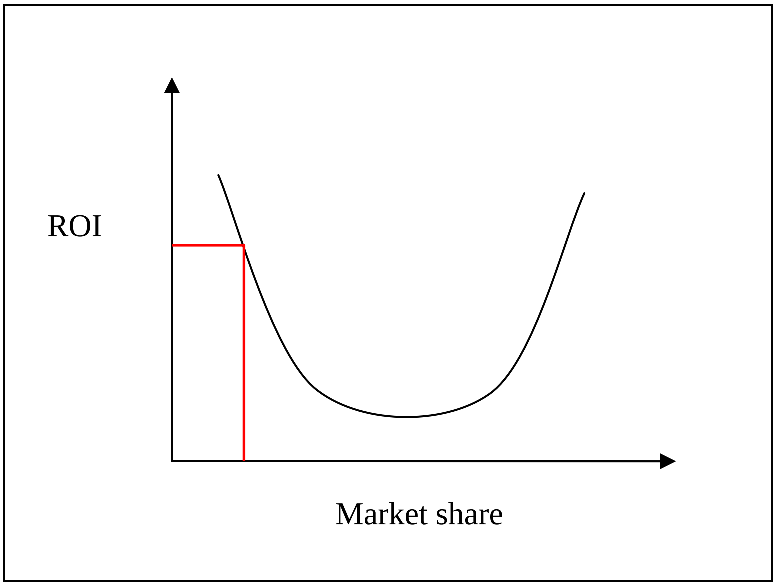


Figure 6.8 Return on Investment (ROI; a measure of profitability) verses market share, adapted from Porter (1980)

Strategy is not simply the formation of a plan, nor does it fit with the usual management role of routinised, operationally focussed activities. Instead, strategic management is ambiguous, complex, organisation wide and fundamental to the focus of the business. In order to generate an organisation that follows this approach and offers freedom to employees to respond to emerging situations, organisational change may be required. However it is argued that any form of change, regardless of how well it is thought out or presented, will experience resistance (Bowman, 1998; Robbins, 1998). A small company with limited personnel may be able to create this change without the pains experienced in larger organisations.

Furthermore, the success of this segmentation strategy will depend on the competencies in the company. These should be robust and difficult to imitate if they are to offer an advantage and may require the addition of new personnel. Torrington *et al.*, (2002) argue that this is the primary way in which a company can generate a competitive advantage, and the recognition by the company of the importance of a human resources function will ensure that key staff are retained and future recruitment of staff can occur in a strategic manner to match the vision of the organisation and supply the required competencies.

To maintain a competitive advantage a marketing function must be in place to take advantage of the association of the company with top-class football clubs to increase brand recognition and awareness. The company would become synonymous with excellence and benefit from the success of the clubs they service. The marketing function would also be responsible for ensuring representation at appropriate trade shows and ensuring key personnel are present at important industry conferences. Articles in trade magazines would ensure Groundsmen understood the quality of the company’s work and understood how their service offering was differentiated from that of their competitors. Finally, work on community, school or Local Authority pitches could be used as positive public relations via effective marketing in the press and via a dynamic website.

The strategic decisions and approach that could be adopted have been discussed in the context of one possible way to utilise the outcome of investment in research and development. The investment may prove to be timely if an increase in the degree of legislation to protect a professional or amateur football player increases. The research will deepen the firms existing capabilities and the method of application in the industry should be analysed carefully to ensure the optimum return on investment can be achieved and the creation of barriers to entry and successful differentiation makes the company a better competitor.

6.5 Conclusions

The objective of the chapter was to describe the industry structure before presenting strategic options to capitalise on R&D. The two sections and discussion highlighted key points that must be taken into account if a small company operating in the football sports turf consultancy industry is to achieve and sustain a competitive advantage. In conclusion the key points are:

1. The threat of entry of new incumbents and competitive rivalry were both classed as medium threats to the company. Mitigating these threats through the development of robust core competencies should be a priority.
2. Buyer power was deemed to be high and was attributed to a lack of differentiation of firms. It was suggested that to succeed a consultancy must differentiate if it is to successfully charge a price premium. Profit from the price premium can be reinvested to reduce costs, creating another barrier to entry.
3. Funding strategies to improve the quality of football facilities in the amateur game has skewed the market, masking segmentation possibilities. Regardless, a segmentation strategy should be employed in order to focus on the supply of solutions to professional league clubs. The price premium can be justified on the grounds of increased player availability through a reduced incidence of injuries and contracts to keep the club and company linked for maintenance and other future pitch issues will create a barrier to entry, develop relationships with the clients (a core competency) while guaranteeing income.
4. Two other core competency requirements were identified; a marketing function and a human resource (HR) function. The marketing function will be employed with the task of increasing brand awareness and association through appropriate messages in the relevant press while the HR function will ensure the strategic recruitment of staff aligned with the company’s goals and be capable of ensuring that suitable retention and staff-care strategies are in place.
5. A focus on organisation-wide, non-routine business elements will ensure a company culture which encourages the recognition and adoption of new opportunities. This may require changes within the company, but in a small company, this may be a less challenging experience for employees.

Outsourced R&D will be capable of supplying a return on investment if the results are used appropriately. They have presented an ideal opportunity for the company to establish itself as a market leader in the chosen segment that should not be squandered.

Chapter 7 Concluding discussion

7.1 *Discussion*

Each chapter included a detailed discussion of the completed work and the conclusions that could be drawn. This discussion chapter will serve to review the key points from each discussion and argue their relevance and importance to the academic community researching sports pitch construction and management, managers of sports facilities and the Groundsmen addressing the day to day requirements of the surface.

7.1.1 The concept of effective stress

The effective stress concept was used to link a measure of soil moisture status (matric potential) and information regarding the pore size distribution of the soil (relative saturation at that matric potential) to determine soil strength. Water remaining in soils after drainage is held under tension and effectively holds the soil matrix together to resist deformation and ultimately shear. Although originally developed to explain tensile failure, its application to soil failure around a penetrating cone had been shown to be worthwhile therefore the studies detailed in chapter 3 used a cone penetrometer. The result was the production of positive linear relationships, and unlike previous research, the data were not log-transformed. A pure sand rootzone material was also included and successfully modelled. Although the tensiometer used in chapter 4 prevented *in situ* experiments from verifying the relationships, the use of effective stress may be worthy of future study. The effective stress (strength) profile for each soil would provide an indication to Groundsmen of how soil moisture status changes affect strength in more detail than a simple of measure of moisture content. However, it will be difficult to determine *in situ* and is influenced by both density and grass roots, complicating interpretation.

If used, effective stress theory may affect drainage designs by demonstrating that a greater or lesser degree of drainage is required for a particular soil type in order to achieve the strength gains resulting from drier soil. In summer months dry sand would have almost no strength and water additions may be required; not an environmentally conscious action and potentially expensive as water extraction licences and mains water continue to rise in price. As discussed, the main difficulty in the application of effective stress is how to monitor matric potential in real-time. The reading would need to be rapid and accurate; neither of which the tensiometer used in this study managed. The development of sensors which remain *in situ* has been applied to agricultural fields, however, after crop establishment, little soil work is conducted. Sports surfaces are continually being managed to relieve compaction and simultaneously aid drainage and aeration, which would limit the possibility of having sensors buried permanently in the rootzone. A tensiometer similar to that used in this study would be required, but further development must ensure that the characteristics of the ceramic cap are closely matched to soil properties. This will ensure that the readings are reliable. The need to ensure air-tight connections and a robust design must be given priority.

The results of chapter 3 did however highlight why there is an injury risk on newly established or repaired areas of pitches and why the addition of grass roots into these areas must be a priority of groundsmanship. Loose sand placed into divot marks, or heavily worn goal areas will be of a low bulk density and be devoid of roots. At low densities, soil strength was shown to be reduced compared to high densities for each soil type analysed. The addition of grass roots increased soil strength at a given effective stress and for each bulk density; in the majority of instances this increase was shown to be statistically significant. Maximising rooting depth and establishment of repaired areas will reduce the risk of injury to a player running from established, consolidated areas of the pitch, onto newly repaired areas.

7.1.2 Tests for player-surface interaction quality

The two tests for player-surface interaction quality were not developed to mimic sports injury occurrence, or to predict the injury potential of a surface. Instead the traction equipment was developed to feed the development of a turf wear simulator and the Clegg hammer was originally intended to evaluate pavement base courses. It is arguable that neither test accurately reflects the sports injury potential of a surface; a player generally will not turn on the spot, with all their force perpendicular to the playing surface, instead, turns will be made at speed, often involving a rapid change in direction. The peak forces on the foot at the time of the turn, with the addition of deceleration and gravity, exceed the ability of the current traction equipment to adequately replicate. The Clegg hammer utilises a lightweight 0.5kg hammer dropped from a height of 0.55m. Studies have shown the final reading to be influenced by grass cover and during use it was observed to be influenced by friction within the guide tube if the tube was not perfectly upright. The use in American literature of a 2.25kg hammer has shown readings to be less influenced by the grass and effectively isolates the hardness of the surface to give a clearer indication of pitch hardness. The advantages of the Clegg hammer are that it is light weight, generates a comparative reading that can be used to compare pitches and is relatively inexpensive. Its use in general is not questioned, but after STRI research highlighted the possible interaction between the hammer and the grass, why the adoption of the heavier hammer did not ensue is unclear.

Had research into sports injuries in football been complemented by pitch analysis using these tests, the uptake and use of performance standards among Groundsmen may have been more widespread. The results may have demonstrated which injuries were directly attributable to the surface and the corresponding quality test result at the time of injury. What was lacking throughout their development and subsequent dissemination throughout the industry was a clear statement of their benefits. A process of education to demonstrate how they could be used by Groundsmen in their daily jobs to ensure pitch quality remained at an optimum is required. Poor availability of the equipment and limited research results in an accessible form both contributed to their poor uptake.

Although twenty years since the review of the playing quality of sports pitches by Bell *et al.,* (1985) the proliferation of, and agreement on, playing performance standards has been poor and those responsible for their funding and development must assume responsibility for this. Never in their development was there a clear indication of the impact of pitch management on the outcome of tests for quality and this rather ignored the possibility that Groundsmen could influence the results. This has also limited their uptake.

The cost of injuries in professional football is particularly high. Not having a complete squad to select players from, may result in failure to progress in lucrative cup competitions, a poor finishing position in their league, or at worst, relegation from that league. In the amateur game, a rise in the cost to industry as a result of sports injuries must not be an additional outcome of the British Governments desire to increase exercise levels, partly through increased sports participation. Furthermore, Local Authority run pitches and school pitches are traditionally on poor quality sites, characterised by heavy textured soils and limited resources available for their management. Defined pitch management to impact directly on the outcome of player-surface interaction quality is a new opportunity for performance standards to become central to daily pitch management and maintenance regimes. To achieve this, further research is required to understand which management practices are detrimental to quality, which improve or maintain it and under what moisture status conditions certain tools should or should not be used. A focus on pitch management to achieve the desired test results may minimise liability in the event of a serious injury whose cause can be linked to surface conditions.

Even with the limitations of the player-surface interaction tests presented, their reliance on above and below ground factors demonstrates a need for soil science knowledge to be a requirement for any Groundsman. It also suggests that to achieve the status of ‘Head Groundsman’ a clear education and career path should be in place. Education needs to incorporate teaching of soil science and soil-plant-water relationships; taking a more holistic approach to demonstrate how all the factors inter-relate.

The influence of moisture status on the outcome of the tests, highlighted the impact that precipitation, irrigation and drainage can have on the playing quality of a surface. A difficult balance needs to be achieved; in winter excess moisture needs to be removed rapidly but during the summer months, irrigation will be required, adding to the cost of managing pitches. For optimum use of water, reliable crop coefficients are required to enable accurate water loss predictions and ensure the volume of applied water is optimum for plant survival, and not wasted. Bespoke coefficients for different grass species, in different geographical locations are required.

Interestingly the research that supported the pitch quality monitoring software produced a number of results in contradiction to previously published data; no significant variation according to pitch position was found for traction or hardness. This held true even when the data set was separated according to soil type and sampling date, although trends can be observed. Furthermore, this study identified non-normally distributed variables and it is possible that previous studies failed to account for this (or explicitly state that this had been considered), possibly affecting the outcome. Also possible is the effect of sampling date and the sampling strategy used in this study on the results, with the tests during May and June skewing readings. It is probable that the data presented in chapter 4 has flaws which prevent strong conclusions being drawn.

7.1.3 Decision support software

PitchQual was an example of how the regression equations could be utilised. It demonstrated that it is possible to link the outcome of quality tests to pitch parameters that are easy to determine and package it in a way that is accessible to Groundsmen. Although not yet a marketable solution, the development of this software was the first step towards making the notion of performance standards a core consideration to Groundsmen; something that other bodies have failed to achieve in the 20 years since performance standards began to receive concerted research.

The model as it was presented only incorporated sand-based pitches although with further programming input it could incorporate the 6 primary soil textural classes identified in this study. The sand regression models were shown to vary in strength but this may have been a function of heavy topdressing skewing the outcome of textural class analysis. In reality, below the upper 50 mm of a ‘sand’ pitch, a different soil type may have existed. Future textural class analysis should consider samples from a range of depths within the rootzone to discover the true soil properties. However, the production of regression equations with an R^2 value > 0.50 at each bulk density for traction under wet conditions and hardness under dry conditions, demonstrates that future research could be used to improve these relationships. There should be fewer pitches where all the soil data is known and testing can occur more frequently. Under dry conditions the ability to predict traction becomes less reliable with R^2 values ranging from 0.32 to 0.42. This may have been due to friction and grass roots being the dominant factors in this and the regression models not being able to identify these factors with the available parameters. The inability to predict hardness under wet conditions for two out of three bulk densities and poorly for the third (R^2 = 0.12) demonstrated the variability of sand under wet conditions and possibly the effect of test position relative to drains, particularly slit drains. This suggests the need for adequate drainage, but this may be to the detriment of summer hardness, particularly as the playing season is extending further into the summer.

Importantly however, this model and the research that supports it, only considered player-surface interaction tests for quality. There are a range of quality requirements for pitches, including ball-surface interaction and other visual assessments of quality. Groundsmen need to manage a surface to provide all aspects of quality, not just player-surface. Future research needs to establish firstly whether the other tests for quality are appropriate, what they are reliant on and then, how to manage a pitch to achieve the desired outcome.

7.1.4 Improved sports pitch studies

This research achieved the objectives outlined in chapter 1, however for performance standards to directly impact on the Groundsman and hence the playing quality of the surface, further study is required.

It has already been discussed that the renewed focus on sport by the Government and additional income as a result, must not be met by increased injury rates in the amateur game. The cost of injuries to professional clubs should ensure their interest in helping with further research, as long as it is sold to them on this basis. Future studies should become more holistic, not just incorporating pitch measurements, but incorporate clinical measures to correlate the results of quality tests to player injury; incidence and type. The current acceptable ranges of test results are based on feedback from players regarding their perceptions of their performance on the surface, and how the conditions felt underfoot. Professional athletes often require pitches that enable them to perform at their best, with little regard to injury potential. A holistic study that addresses both aspects, including player perceptions, will provide data that all other studies failed to prove; a link between the current tests and actual injury potential arising from the surface. This would be complicated however by the range of football boot designs and stud patterns available.

To demonstrate the benefit of performance standards to Groundsmen any information must assist in the daily management of pitches to achieve or maintain a particular quality rating. Studies must investigate the impact of pitch management tools on measures of quality immediately after use, and over a period of time afterwards to determine how the quality of the surface responds. To achieve the same traction and hardness values on different soil types, different management techniques would be required. Studies to determine the appropriateness of a single value, applied uniformly regardless of pitch type, should also occur.

Although the study detailed in chapter 4 could not evaluate effective stress due to equipment problems *in situ*, future studies should investigate the potential for using this to predict soil strength. This should perhaps focus only on soil-based pitches where management is less intensive and strictly budgeted. The presence of fine pores makes the use of effective stress more reliable than on sand-based or pure sand pitches.

7.1.5 Commercialisation

Investment in further research will be required to realise the full potential of the decision support software. When marketing the software, continued support will be required in the form of regular pitch testing for bulk density and particle size range changes.

Chapter 6 also addressed the competencies required of a technically-focussed consultancy firm to ensure that they can compete adequately in the market place and generate barriers to entry, protecting their market share. The input of funds through a variety of channels was argued to be the primary cause of competition and therefore it was suggested that segmentation of the market has been made more difficult. Amateur clubs, community-run clubs and Local Authorities are now more able to afford elaborate solutions, making segmentation strategies less worthwhile. However, in order to create a barrier to entry and improve profitability, the ability to ring-fence a customer and engage in a long-term agreement with them will ensure a continued income. To achieve this, the company should concentrate on Premiership level clubs and adopt a focussed differentiation strategy. The approach would be to emphasise the importance of a safe playing surface and need to minimise injuries and the risk of injury. A possible danger is the ability of wealthier clubs to use litigation against the consultancy should pitch quality diminish, and injuries are sustained which can be directly attributed to the surface. Currently however, establishing the surface as the cause of an injury is prohibitively difficult.

To achieve successful implementation of such a strategy, effective strategic management and adoption of hard-to-grasp, ambiguous, competencies are required. The organisational culture must be one that provides staff with a degree of freedom to ‘bend the rules’ in order to achieve the desired strategy and treat each customer in an individual fashion.

Various competencies must also be in place such as an adequate human resource and marketing function. This will ensure the strategic recruitment of suitably qualified staff and their retention, while also serving to propagate the organisational philosophy. The marking function will enable suitable brand management to ensure the company is synonymous with high-quality solutions and that the brand of the company generates an understanding of its expertise and abilities.

7.2 Conclusions

Each chapter contains conclusions specific to the research in that chapter. To address the overall aims of the thesis, as outlined in chapter 1, the following key conclusions can be made:

1. The use of effective stress produced statistically significant positive linear relationships between a measure of soil moisture status and soil strength. The effect of bulk density was to increase soil strength at any given effective stress and the addition of grass roots also increased soil strength. This work was presented at APCST 2005 in Tokyo and used to demonstrate how unconsolidated repaired areas, devoid of grass or with immature grass, pose an

injury threat to participants. It was not possible to create a single model capable of encompassing a range of soil types and bulk densities.

2. The use of effective stress also demonstrated a contradictory requirement; adequate drainage to remove moisture from a sports pitch rootzone and therefore increase soil strength, but retention of moisture is required for grass to survive.
3. Contrary to previously published studies, neither traction nor hardness data varied according to the position on the pitch they were measured. This was true for the entire data set and separation of the data according to textural class. It was suggested that this may have been the result of insufficient sampling occasions and the sampling strategy used on each pitch.
4. Clubs were able to achieve a ‘standard’ quality rating as a combined result for traction and hardness, but this was often the result of one test result rated high and one either standard or basic. This demonstrated the difficulty in managing pitches to maximise both, and would be further complicated by the addition of further tests for quality, such as ball roll and bounce. It indicated that pitch management to achieve one, may be to the detriment of another test and as a result, the tests may not be appropriate. It was also argued that the tests were developed with players’ perception of the playing quality of the surface, but the tests have never been correlated with injury incidence or potential. Development of new tests may further weaken the uptake of performance standards; therefore the existing standards require correlation with injury rates and types to determine what types of injury are due to the surface.
5. Although not every relationship was significant, traction generally increased with increasing grass cover and both traction and hardness reduced as the moisture content increased.
6. For the first time, clear and coherent regression equations between tests for playing quality and simple measures of pitch quality have been established. Test results were a function of above ground and below ground factors and pitch management must concentrate on both of these.
7. The presence of reliable regression models suggests that this research can extend the concept of quality standards to Groundsmen. Their benefits can be demonstrated by explaining how targeted pitch management could alter the outcome of the test results. In the absence of detailed knowledge regarding

how pitch management options effect the surface quality, the regression equations are limited to suggesting a course of action for a given day for maximising quality. The inability to predict readings under wet conditions (hardness) or poorly predict the outcome of tests (dry; traction) again highlights the importance of carefully managing the water balance of sand-based sports pitches.

8. An example of how the regression models could be used to generate a pitch management tool was also presented. It would require a daily input of pitch factors or a measure of moisture content, and these would be used within the model to generate a statement of quality. Sensitivity analyses showed that traction was influenced by grass cover and moisture content and, in cases; silt content. While pitch management should aim to maximise grass cover, the effects were negated by excess moisture and improved by increased silt content; possibly due to cohesion between the particles. The greater the sand content, the fewer factors can be manipulated to influence player-surface interaction quality, although sand-based pitches have been shown to exhibit less temporal variation in quality generally.
9. The driving force in the football consultancy industry is primarily the British Government and their targets for increased exercise levels leading to increased sport participation. This has resulted in widespread investment in the upgrade of sports surfaces and associated facilities. Large-scale investment has attracted new incumbents into the industry who are threatening the long-term profitability of the industry as competition drives down prices and offers greater choice to those requiring the services of a consultancy. It was recommended that to succeed a firm will need to differentiate their service offering and attempt to segment the market in order to build barriers to entry based on knowledge, trust and relationships with those in the segment. This strategy was shown to maximise profit rather then maximise market share.
10. To reap the benefits of investment in RandD and achieve the recommendations highlighted, a small consultancy firm is faced with strategic options, which must be addressed. The options included factors that would already exist within the company, but also considerations that a technically focussed company may overlook, or dismiss. These included the need to address the more ambiguous aspects of the business such as the culture of the

organisation and the manner in which it deals with clients. Novel approaches and flexibility should be organisation wide and ingrained within the culture, not an *ad hoc* approach.

11. A marketing function is required to ensure the brand of the organisation is associated with superior quality solutions. The HR function will ensure recruitment can be addressed strategically and retention of staff made a priority. The HR function can also ensure corporate changes, particularly changes to the corporate philosophy and direction, can permeate through the organisation.

7.3 Future work

As a result of the discussion sections in each chapter, and this chapter which brought together the key themes of the thesis, a number of requirements for future research and extension of this research have been identified:

1. The current tests for player-surface interaction quality have been linked to player perception regarding their ability to perform on the surface. There is no research that links these tests to injuries sustained during matches and training. This is required in order to demonstrate that the current tests are appropriate when assessing pitch quality with the focus on player safety, rather than solely player performance.
    a. Future studies need to monitor injuries and pitch quality in order to determine the incidence and types of injuries sustained as a direct result of the surface. Only when this has been accomplished will the relevance of the current tests be established.
    b. When the textural class of a pitch is being established, samples should be taken from a range of depths to establish the true picture. It was clear during this study that surface samples were biased as a result of top dressing. Pitches that were established on the prevailing soil type were classed as sand and although it is unclear how this impacted on the outcome of the correlation and regression analysis, more detail regarding the pitch soil type and sand fraction particle size distribution should be included in future.

    c. Studies should also concentrate on fewer pitches of known soil type but perform more intensive testing and under a wide range of climatic conditions. This would ensure that sufficient data under wet and dry conditions have been collected to enable detailed analysis and suitable conclusions to be made.
    d. Studies should not focus only on player-surface interaction tests. Groundsmen are required to produce pitches that are not only safe but also do not detrimentally interfere with ball-surface interaction. Studies should be holistic and encompass ball and player-surface interactions alongside a long-term injury study.
    e. Studies must also occur to assess the impact of pitch management tools on surface quality. With this information Groundsmen can begin to make informed decisions regarding the selection of machinery and daily management options.

2. Future studies need to consider how the results are to be disseminated to those employed to manage pitches on a daily basis. There must be improved communication of the results in order for the benefits of adopting a pitch management approach specifically to target playing quality and player safety to be clearly visible.
    a. Continued research should feed the development of a model similar to that presented in chapter 5. This way a club or pitch manager can limit their liability by ensuring that pitch quality is being constantly monitored. This would also provide a groundsman with greater leverage when seeking salary increases or when trying to justify the purchase of new machinery; data on pitch quality will be available and could be used to support their argument.

3. The concept of effective stress requires further investigation. Although able to predict soil strength in the laboratory, future research is needed to produce *in situ* verification and to establish whether tests for player-surface quality can be predicted

a. To achieve this, development of a suitable means of determining matric potential is required. It must be robust and respond quickly.
b. Modification of the effective stress equation to account for bulk density and its use in pure sand mixtures, particularly rootzone mixtures, may be necessary. This research demonstrated it is possible, but there are many sand specifications used in rootzone construction and each should receive consideration.

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Appendices

CD-Rom details

File No.	Description of contents
1	Abstract
2	Contents
3	List of figures
4	List of tables
5	Introduction (chapter 1)
6	PQS – a review (chapter 2)
7	Effective stress investigation (chapter 3)
8	PQS in situ investigation (chapter 4)
9	Decision support model (chapter 5)
10	Commercial investigation (chapter 6)
11	Concluding discussion (chapter 7)
12	References
13	Appendices
14	PitchQual Excel spreadsheet
Folder 1	Chapter 3, 3.2.2 data
Folder 2	Chapter 3, 3.2.3 data
Folder 3	Chapter 4, site visit data

Appendix I; Traction coefficient conversion

Traction coefficients
Data from Baker and Bell (1986)

	Mean	Goalmouth		Centre circle		Wing	
Venue	MC	Coeff	Nm	Coeff	Nm	Coeff	Nm
Lilleshall	-	-	-	-	-	-	-
Crewe	28.4	1.79	39.51	1.41	31.12	2.13	47.01
Wigan	19.9	1.37	30.24	1.56	34.43	1.28	28.25
Rochdale	20.7	1.45	32.01	1.43	31.56	1.74	38.41
Coventry	17.6	1.08	23.84	1.18	26.05	1.51	33.33
Wembley	33.2	1.82	40.17	2.17	47.90	1.99	43.92
Fulham	10.8	1.11	24.50	1.19	26.27	1.74	38.41
Balckburn	10.5	1.34	29.58	1.41	31.12	2.07	45.69
Everton	16.8	1.02	22.51	1.31	28.91	1.64	36.20
Shrewsbury	-	-	-	-	-	-	
Correlation between MC and Nm=			0.83		0.75		0.27

Conversion

μ = 3 x T / 2 x W x R
Rearranged T = m x 2 x W x R / 3

W (N)	441.45
μ	2.5
R (m)	0.075

Appendix II; Analysis of penetration speed data

Rep	2mm/min	20mm/min	100mm/min	200mm/min
1	0.71	0.68	0.67	0.81
2	0.83	0.83	0.61	0.72
3	0.82	1.00	0.95	0.89

	2mm/min	10mm/min	50mm/min	100mm/min
Mean	0.79	0.84	0.74	0.81
St Dev	0.07	0.16	0.18	0.09
St Error	0.04	0.09	0.10	0.05

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2mm/min	3	2.3652375	0.7884125	0.0045632
50mm/min	3	2.5064222	0.8354741	0.0254146
50mm/min	3	2.225251	0.7417503	0.0328347
100mm/min	3	2.4244392	0.8081464	0.0072512

ANOVA

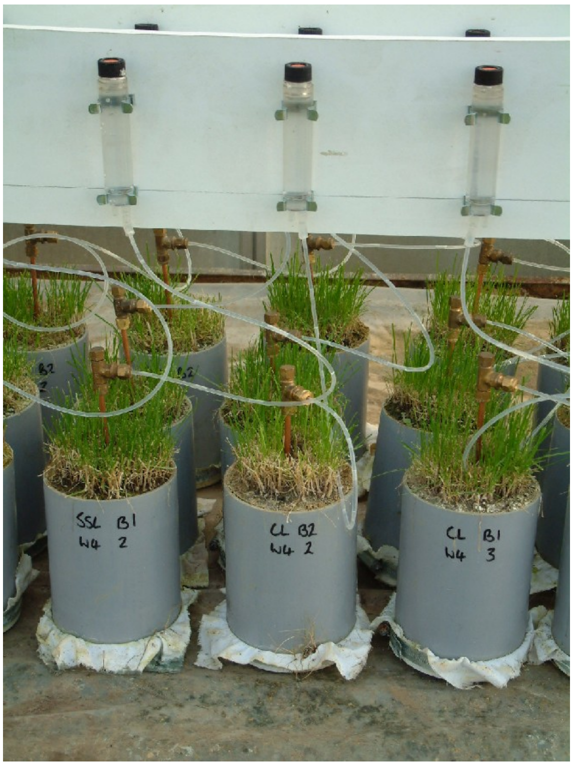
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.014041	3	0.0046802	0.2671993	0.84732	4.06618
Within Groups	0.140127	8	0.0175159			
Total	0.154168	11				

Appendix III; Sand Specification details

Sand specification used in section 3.2.2 and 3.2.3

Sieve (mm)	Weight (g)	Weight with sand (g)	Sand (g)	% of total
2	417.58	417.58	0	0
1	444.93	446.01	1.08	1
0.5	342.52	352.04	9.52	10
0.25	358.69	423.46	64.77	69
0.15	303.3	319.36	16.06	17
Receiver	337.25	340.37	3.12	3
		Total	94.55	

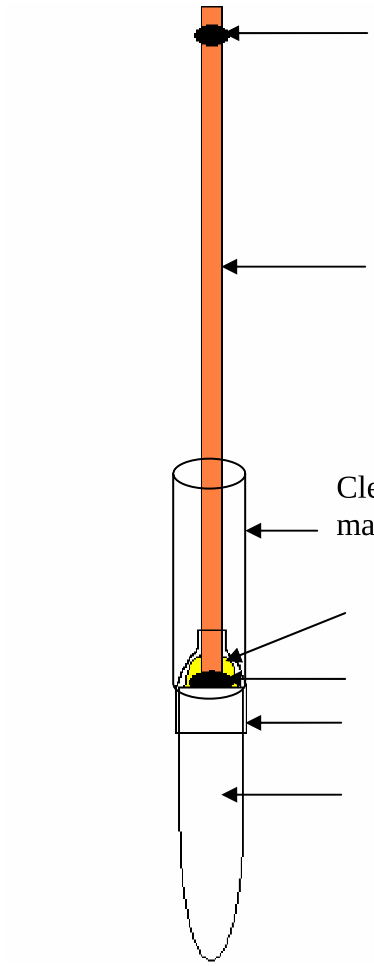
Appendix IV; Tensiometer design and construction (WG)



The design of the tensiometers is shown in **Error! Reference source not found.**. The body of each was made by hand and the manufacture of the polyurethane reservoir and septum cap was out-sourced to:

Soil Monitoring Engineering (S.M.E)
Contact: richard@soilmonitoring.com

Tensiometer body design



Olive to enable T-piece to be attached, ensuring a water tight fit

150 mm copper pipe; outside diameter 4.76mm

Clear tubing to prevent the soil collapsing into the hole made for the tensiometer

Araldite (yellow)

Olive to aid the junction of the cap and copper pipe

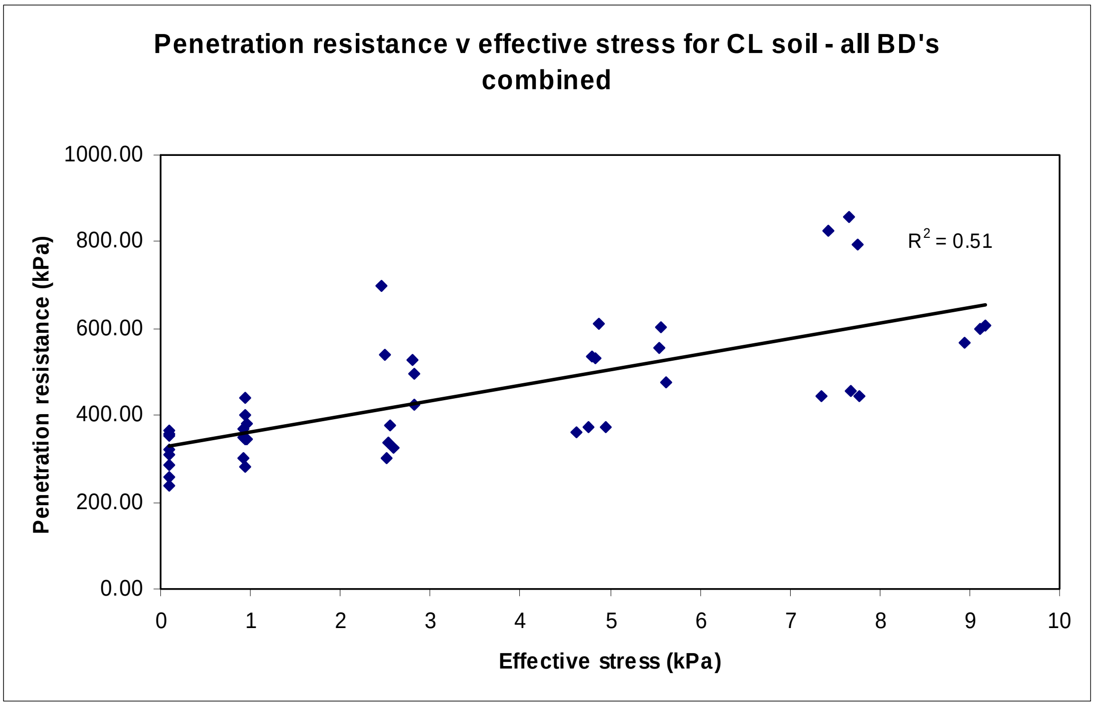
Shrink wrap piping to ensure water tight fit

Ceramic cap; 60mm long x 12mm diameter

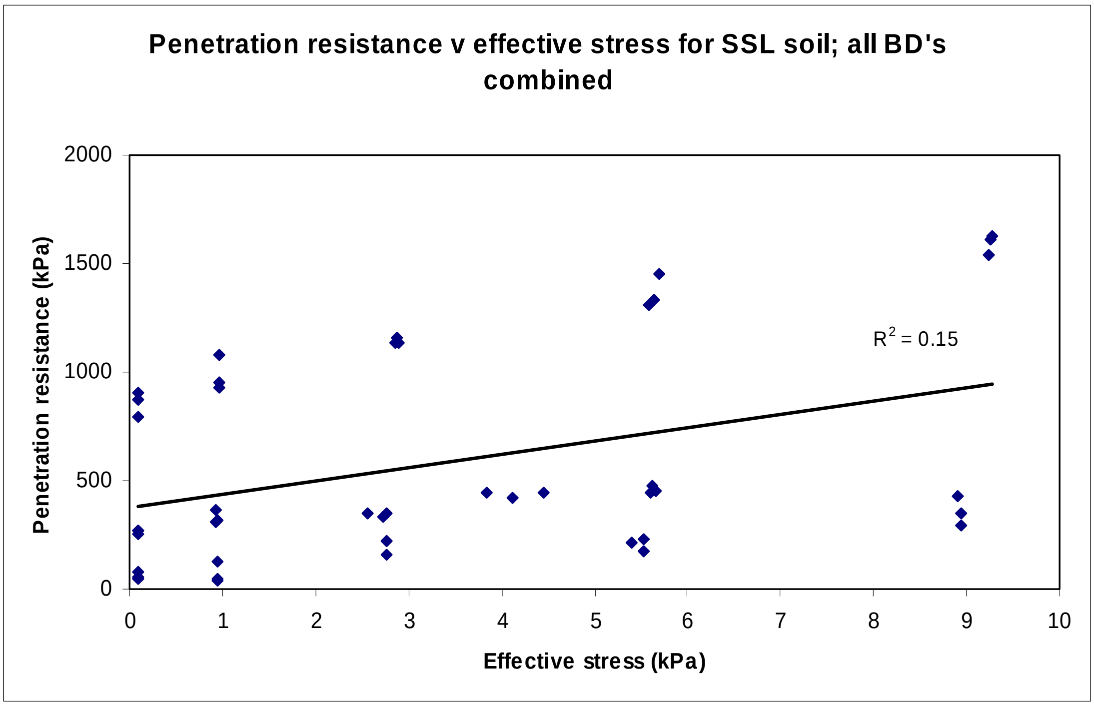
Appendix IV; NG data

All densities combined (effective stress)

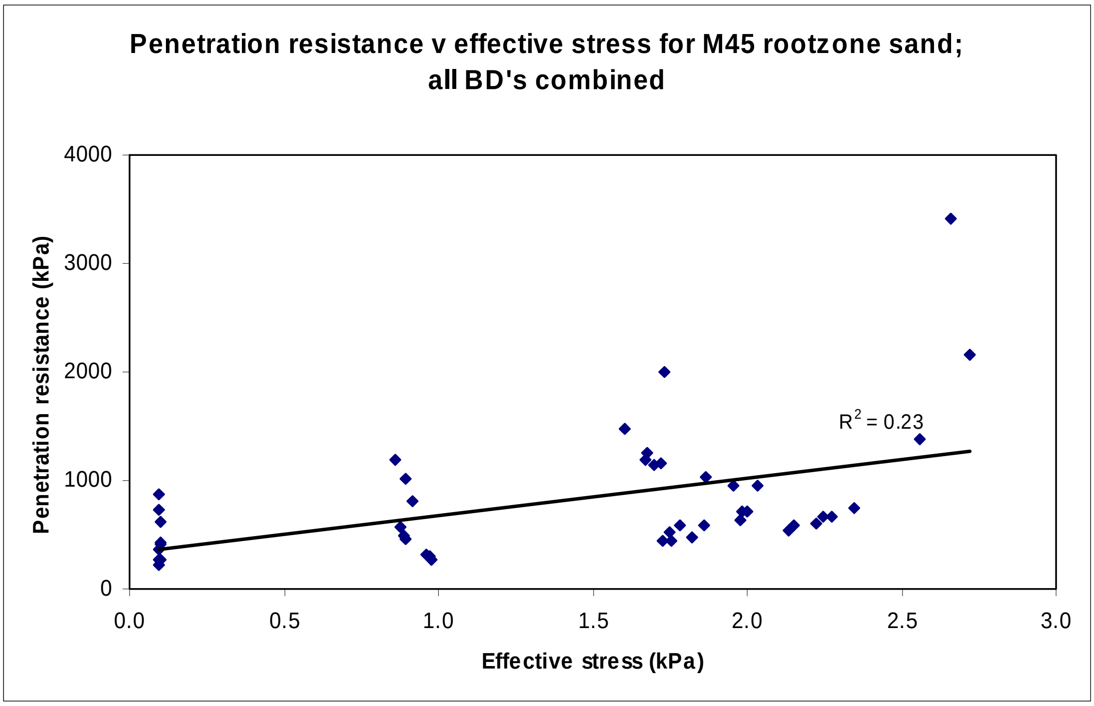
CL



SSL

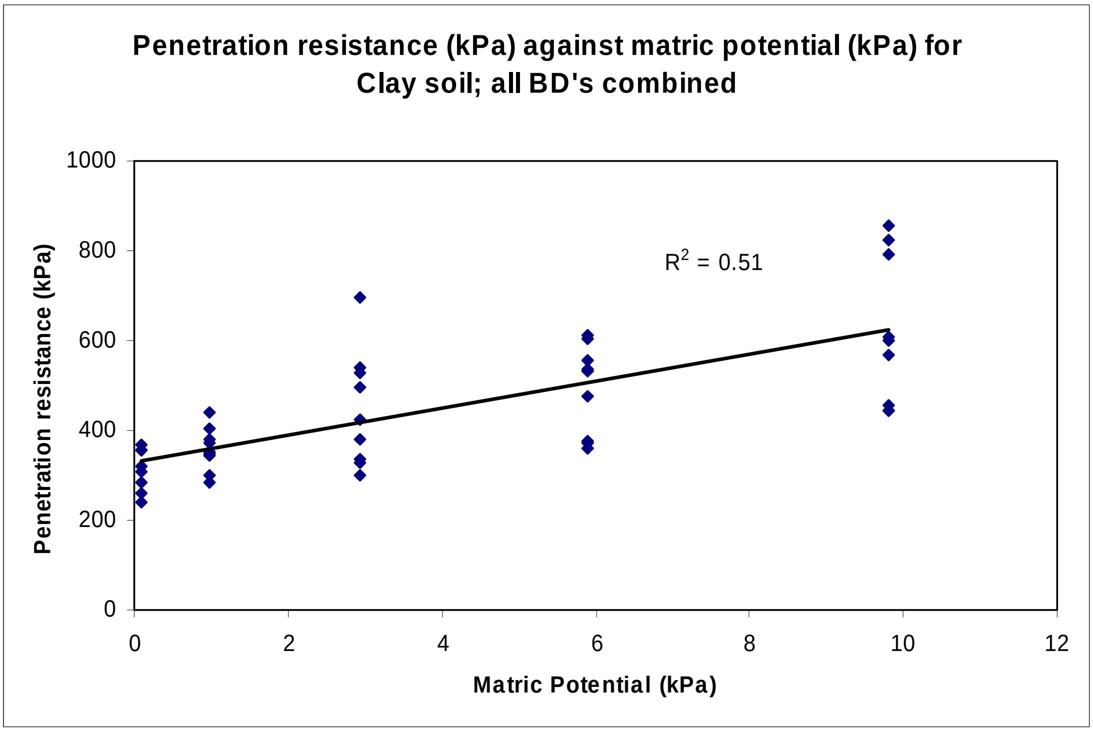


M45 rootzone



All densities combined (matric potential)

CL



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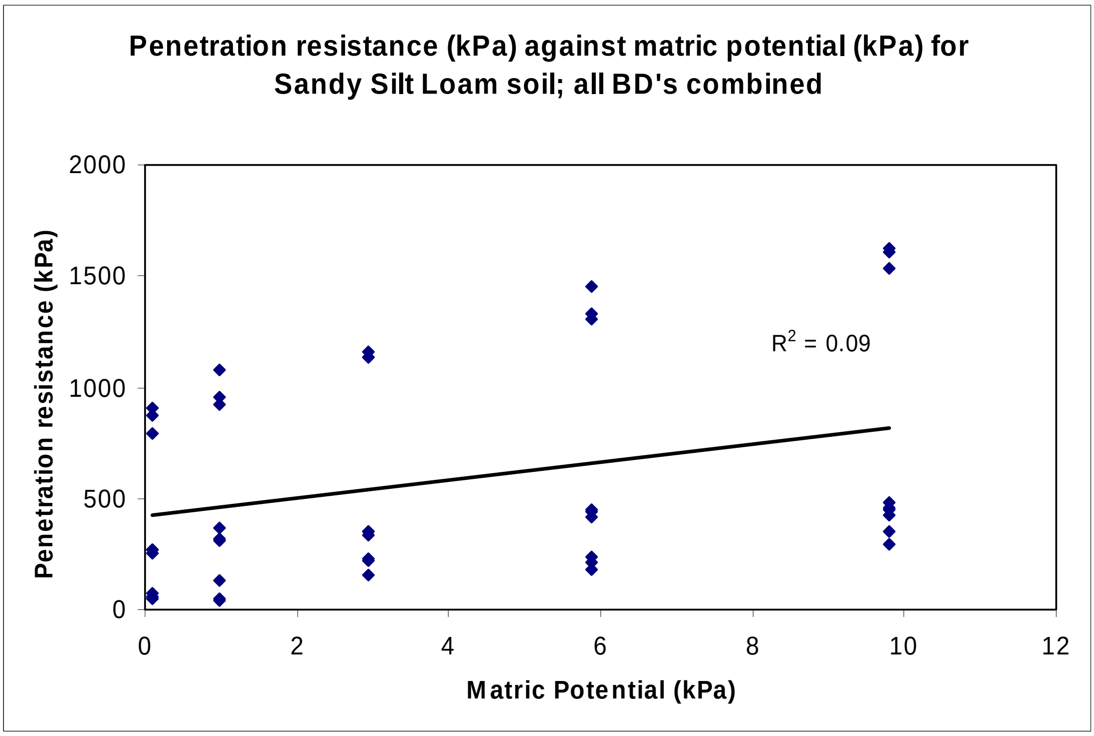
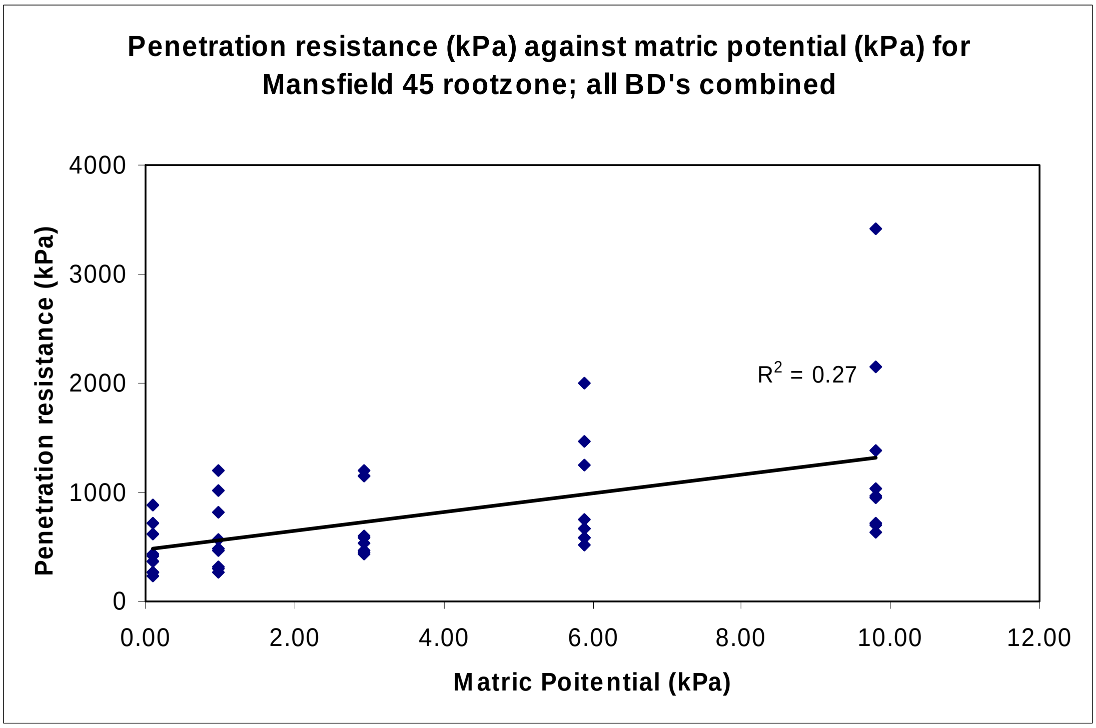
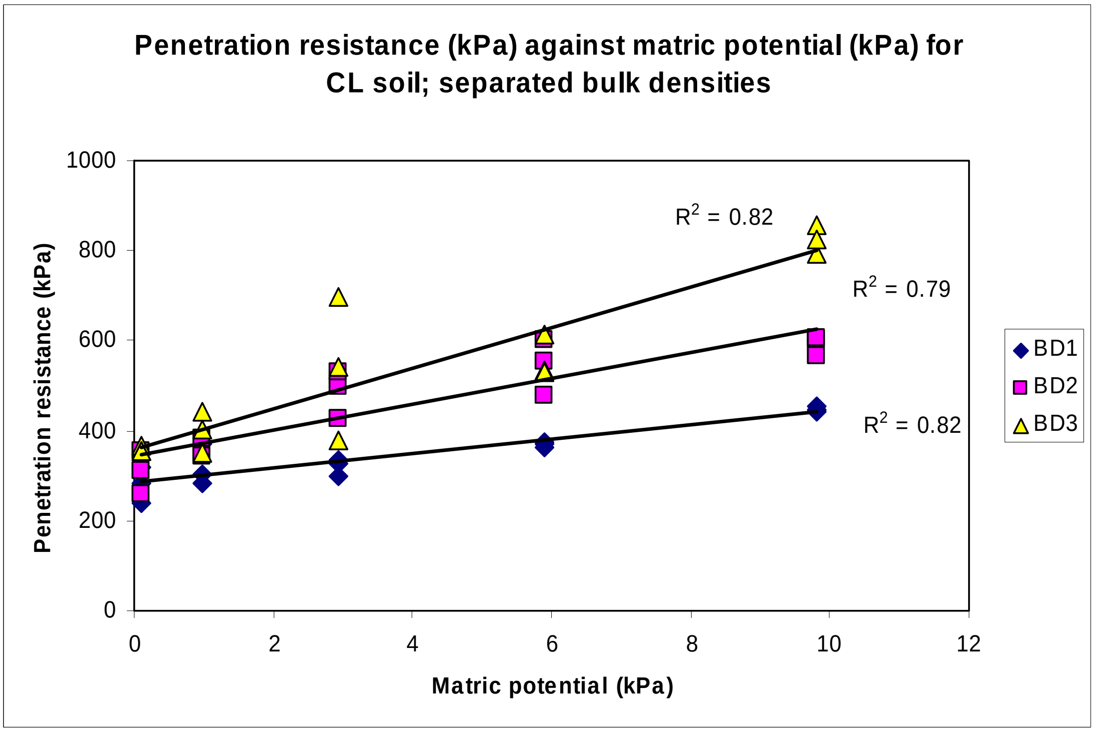


M45 rootzone



Penetration resistance against matric potential, by bulk density

CL



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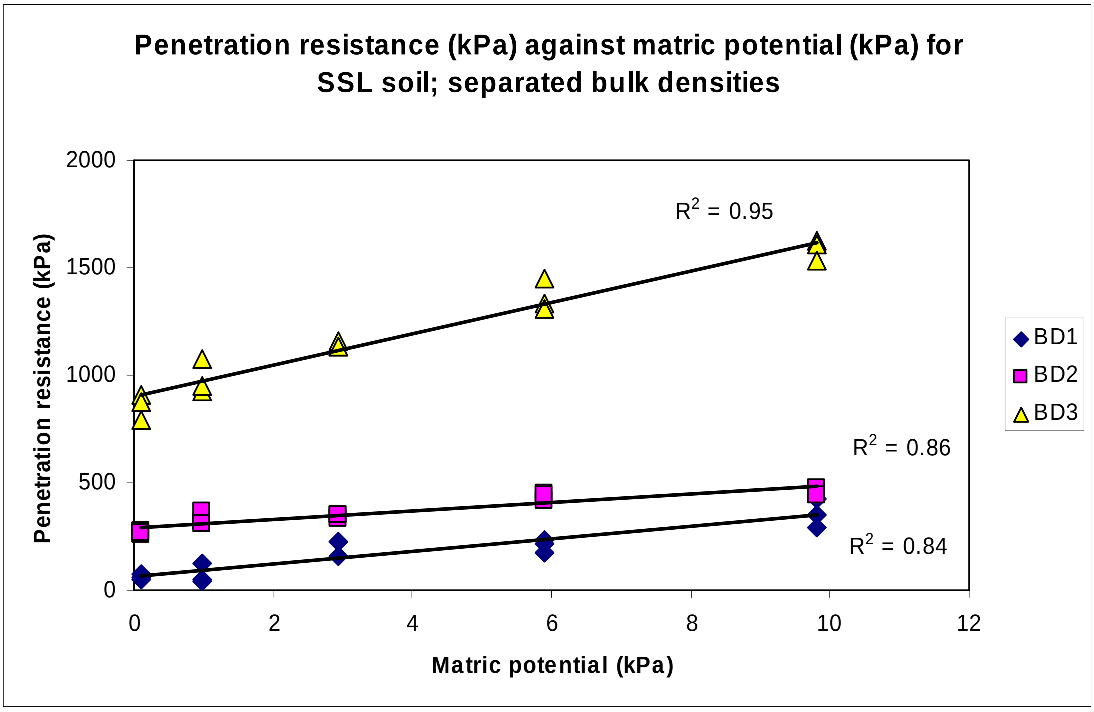
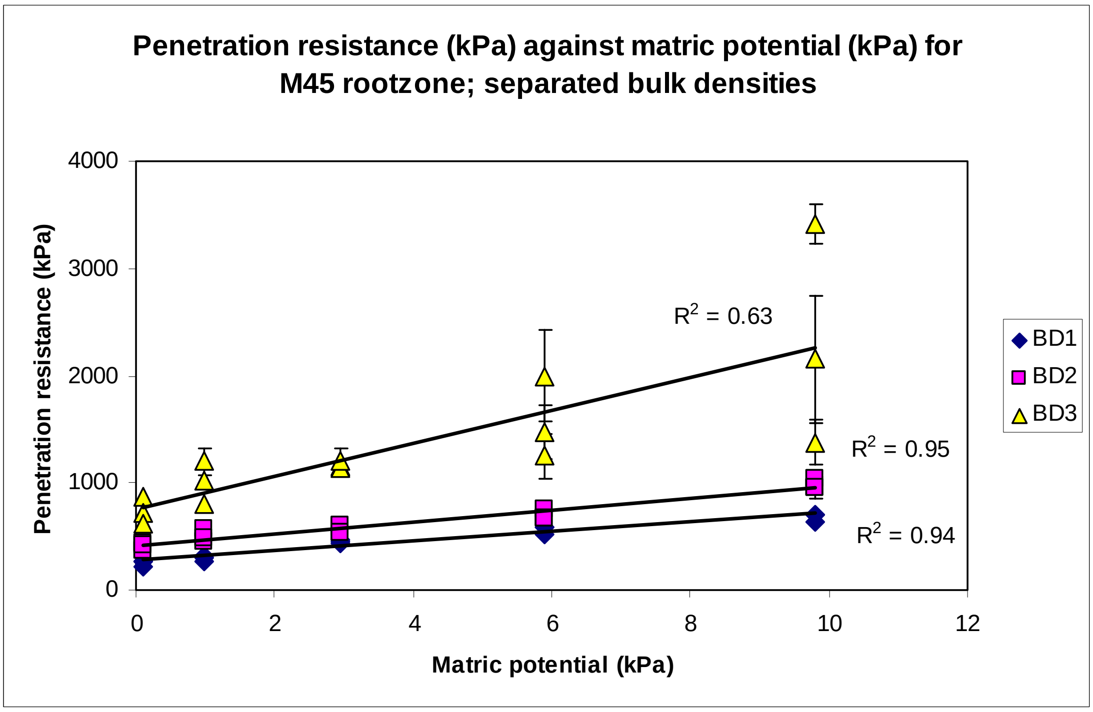


M45 rootzone



Appendix V; Significant difference matrix (NG)

The tables shows the difference between the two variables. LSD was 289.7. Each soil type is shown, the tension in cm is given and the three bulk densities are labelled low, medium and high. Differences > 289.7 are shown in red and significant at the p<0.05 level.

				No Grass																										
				CL									M45									SSL								
				0	0	0	60	60	60	100	100	100	0	0	0	60	60	60	100	100	100	0	0	0	60	60	60	100	100	100
				Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	60	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
No Grass	CL	0	Low		27	78	88	264	279	167	310	544	-19	134	478	300	432	1335	423	730	2100	-219	-8	603	-67	168	1122	86	192	1353
		0	Med			51	61	237	252	140	283	517	-46	107	451	273	405	1308	396	703	2073	-246	-35	576	-94	141	1095	59	165	1326
		0	High				10	186	201	89	232	466	-97	56	400	222	354	1257	345	652	2022	-297	-86	525	-145	90	1044	8	114	1275
		60	Low					176	191	79	222	456	-107	46	390	212	344	1247	335	642	2012	-307	-96	515	-155	80	1034	-2	104	1265
		60	Med						15	-97	46	280	-283	-130	214	36	168	1071	159	466	1836	-483	-272	339	-331	-96	858	-178	-72	1089
		60	High							-112	31	265	-298	-145	199	21	153	1056	144	451	1821	-498	-287	324	-346	-111	843	-193	-87	1074
		100	Low								143	377	-186	-33	311	133	265	1168	256	563	1933	-386	-175	436	-234	1	955	-81	25	1186
		100	Med									234	-329	-176	168	-10	122	1025	113	420	1790	-529	-318	293	-377	-142	812	-224	-118	1043
		100	High										-563	-410	-66	-244	-112	791	-121	186	1556	-763	-552	59	-611	-376	578	-458	-352	809
	M45	0	Low											153	497	319	451	1354	442	749	2119	-200	11	622	-48	187	1141	105	211	1372
		0	Med												344	166	298	1201	289	596	1966	-353	-142	469	-201	34	988	-48	58	1219
		0	High													-178	-46	857	-55	252	1622	-697	-486	125	-545	-310	644	-392	-286	875
		60	Low														132	1035	123	430	1800	-519	-308	303	-367	-132	822	-214	-108	1053
		60	Med															903	-9	298	1668	-651	-440	171	-499	-264	690	-346	-240	921
		60	High																-912	-605	765	-1554	-1343	-732	-1402	-1167	-213	-1249	-1143	18
		100	Low																	307	1677	-642	-431	180	-490	-255	699	-337	-231	930
		100	Med																		1370	-949	-738	-127	-797	-562	392	-644	-538	623
		100	High																			-2319	-2108	-1497	-2167	-1932	-978	-2014	-1908	-747
	SSL	0	Low																				211	822	152	387	1341	305	411	1572
		0	Med																					611	-59	176	1130	94	200	1361
		0	High																						-670	-435	519	-517	-411	750
		60	Low																							235	1189	153	259	1420
		60	Med																								954	-82	24	1185
		60	High																									-1036	-930	231
		100	Low																										106	1267
		100	Med																											1161
		100	High																											

ANOVA results (NG)

A *General Analysis of Variance* was performed with the following set-up

BLOCK	Pot/rep
TREATMENTS	Treatment*Bulk_density*Soil_type*tension kPa
COVARIATE	No Covariate
LSD	Selected
MEANS	Selected
LSD level	5
Y VARIABLE	Penetration resistance

Variate: Penetration_resistance_y

Source of variation Pot stratum	d.f	s.s.	m.s.	v.r.	F pr.
Treatment	4	1.436E+07	3.590E+06	37.53	<.001
Bulk_density	2	3.802E+07	1.901E+07	198.75	<.001
Soil_type	2	1.026E+07	5.129E+06	53.61	<.001
Treatment.Bulk_density	8	4.209E+06	5.261E+05	5.50	<.001
Treatment.Soil_type	8	3.238E+06	4.047E+05	4.23	<.001
Bulk_density.Soil_type	4	1.155E+07	2.888E+06	30.19	<.001
Treatment.Bulk_density.Soil_type	16	1.836E+06	1.148E+05	1.20	0.284
Residual	90	8.609E+06	9.566E+04	1.59	
Pot.Rep stratum	270	1.623E+07	6.011E+04		
Total	404	1.083E+08			

Variate: Penetration_resistance_y

Grand mean 625.

Treatments are labelled as NG (no grass) and a number to show the amount of tension (cm)

treatment				
NG 0	NG 10	NG 30	NG 60	NG 100
400	485	586	717	937

Bulk density		
Low	Medium	High
332	495	1048

Soil type		
CL	SSL	M45
447	595	833

Treatment bulk density	Low	Med	High
NG 0	202	332	667
NG 10	232	407	816
NG 30	331	477	950
NG 60	388	569	1193
NG 100	506	692	1613

Treatment Soil_type	CL	SSL	M45
NG 0	316	407	479
NG 10	358	477	621
NG 30	448	579	731
NG 60	491	689	970
NG 100	621	824	1365

Bulk_density Soil_type	CL	SSL	M45
Low	347	185	463
Medium	457	378	651
High	536	1222	1386

Treatment Bulk_density Soil_type		CL	M45	SSL
NG 0	Low	281	262	62
	Medium	308	415	273
	High	359	759	884
NG 10	Low	318	302	75
	Medium	357	523	341
	High	398	1038	1014
NG 30	Low	321	465	207
	Medium	484	593	355
	High	539	1136	1175
NG 60	Low	369	581	214
	Medium	545	713	449
	High	560	1616	1403
NG 100	Low	448	704	367
	Medium	591	1011	473
	High	825	2381	1634

Least Significant differences of means (5%)

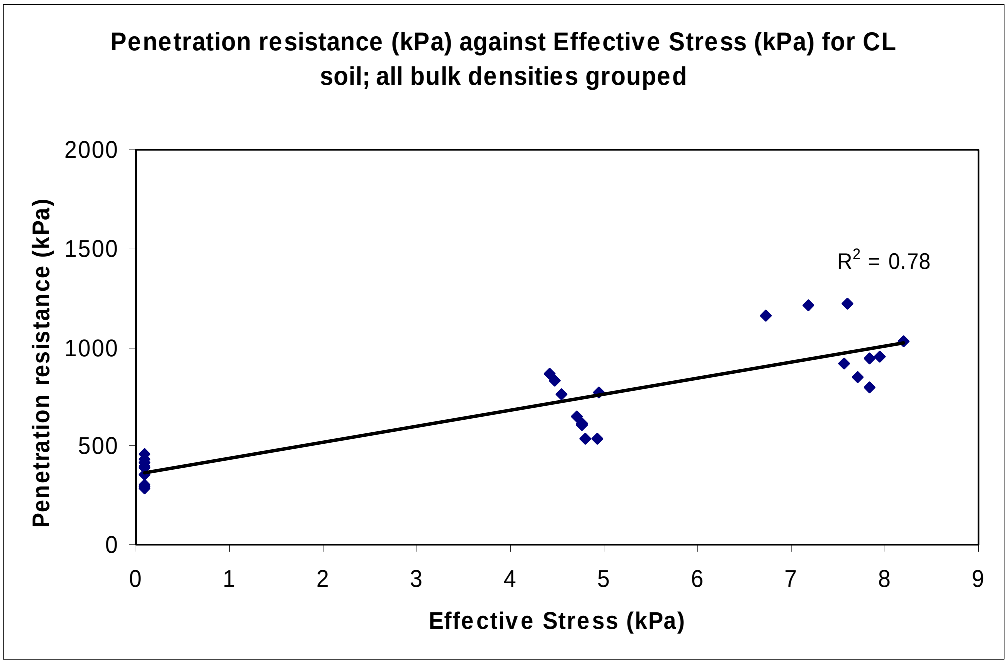
Table	Treatment	Bulk_density	Soil_type	Treatment Bulk_density
rep.	81	135	135	27
d.f.	90	90	90	90
l.s.d.	96.6	74.8	74.8	167.2

Table	Treatment Soil_type	Bulk_density Soil_type	Treatment Bulk_density Soil_type
rep.	27	45	9
l.s.d.	167.2	129.5	**289.7**
d.f.	90	90	90

Appendix VI; WG data

All densities combined (effective stress)

CL



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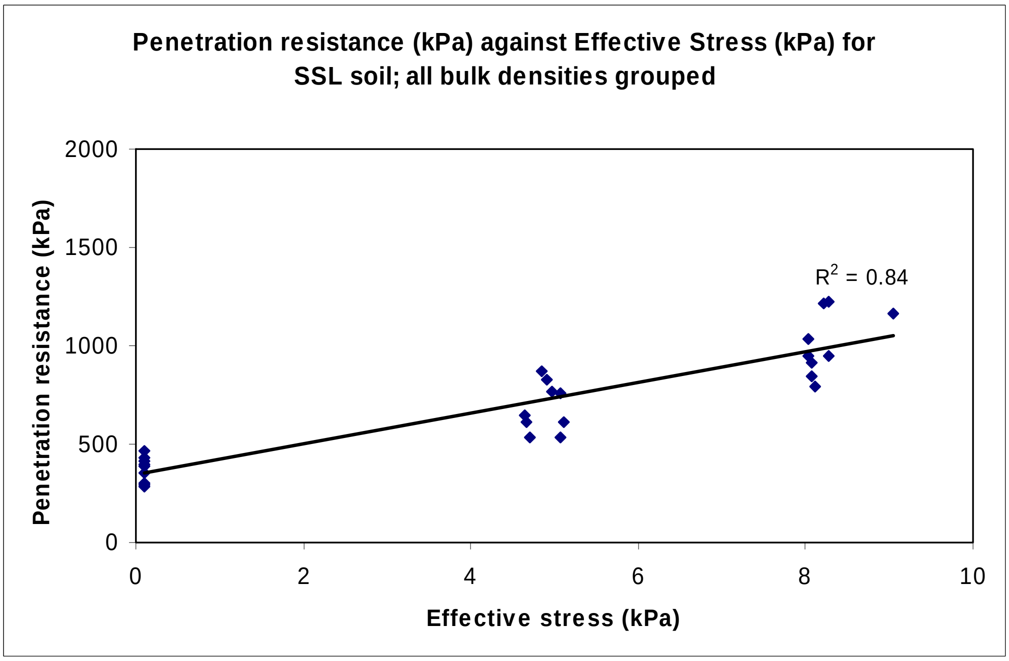
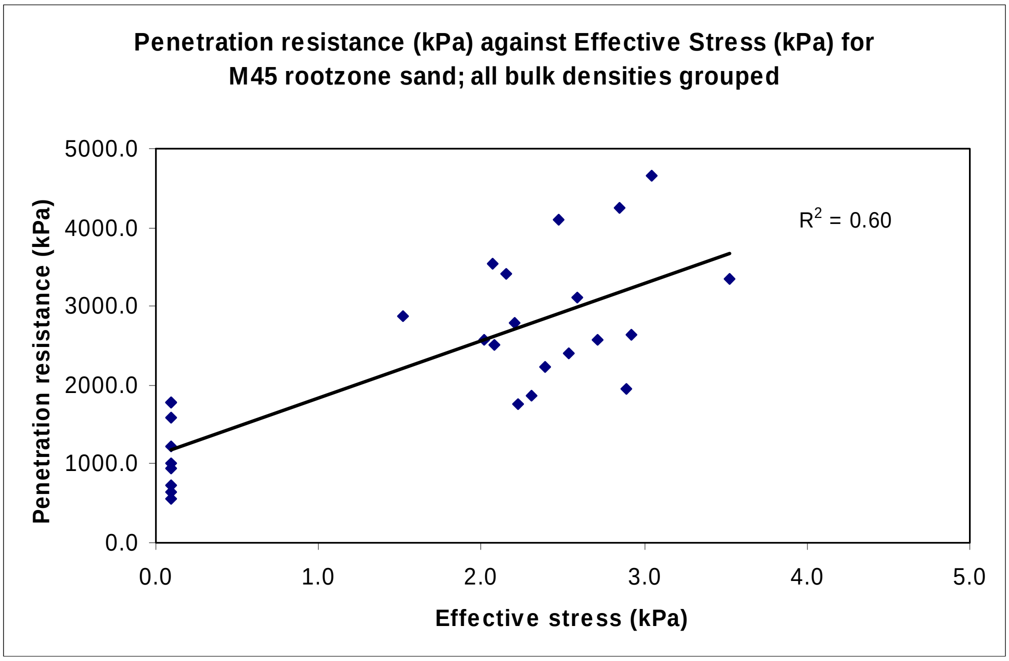
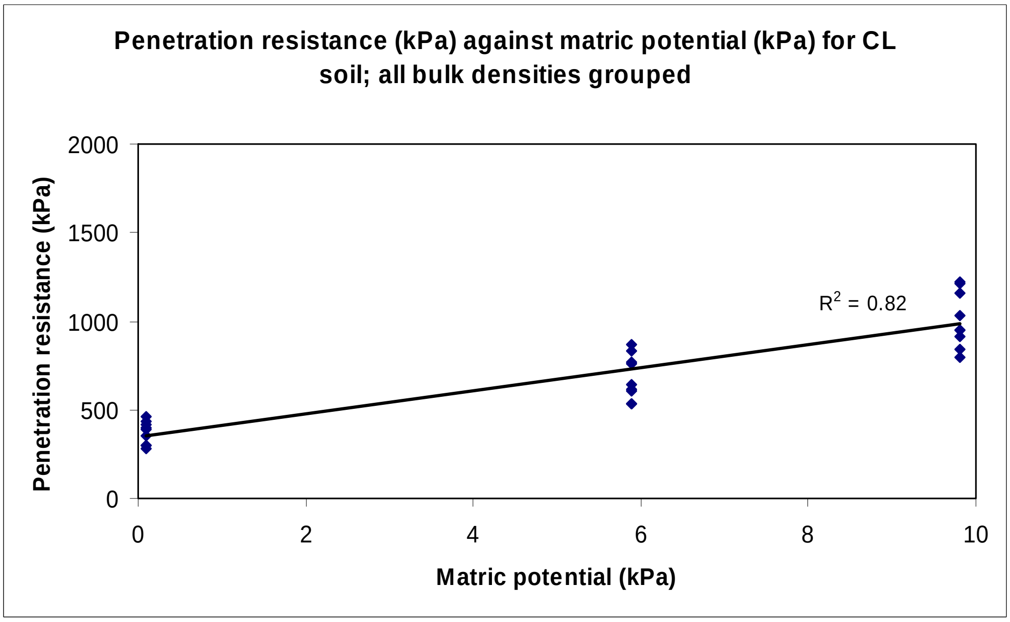


M45 rootzone



All densities combined (matric potential)

CL



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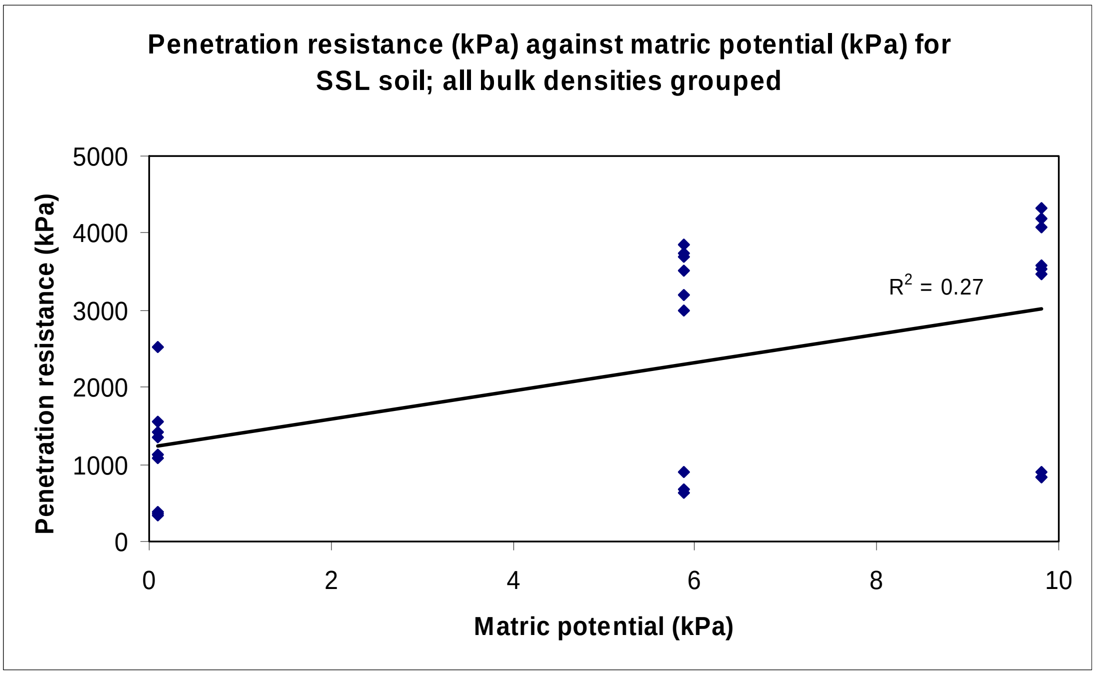
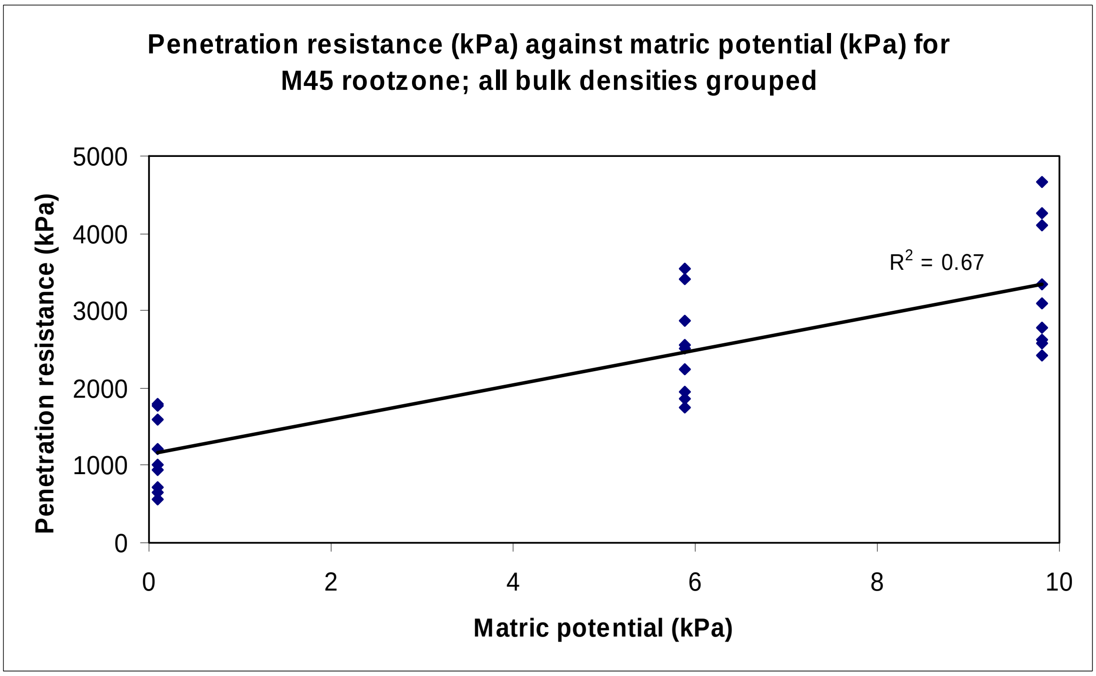
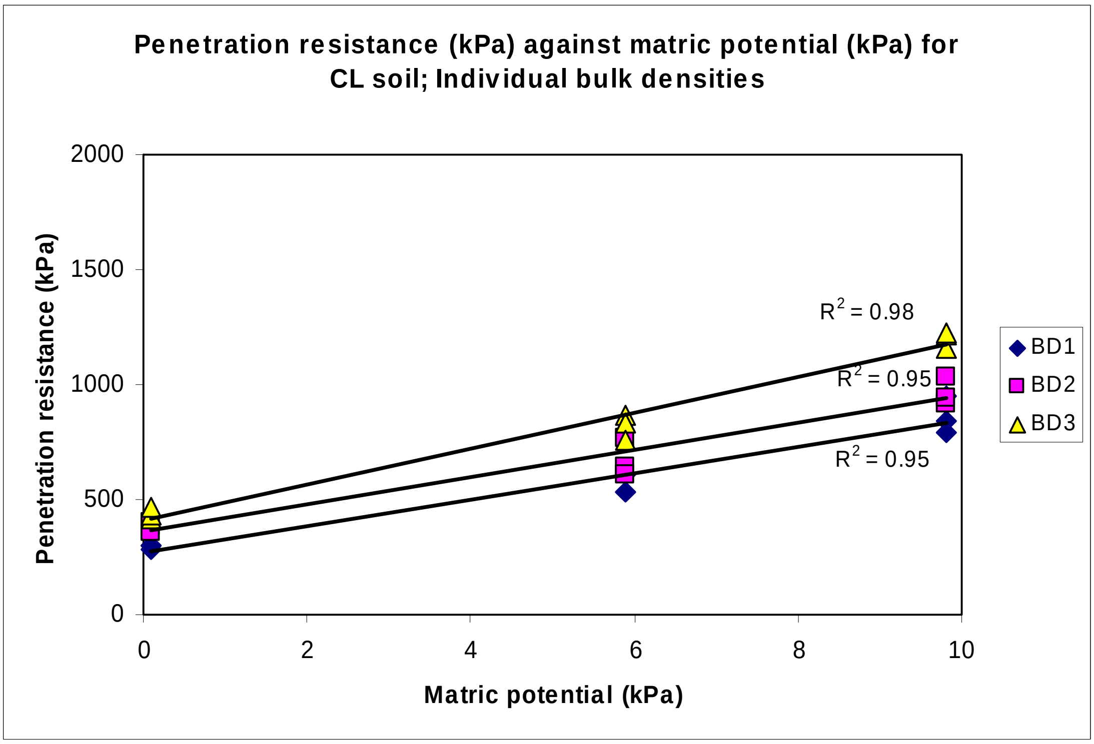


M45 rootzone



Penetration resistance against matric potential, by bulk density (WG)

CL



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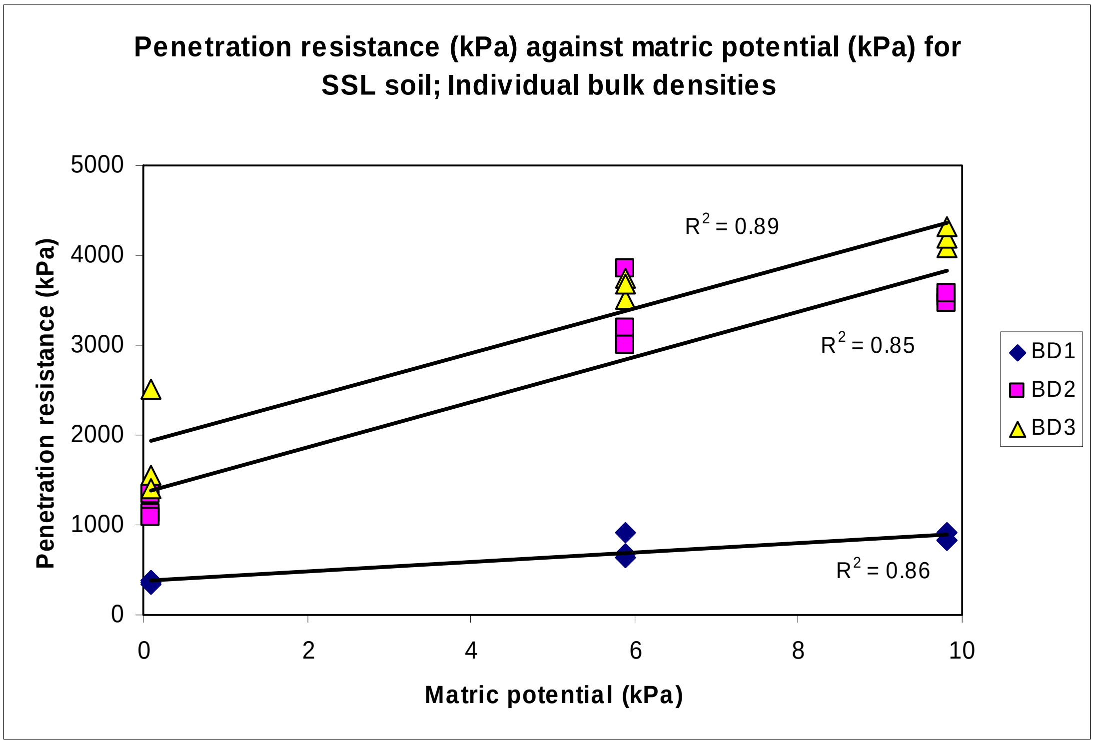
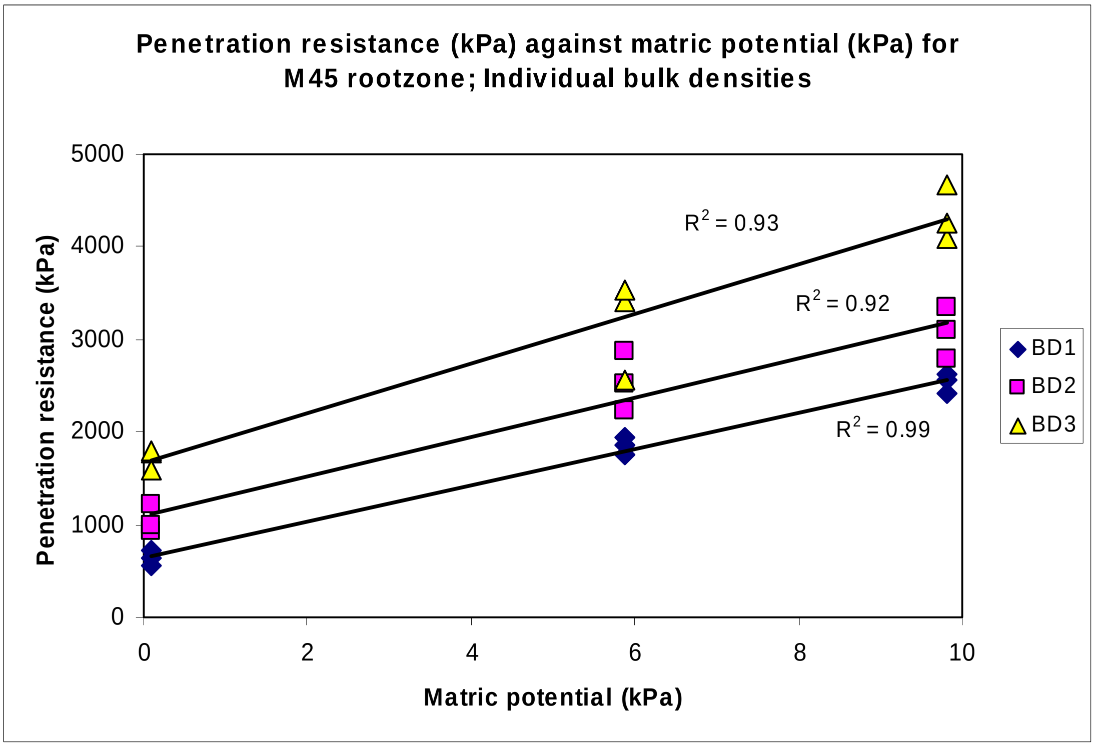


M45 rootzone


Penetration resistance (kPa) against matric potential (kPa) for M45 rootzone; Individual bulk densities
Penetration resistance (kPa)
5000
4000
3000
2000
1000
0
0
2
4
6
8
10
Matric potential (kPa)
R² = 0.93
R² = 0.92
R² = 0.99
◆ BD1
■ BD2
△ BD3

Appendix VII; Significant difference matrix (WG)

The table shows the difference between the two variables. LSD was 355. Each soil type is shown, the tension in cm is given and the three bulk densities are labelled low, medium and high. Differences > 355 are shown in red and significant at the p<0.05 level.

				With Grass																										
				CL									M45									SSL								
				0	0	0	60	60	60	100	100	100	0	0	0	60	60	60	100	100	100	0	0	0	60	60	60	100	100	100
				Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	60	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
With Grass	CL	0	Low		88	144	267	382	504	570	672	906	352	758	1429	1559	2248	2880	2246	2787	4046	65	889	1533	449	3051	3352	564	3231	3902
		0	Med			56	179	294	416	482	584	818	264	670	1341	1471	2160	2792	2158	2699	3958	-23	801	1445	361	2963	3264	476	3143	3814
		0	High				123	238	360	426	528	762	208	614	1285	1415	2104	2736	2102	2643	3902	-79	745	1389	305	2907	3208	420	3087	3758
		60	Low					115	237	303	405	639	85	491	1162	1292	1981	2613	1979	2520	3779	-202	622	1266	182	2784	3085	297	2964	3635
		60	Med						122	188	290	524	-30	376	1047	1177	1866	2498	1864	2405	3664	-317	507	1151	67	2669	2970	182	2849	3520
		60	High							66	168	402	-152	254	925	1055	1744	2376	1742	2283	3542	-439	385	1029	-55	2547	2848	60	2727	3398
		100	Low								102	336	-218	188	859	989	1678	2310	1676	2217	3476	-505	319	963	-121	2481	2782	-6	2661	3332
		100	Med									234	-320	86	757	887	1576	2208	1574	2115	3374	-607	217	861	-223	2379	2680	-108	2559	3230
		100	High										-554	-148	523	653	1342	1974	1340	1881	3140	-841	-17	627	-457	2145	2446	-342	2325	2996
	M45	0	Low											406	1077	1207	1896	2528	1894	2435	3694	-287	537	1181	97	2699	3000	212	2879	3550
		0	Med												671	801	1490	2122	1488	2029	3288	-693	131	775	-309	2293	2594	-194	2473	3144
		0	High													130	819	1451	817	1358	2617	-1364	-540	104	-980	1622	1923	-865	1802	2473
		60	Low														689	1321	687	1228	2487	-1494	-670	-26	-1110	1492	1793	-995	1672	2343
		60	Med															632	-2	539	1798	-2183	-1359	-715	-1799	803	1104	-1684	983	1654
		60	High																-634	-93	1166	-2815	-1991	-1347	-2431	171	472	-2316	351	1022
		100	Low																	541	1800	-2181	-1357	-713	-1797	805	1106	-1682	985	1656
		100	Med																		1259	-2722	-1898	-1254	-2338	264	565	-2223	444	1115
		100	High																			-3981	-3157	-2513	-3597	-995	-694	-3482	-815	-144
	SSL	0	Low																				824	1468	384	2986	3287	499	3166	3837
		0	Med																					644	-440	2162	2463	-325	2342	3013
		0	High																						-1084	1518	1819	-969	1698	2369
		60	Low																							2602	2903	115	2782	3453
		60	Med																								301	-2487	180	851
		60	High																									-2788	-121	550
		100	Low																										2667	3338
		100	Med																											671
		100	High																											

ANOVA results (WG)

A *General Analysis of Variance* was performed with the following set-up

BLOCK	Pot/rep
TREATMENTS	Treatment*Bulk_density*Soil_type*tension kPa
COVARIATE	No Covariate
LSD	Selected
MEANS	Selected
LSD level	5
Y VARIABLE	Penetration resistance

Variate: Penetration_resistance_y

Source of variation Pot stratum	d.f	s.s.	m.s.	v.r.	F pr.
Treatment	2	9.792E+07	4.896E+07	347.03	<.001
Bulk_density	2	8.164E+07	4.082E+07	289.34	<.001
Soil_type	2	1.340E+08	6.702E+07	475.02	<.001
Treatment.Bulk_density	4	7.404E+06	1.851E+06	13.12	<.001
Treatment.Soil_type	4	2.022E+07	5.055E+06	35.83	<.001
Bulk_density.Soil_type	4	4.516E+07	1.129E+07	80.01	<.001
Treatment.Bulk_density.Soil_type	8	6.931E+06	8.663E+05	6.14	<.001
Residual	54	7.619E+06	1.411E+05	1.39	
Pot.Rep stratum	162	1.649E+07	1.018E+05		
Total	242	4.174E+08			

Variate: Penetration_resistance_y

Grand mean 1733.

Treatments are labelled as WG (with grass) and by the amount of tension (e.g. 60 for 60cm tension)

Treatment		
WG 0	WG 60	WG 100
877	1925	2396

Bulk density		
Low	Medium	High
968	1860	2370

Soil type		
CL	SSL	M45
686	2186	2327

Treatment bulk density	Low	Med	High
WG 0	432	871	1328
WG 60	1051	2187	2538
WG 100	1420	2523	3244

Treatment Soil_type	CL	SSL	M45
WG 0	370	1122	1139
WG 60	677	2577	2522
WG 100	1009	2859	3319

Bulk_density Soil_type	CL	SSL	M45
Low	572	652	1679
Medium	674	2683	2224
High	811	3222	3078

Treatment Bulk_density Soil_type		CL	M45	SSL
NG 0	Low	293	645	358
	Medium	381	1051	1182
	High	437	1722	1826
WG 60	Low	560	1852	742
	Medium	675	2541	3344
	High	797	3173	3645
WG 100	Low	863	2539	857
	Medium	965	3080	3524
	High	1199	4339	4195

Least Significant differences of means (5%)

Table	Treatment	Bulk_density	Soil_type	Treatment Bulk_density
rep.	81	135	135	27
d.f.	54	54	54	54
l.s.d.	118.3	118.3	118.3	205.0

Table	Treatment Soil_type	Bulk_density Soil_type	Treatment Bulk_density Soil_type
rep.	27	45	9
l.s.d.	205.0	205.0	**355**
d.f.	54	54	54

Appendix VIII; Significant difference matrix for WG compared to NG experiments

The table shows the difference between the two variables. LSD was 353.6. Although 5 tensions were used for NG, only three were used for WG, therefore only these are compared. Each soil type is shown, the matric potential in cm is given and the three bulk densities are labelled low, medium and high. Differences > 353.6 are shown in red and significant at the p<0.05 level

				No Grass																										
				CL									M45									SSL								
				0	0	0	60	60	60	100	100	100	0	0	0	60	60	60	100	100	100	0	0	0	60	60	60	100	100	100
				Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	60	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
With Grass	CL	0	Low	12	-15	-66	-76	-252	-267	-155	-298	-532	31	-122	-466	-288	-420	-1323	-411	-718	-2088	231	20	-591	79	-156	-1110	-74	-180	-1341
		0	Med	100	73	22	12	-164	-179	-67	-210	-444	119	-34	-378	-200	-332	-1235	-323	-630	-2000	319	108	-503	167	-68	-1022	14	-92	-1253
		0	High	156	129	78	68	-108	-123	-11	-154	-388	175	22	-322	-144	-276	-1179	-267	-574	-1944	375	164	-447	223	-12	-966	70	-36	-1197
		60	Low	279	252	201	191	15	0	112	-31	-265	298	145	-199	-21	-153	-1056	-144	-451	-1821	498	287	-324	346	111	-843	193	87	-1074
		60	Med	394	367	316	306	130	115	227	84	-150	413	260	-84	94	-38	-941	-29	-336	-1706	613	402	-209	461	226	-728	308	202	-959
		60	High	516	489	438	428	252	237	349	206	-28	535	382	38	216	84	-819	93	-214	-1584	735	524	-87	583	348	-606	430	324	-837
		100	Low	582	555	504	494	318	303	415	272	38	601	448	104	282	150	-753	159	-148	-1518	801	590	-21	649	414	-540	496	390	-771
		100	Med	684	657	606	596	420	405	517	374	140	703	550	206	384	252	-651	261	-46	-1416	903	692	81	751	516	-438	598	492	-669
		100	High	918	891	840	830	654	639	751	608	374	937	784	440	618	486	-417	495	188	-1182	1137	926	315	985	750	-204	832	726	-435
	M45	0	Low	364	337	286	276	100	85	197	54	-180	383	230	-114	64	-68	-971	-59	-366	-1736	583	372	-239	431	196	-758	278	172	-989
		0	Med	770	743	692	682	506	491	603	460	226	789	636	292	470	338	-565	347	40	-1330	989	778	167	837	602	-352	684	578	-583
		0	High	1441	1414	1363	1353	1177	1162	1274	1131	897	1460	1307	963	1141	1009	106	1018	711	-659	1660	1449	838	1508	1273	319	1355	1249	88
		60	Low	1571	1544	1493	1483	1307	1292	1404	1261	1027	1590	1437	1093	1271	1139	236	1148	841	-529	1790	1579	968	1638	1403	449	1485	1379	218
		60	Med	2260	2233	2182	2172	1996	1981	2093	1950	1716	2279	2126	1782	1960	1828	925	1837	1530	160	2479	2268	1657	2327	2092	1138	2174	2068	907
		60	High	2892	2865	2814	2804	2628	2613	2725	2582	2348	2911	2758	2414	2592	2460	1557	2469	2162	792	3111	2900	2289	2959	2724	1770	2806	2700	1539
		100	Low	2258	2231	2180	2170	1994	1979	2091	1948	1714	2277	2124	1780	1958	1826	923	1835	1528	158	2477	2266	1655	2325	2090	1136	2172	2066	905
		100	Med	2799	2772	2721	2711	2535	2520	2632	2489	2255	2818	2665	2321	2499	2367	1464	2376	2069	699	3018	2807	2196	2866	2631	1677	2713	2607	1446
		100	High	4058	4031	3980	3970	3794	3779	3891	3748	3514	4077	3924	3580	3758	3626	2723	3635	3328	1958	4277	4066	3455	4125	3890	2936	3972	3866	2705
	SSL	0	Low	77	50	-1	-11	-187	-202	-90	-233	-467	96	-57	-401	-223	-355	-1258	-346	-653	-2023	296	85	-526	144	-91	-1045	-9	-115	-1276
		0	Med	901	874	823	813	637	622	734	591	357	920	767	423	601	469	-434	478	171	-1199	1120	909	298	968	733	-221	815	709	-452
		0	High	1545	1518	1467	1457	1281	1266	1378	1235	1001	1564	1411	1067	1245	1113	210	1122	815	-555	1764	1553	942	1612	1377	423	1459	1353	192
		60	Low	461	434	383	373	197	182	294	151	-83	480	327	-17	161	29	-874	38	-269	-1639	680	469	-142	528	293	-661	375	269	-892
		60	Med	3063	3036	2985	2975	2799	2784	2896	2753	2519	3082	2929	2585	2763	2631	1728	2640	2333	963	3282	3071	2460	3130	2895	1941	2977	2871	1710
		60	High	3364	3337	3286	3276	3100	3085	3197	3054	2820	3383	3230	2886	3064	2932	2029	2941	2634	1264	3583	3372	2761	3431	3196	2242	3278	3172	2011
		100	Low	576	549	498	488	312	297	409	266	32	595	442	98	276	144	-759	153	-154	-1524	795	584	-27	643	408	-546	490	384	-777
		100	Med	3243	3216	3165	3155	2979	2964	3076	2933	2699	3262	3109	2765	2943	2811	1908	2820	2513	1143	3462	3251	2640	3310	3075	2121	3157	3051	1890
		100	High	3914	3887	3836	3826	3650	3635	3747	3604	3370	3933	3780	3436	3614	3482	2579	3491	3184	1814	4133	3922	3311	3981	3746	2792	3828	3722	2561

Anova results WG and NG combined

A *General Analysis of Variance* was performed with the following set-up

BLOCK	Pot/rep
TREATMENTS	Treatment*Bulk_density*Soil_type*tension
COVARIATE	No Covariate
LSD	Selected
MEANS	Selected
LSD level	5
Y VARIABLE	Penetration resistance

Variate: Penetration_resistance_y

Source of variation Pot stratum	d.f.	s.s	. m.s	. v.r.	F pr
Treatment	5	2.432E+08	4.863E+07	339.44	<.001
Bulk_density	2	9.760E+07	4.880E+07	340.61	<.001
Soil_type	2	9.969E+07	4.985E+07	347.93	<.001
Treatment.Bulk_density	10	2.317E+07	2.317E+06	16.17	<.001
Treatment.Soil_type	10	6.604E+07	6.604E+06	46.09	<.001
Bulk_density.Soil_type	4	3.896E+07	9.739E+06	67.98	<.001
Treatment.Bulk_density.Soil_type	20	2.282E+07	1.141E+06	7.96	<.001
Residual	109	1.562E+07	1.433E+05	1.48	
Pot.Rep stratum	323	3.137E+07	9.712E+04		
Total	485	6.384E+08			

Variate: Penetration_resistance_y

Grand mean 1209.

Treatments labelled as with grass or no grass (WG/NG) and amount of tension (cm)

Treatment					
NG 0	NG 60	NG100	WG 0	WG 60	WG 100
400	717	937	877	1925	2396

Bulk Density		
Low	Medium	High
667	1196	1764

Soil type		
CL	SSL	M45
581	1413	1632

Treatment bulk density	Low	Med	High
NG 0	202	332	667
NG 60	388	569	1193
NG 100	506	692	1613
WG 0	432	871	1328
WG 60	1051	2187	2538
WG 100	1420	2523	3244

Treatment Soil_type	CL	SSL	M45
NG 0	316	407	479
NG 60	491	689	970
NG 100	621	824	1365
WG 0	370	1122	1139
WG 60	677	2577	2522
WG 100	1009	2859	3319

Bulk_density Soil_type	CL	SSL	M45
Low	469	433	1097
Medium	577	1541	1468
High	696	2264	2332

Treatment Soil_type	Bulk_density		CL	SSL	M45
NG 0		Low	281	62	262
		Medium	308	273	415
		High	359	884	759
NG 60		Low	369	214	581
		Medium	545	449	713
		High	560	1403	1616
NG 100		Low	448	367	704
		Medium	591	473	1011
		High	825	1634	2381
WG 0		Low	293	358	645
		Medium	381	1182	1051
		High	437	1826	1722
WG 60		Low	560	742	1852
		Medium	675	3344	2541
		High	797	3645	3173
WG 100		Low	863	857	2539
		Medium	965	3524	3080
		High	1199	4195	4339

Least Significant differences of means (5%)

Table	Treatment	Bulk_density	Soil_type	Treatment Bulk_density
rep.	81	162	162	27
d.f.	109	109	109	109
l.s.d.	117.9	83.4	83.4	204.2

Table	Treatment Soil_type	Bulk_density Soil_type	Treatment Bulk_density Soil_type
rep.	27	54	9
l.s.d.	204.2	144.4	**353.6**
d.f.	109	109	109

Appendix IX; K_{sat} experiments

Introduction

The water release characteristic curves for the clay and Mansfield sand rootzone sand demonstrate that the relative saturation of the soil is increased with the addition of grass roots. It is hypothesised that this is due to the grass roots occupying drainage pores and inhibiting the movement of water, at any matric potential. To investigate this, an experiment was conducted in order to demonstrate the effect of grass roots on the saturated hydraulic conductivity (K_{sat}) of the soil. The aim was to conduct the experiment over a short time period; 2 months from initial testing to retesting after grass establishment. This would ensure that root decay had not occurred and that the roots would only explore the pores in existence and not explore the bulk soil. The null hypothesis was that roots make no difference to the saturated hydraulic conductivity of the soil.

Methods

1. Cylinder packing

A clay soil (CL), a sandy silt loam (SSL) and a Mansfield 45 rootzone material (M45; 85% sand: 15% soil) were packed into cylinders measuring 732.9cm^3 (CL and SSL) and 817.1cm^3 (M45). For each soil type there were 3 bulk densities and three replications of each, giving a total of 9 cylinders per soil type. The cylinders were then saturated. Once saturation had occurred measured by a stabilisation in weight to ±1% over a 24 hour period, a constant 50mm head of water was applied to the sample and using a funnel and measuring beaker, the outflow from the base of the sample was collected over a known time period. It was necessary to use a different time period for the three soils, however the results were normalised to mm/min. For each cylinder, three tests were performed.

After this data had been collected, the cylinders were transferred to the glass house and Perennial Rye Grass (cultivar 'Dali') was sown at 35 g/m^2. This was left to establish for two months. After two months, the grass was trimmed to 1cm height (the cuttings were kept and oven dried) and the test re-run in an identical fashion.

2. Fertiliser routine

Only the M45 cylinders received fertiliser in the form of an 8:12:8 (N:P:K) slow release mixture, applied at the equivalent rate of 300 kg/ha.

3. Photographs

Figure 1 Cylinders of each soil type, supported above funnels and measuring beakers, during saturation.

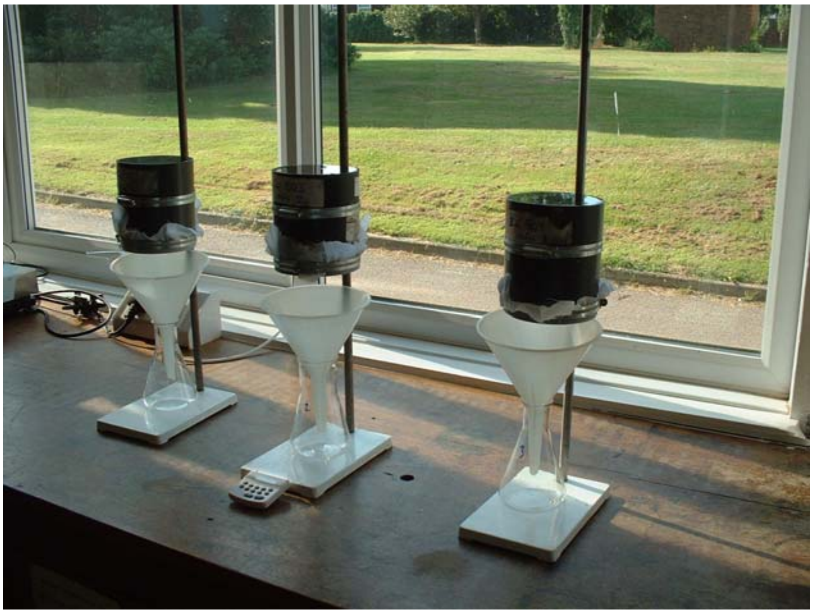


Figure 2 CL BD3 soil, saturated with a 50mm head of water. Note the absence of any drainage.

Figure 3 Soil core after the 2 month growing period (SSL; BD2). Roots generally explored the gaps between the cylinder and the soil with little root growth into the bulk soil.

Results

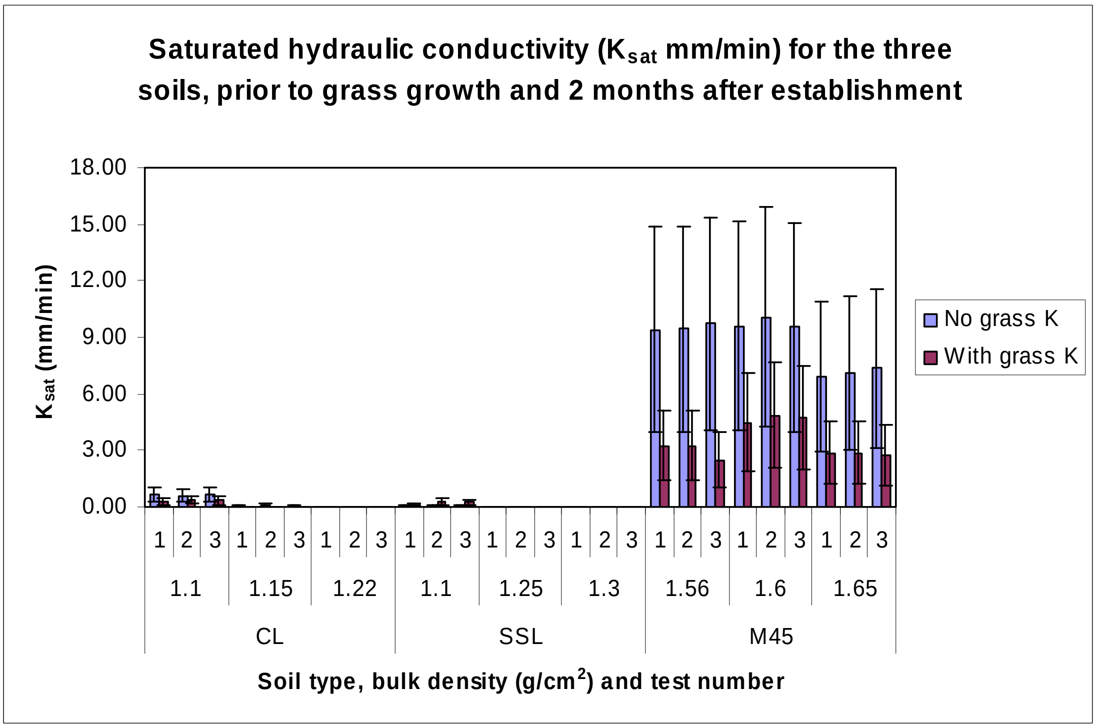


Figure 4 K_{sat} values (each bar is the mean of three runs) for 3 soils at 3 bulk densities after 2 months grass growth with SE bars

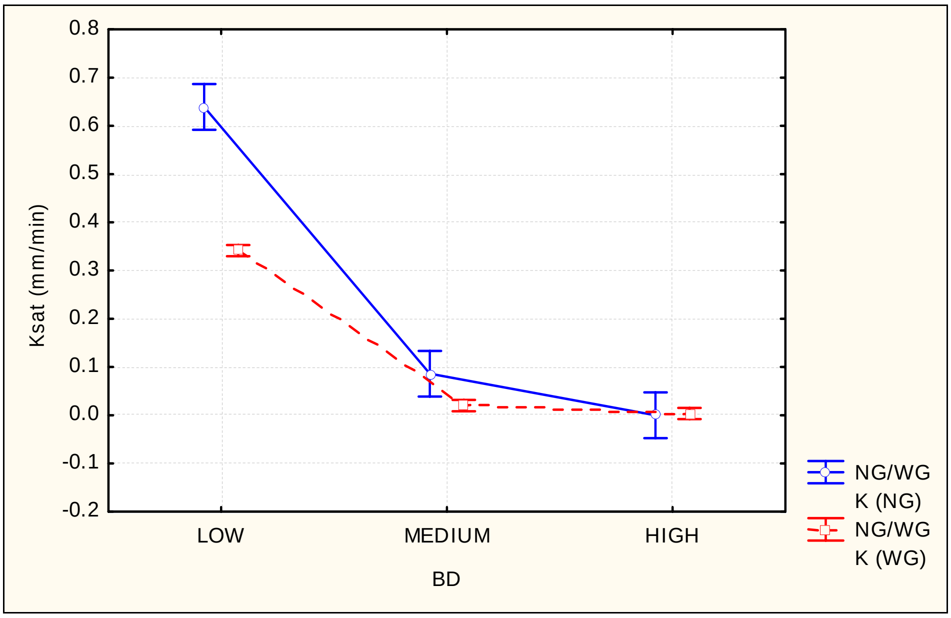
Statistics

Repeated measures ANOVA was conducted to assess determine the effect on Ksat of grass roots. This method would also enable differences due to soil type to be detected. Due to the inconsistent variability in the data, each soil type was addressed individually. The figures and tables below show the results of the analysis for each soil type.

- CL soil

LSD test; variable DV_1 (CL only data)
Homogenous Groups, alpha = .05000
Error: Between; Within; Pooled MS = .00251, df = 45.92

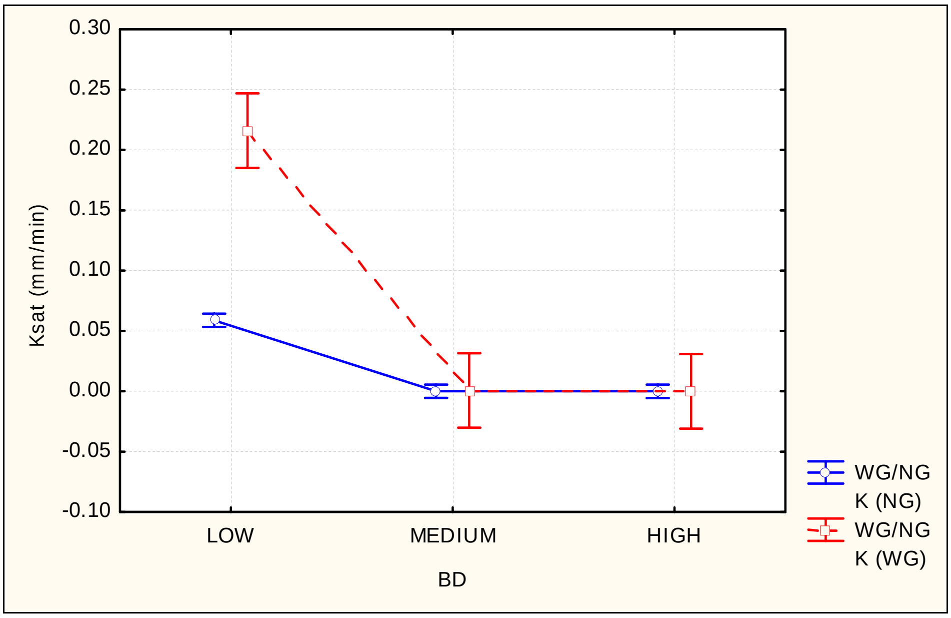
Cell No.	BD	NG/WG	DV_1 Mean	1	2	3	4
5	HIGH	K (NG)	0.000000	****			
6	HIGH	K (WG)	0.003537	****			
4	MEDIUM	K (WG)	0.019957	****			
3	MEDIUM	K (NG)	0.086003		****		
2	LOW	K (WG)	0.341305			****	
1	LOW	K (NG)	0.639186				****



- SSL soil

LSD test; variable DV_1 (SSL only data)
Homogenous Groups, alpha = .05000
Error: Between; Within; Pooled MS = .00104, df = 47.894

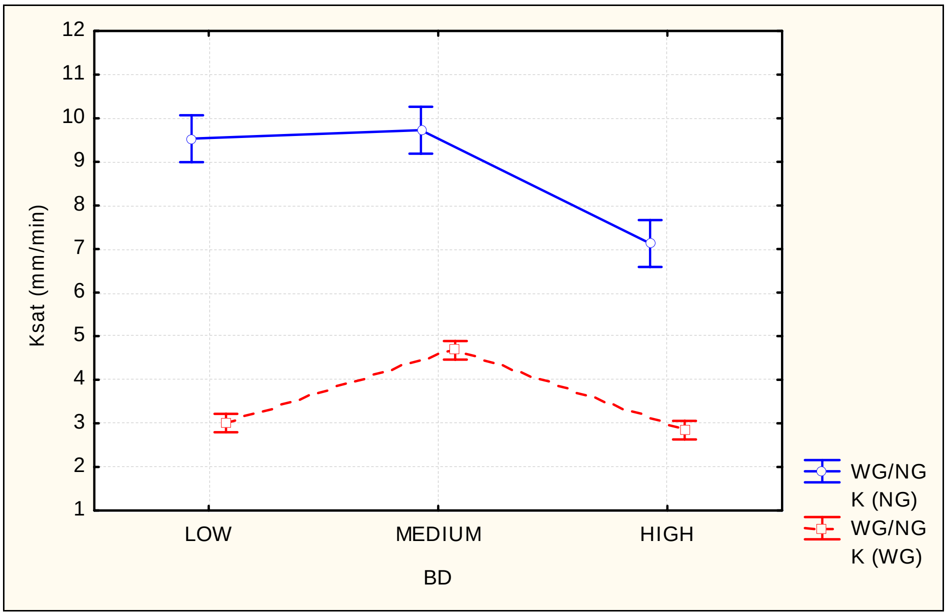
Cell No.	BD	WG/NG	DV_1 Mean	1	2	3
6	HIGH	K (WG)	0.000000	****		
5	HIGH	K (NG)	0.000000	****		
3	MEDIUM	K (NG)	0.000013	****		
4	MEDIUM	K (WG)	0.000721	****		
1	LOW	K (NG)	0.058885		****	
2	LOW	K (WG)	0.216069			****



- M45 rootzone material

LSD test; variable DV_1 (M45 only data)
Homogenous Groups, alpha = .05000
Error: Between; Within; Pooled MS = .35293, df = 47.995

Cell No.	BD	WG/NG	DV_1 Mean	1	2	3	4
6	HIGH	K (WG)	2.841890	****			
2	LOW	K (WG)	3.007933	****			
4	MEDIUM	K (WG)	4.677942			****	
5	HIGH	K (NG)	7.128154				****
1	LOW	K (NG)	9.530030		****		
3	MEDIUM	K (NG)	9.726767		****		



Discussion

The analysis of the water release characteristic showed a reduction in relative saturation for each matric potential, as a result of the addition of grass roots. This experiment was conducted in order to demonstrate how grass roots affected the hydraulic properties of the soil, which may explain the change observed in the WRC.

For the CL soil and M45 rootzone material, the NG soil demonstrated higher Ksat at each bulk density, compared to the same cylinder, but after 2 months of grass root growth. The reason would be a reduction in porosity as the grass roots explored the soil using the existing pore network. This had a dramatic effect on the rootzone sand and would indicate that vigorous root growth and exploration of the sand will not only help provide suitable traction values, but also help conserve water and added nutrients in the form of fertiliser.

For the CL soil, the ‘low’ bulk density produced the greatest Ksat with and without grass, although the rate was very slow. The effect of grass roots at the medium density was to significantly reduce the Ksat to effectively zero due to the few pores that existed, being filled utilised by the roots. At the high density, K sat was zero without grass but the addition of grass increased Ksat, although this difference was not significant and may have been the result of root decal in the heavy texture, opening channels. The effect of density on M45 sand was to reduce Ksat (NG) at the highest density, due to reduced porosity, but with grass the medium density had the highest K sat. The roots may have explored the soil but due to the poor nutrient retention in sand, had begun to decay, leaving behind pores. A possible explanation for this occurring in the medium density could be that this effect was combined with oxygen stress also; under the low bulk density, the porosity was high enough to enable root growth and survival.

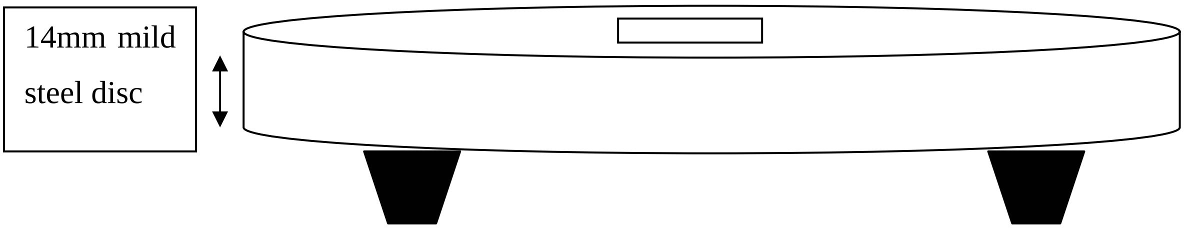
The SSL soil demonstrated a different result. It was very heavy in texture as the grinding process had reduced the soil to a fine dust. When re-packed it produced a ‘massive’ structure which would have inhibited root penetration and drainage water; under the ‘high’ density, no drainage water was collected with or without grass. Under the medium density, the grass roots increased Ksat, but the difference was not significant. At the lowest bulk density, the addition of grass roots significantly increased Ksat compared the same cylinder without grass. As previously discussed, it is possible that root growth and decay had been able to occur in the two months, resulting in the production of channels to transmit water. It should be noted however, that even the highest rate of Ksat recorded was approximately a quarter of a millimetre per minute.

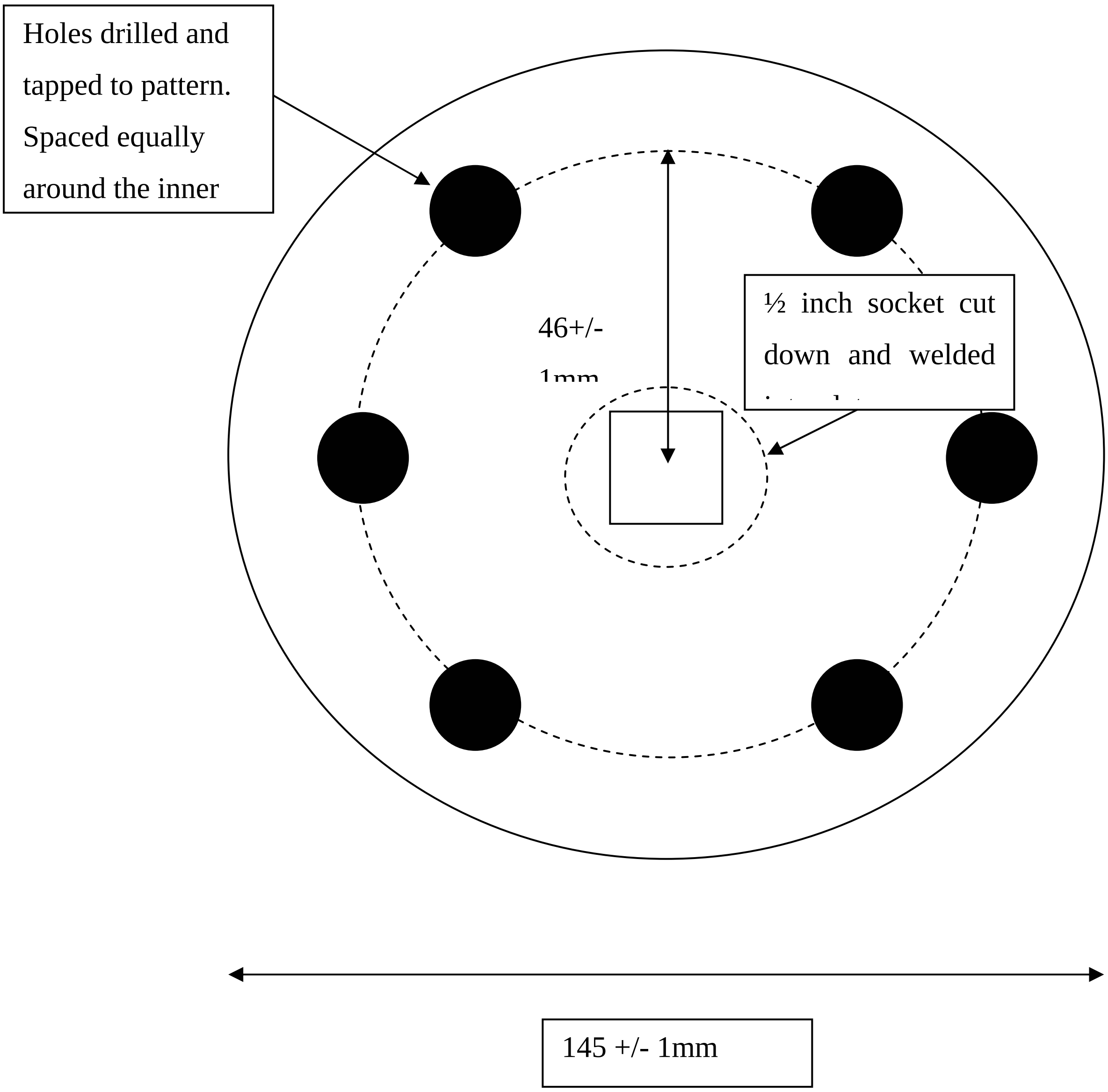
Conclusions

1. In the CL soil, at the densities chosen, Ksat was very low and was reduced further by the addition of grass roots.
2. SSL soil exhibited a significant increase in Ksat at the lowest density and it was argued that root growth and decay had occurred, producing channels to assist drainage.
3. M45 rootzone sand demonstrated the greatest variability in the readings, but the trend was clear; grass roots significantly reduced Ksat at each bulk density.
4. Adequate grass growth was required on sports pitches to not only provide sufficient traction, but to reduce the leaching losses of fertilisers.
5. Conversely, excessive root development may hinder drainage, negating the advantages and justification of using sand as a rootzone material.

Appendix X; Traction test equipment

Plate design



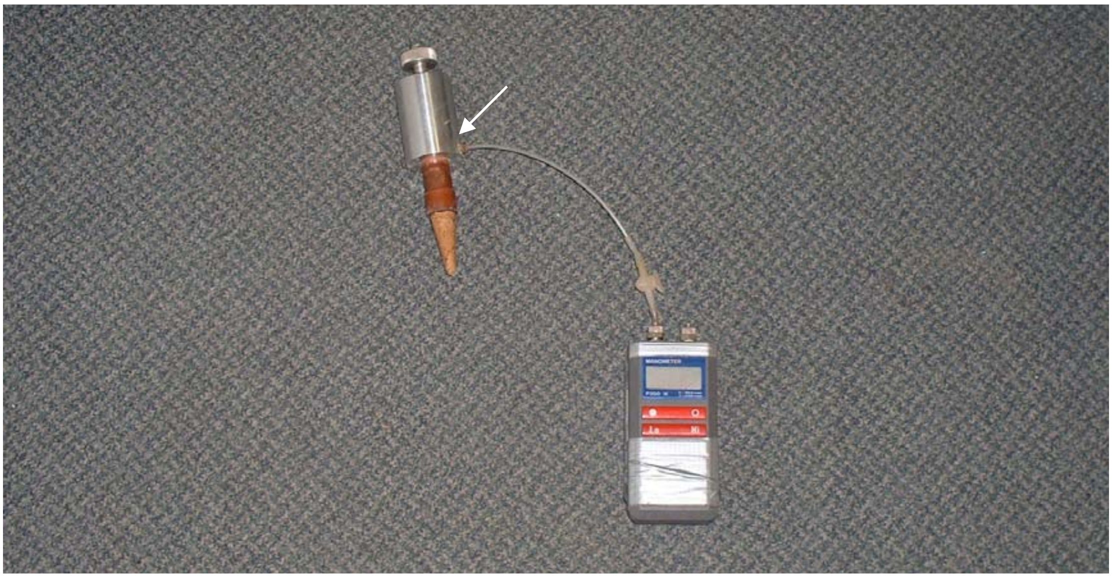


Equipment in use

Figure 5 Traction test equipment. 41 kg of steel weights, plus the weight of the testing equipment equalled approx 45.5 kg. The studded plate is beneath the weights, in the turf.

Appendix XI; Field tensiometer

The quick-draw tensiometer in a customised plastic tray used for protection during transit. The white piping housed wet sponge used to ensure the cap remained saturated. The auger used to make a hole in the ground, marginally smaller than the cap dimensions, is arrowed.



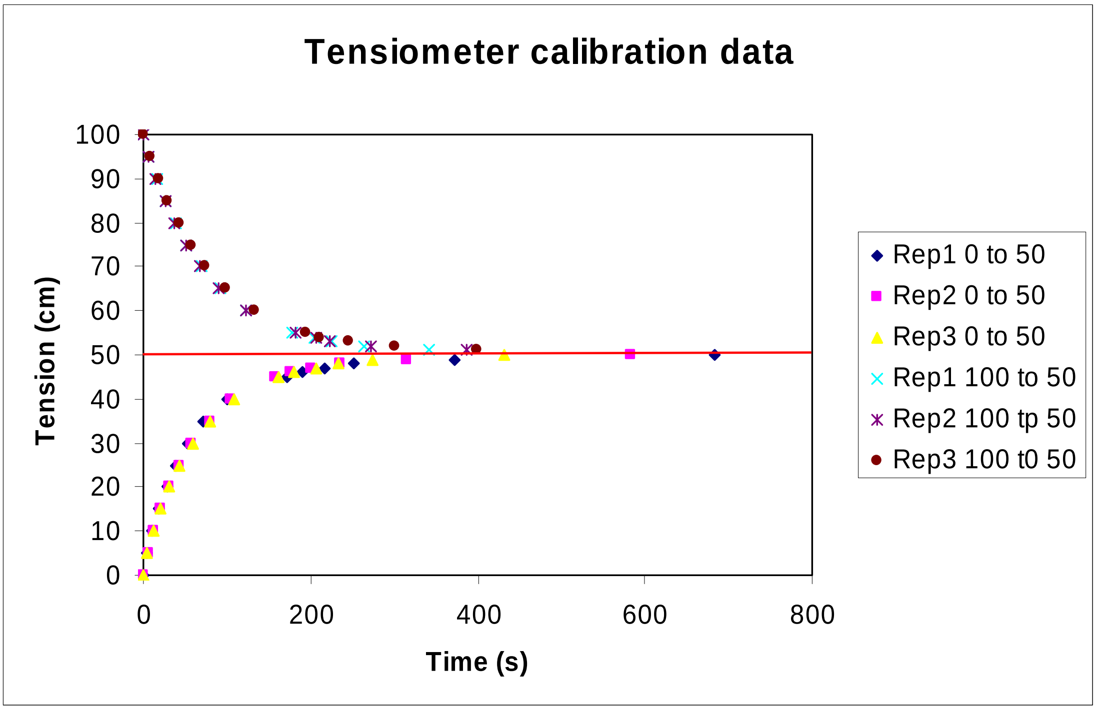
The ceramic cap of the auger was conical in shaper and 50 mm in length. Arrowed is the screw and olive fitting which replaced the initial push fit design. The connections to the manometer were push fit.

Test data

To identify the reliability of the tensiometer and determine the time required to reach equilibrium, a number of tests were conducted. Below, the results of the sand table tests are highlighted which were used to judge accuracy. The Clay loam results were verified by tensiometers permanently installed in the same site, 250 mm from this test.

- Sand table tests.

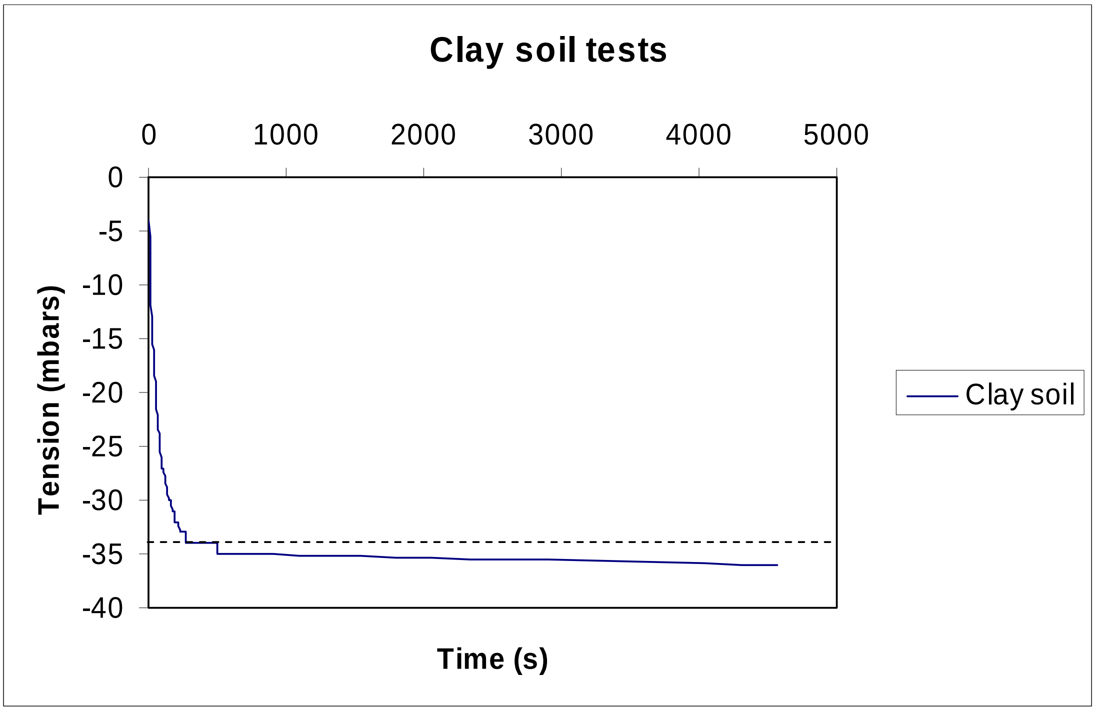
The sand table was set to 50 cm tension; the tensiometer was moved to a new location for each test, and the tension set to zero and 100 on three occasions each using the piston.



- Clay soil

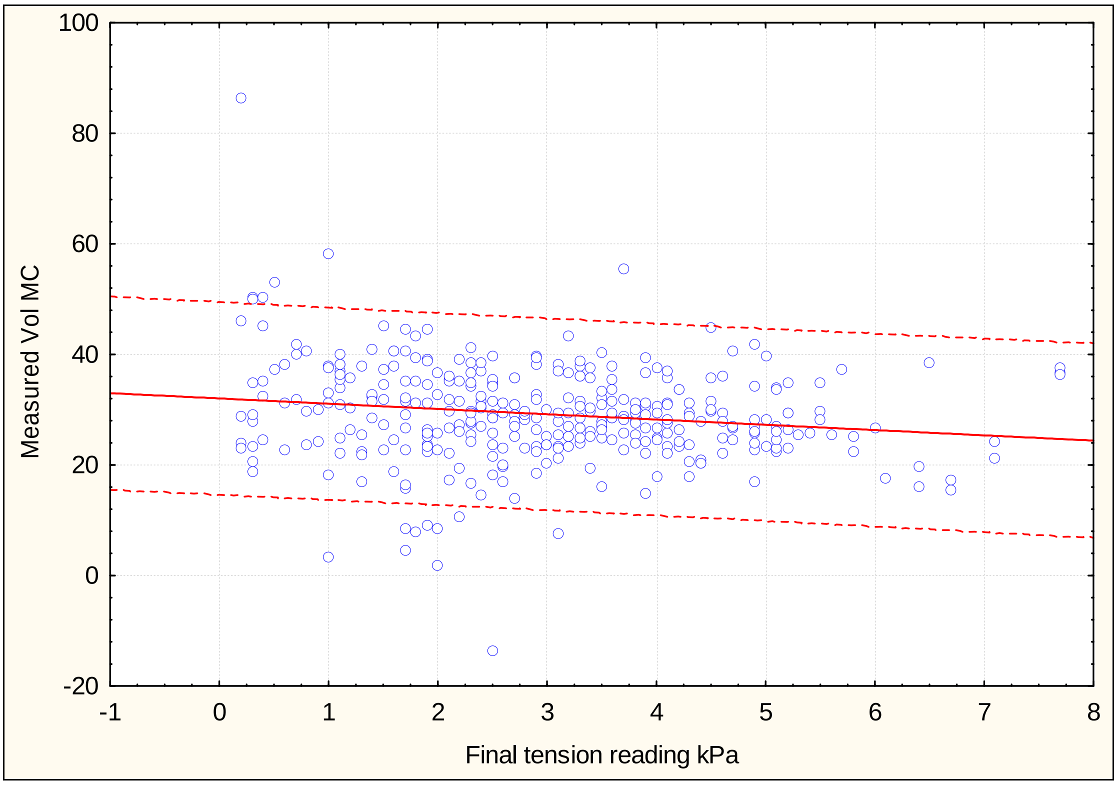
The on-site weather station is established on a clay soil. The tensiometer was placed in the soil, the piston used to set the tension to zero and for ten minutes, the tension reading was recorded every five seconds. A final reading was taken after 76 minutes.

The tension recorded after 76 minutes (4560 seconds), was 1cm greater than that reached in 10 minutes.



Only one replicate is shown, but three tests were made. The figure above is representative of the observed trend. The dashed line indicates the tension reading from the *in-situ* tensiometers, permanently installed in the soil, at a depth of 10mm.

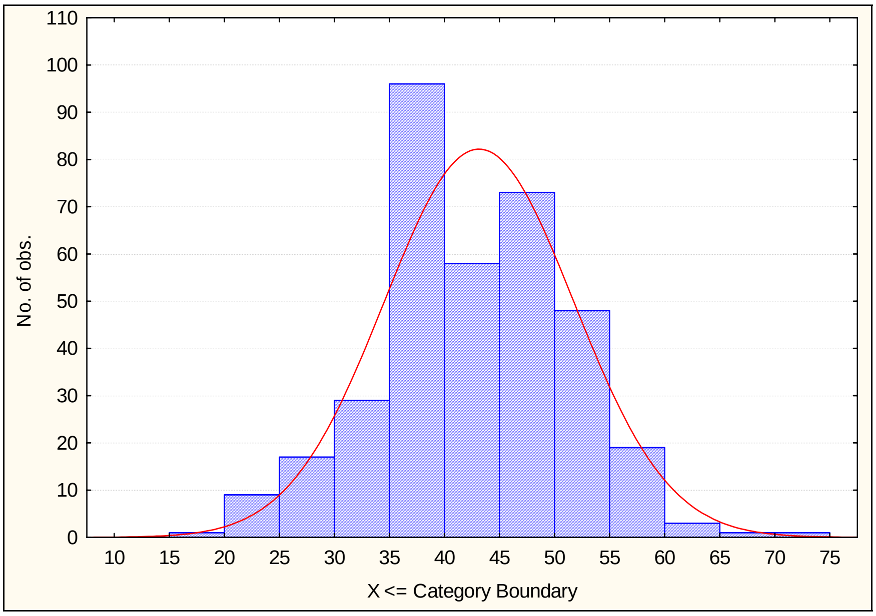
Appendix XII; Moisture content against tension



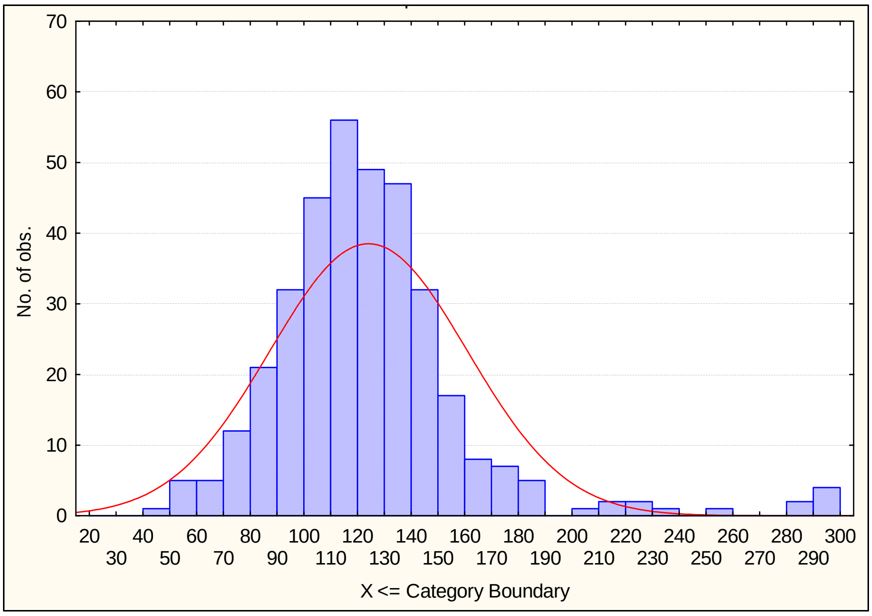
Moisture content and final tension reading for all data. The lines show a prediction interval, demonstrating that at any tension, the possible moisture content falls within a broad range.

The relationship did not improve when separating the data set according to soil type. The general trend was correct; moisture content decreased as the final tension (matric potential) reading increased, but the relationship was poor as demonstrated by low R^2 values.

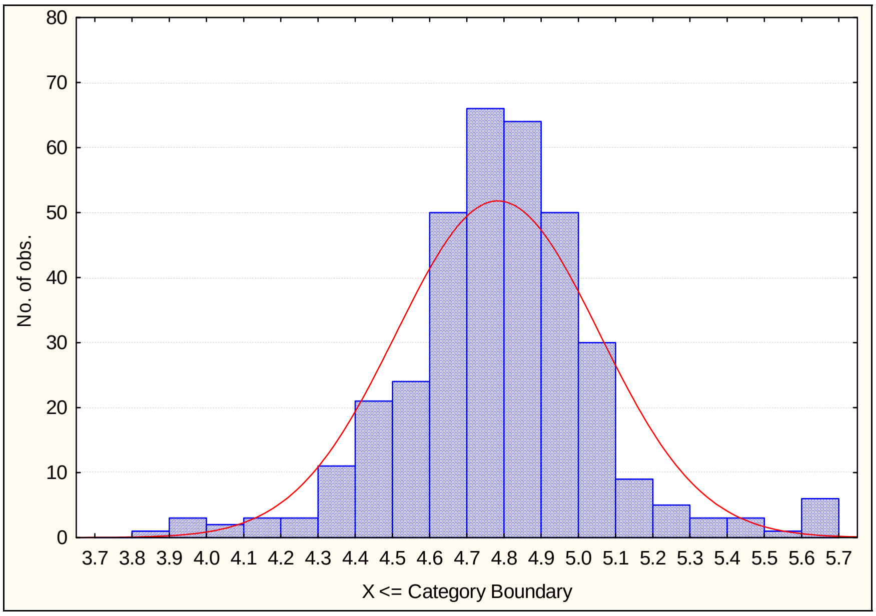
Appendix XIII; Skewness in the data obtained during in-situ experimentation



Traction data were normally distributed.

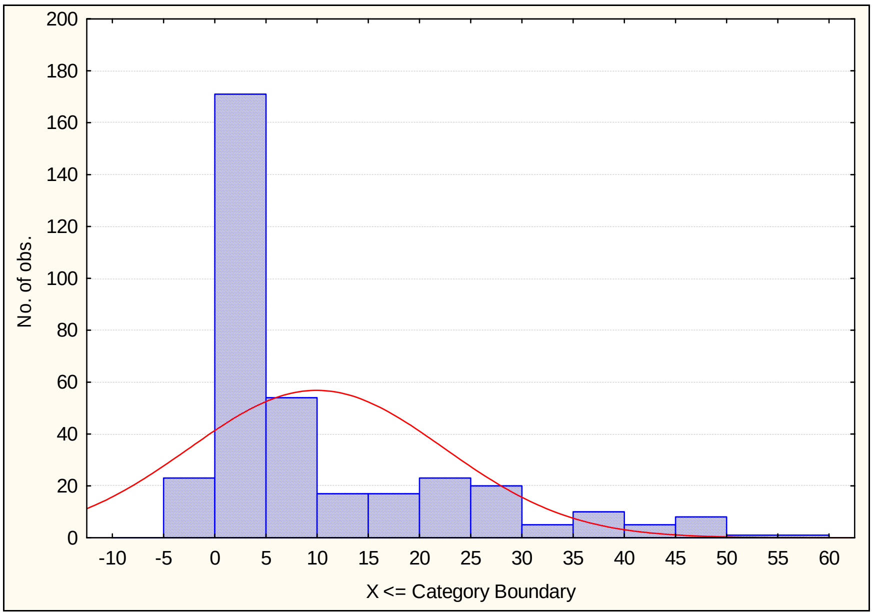


The Clegg data were skewed by a few very hard readings obtained during the hot May/June 2004 site visits.



After taking the Log of the Clegg data, the data were normally distributed.

The other factors that required Log transformation were: penetration resistance, Coarse sand content, fine sand content, clay content and silt content.



Clay content (shown above) and silt content data were heavily skewed.

Appendix XIV; Correlation matrices.

Correlations (All pitches (SCL removed))
Marked correlations are significant at p < .05000
N=328 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.37	-0.07	-0.19	0.63	0.09	0.15	-0.36	-0.03	0.12	0.09	-0.09	-0.20
Log (gmax)	0.37	1.00	-0.09	0.19	-0.02	0.06	-0.11	-0.44	0.08	-0.14	-0.17	0.11	0.08
Grass length (mm)	-0.07	-0.09	1.00	0.15	0.13	-0.35	-0.28	0.08	-0.15	-0.27	-0.05	0.27	0.28
Evenness (mm)	-0.19	0.19	0.15	1.00	-0.26	-0.27	-0.36	0.09	-0.12	-0.33	-0.14	0.27	0.37
Grass cover (%)	0.63	-0.02	0.13	-0.26	1.00	0.04	0.19	-0.18	0.03	0.19	0.05	-0.15	-0.24
Bulk density (upper)	0.09	0.06	-0.35	-0.27	0.04	1.00	0.62	-0.43	0.42	0.55	0.17	-0.40	-0.50
Bulk density (lower)	0.15	-0.11	-0.28	-0.36	0.19	0.62	1.00	-0.15	0.19	0.72	0.25	-0.60	-0.69
Volumetric MC	-0.36	-0.44	0.08	0.09	-0.18	-0.43	-0.15	1.00	-0.28	-0.27	-0.09	0.26	0.26
log coarse sand	-0.03	0.08	-0.15	-0.12	0.03	0.42	0.19	-0.28	1.00	0.39	-0.15	-0.32	-0.29
Medium sand	0.12	-0.14	-0.27	-0.33	0.19	0.55	0.72	-0.27	0.39	1.00	0.18	-0.87	-0.83
log fine sand	0.09	-0.17	-0.05	-0.14	0.05	0.17	0.25	-0.09	-0.15	0.18	1.00	-0.22	-0.24
log silt	-0.09	0.11	0.27	0.27	-0.15	-0.40	-0.60	0.26	-0.32	-0.87	-0.22	1.00	0.71
log clay	-0.20	0.08	0.28	0.37	-0.24	-0.50	-0.69	0.26	-0.29	-0.83	-0.24	0.71	1.00

Correlations (All pitches (SCL removed) DRY)
Marked correlations are significant at p < .05000
N=135 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	**0.64**	0.06	-0.06	**0.55**	0.04	0.12	**-0.55**	-0.08	0.04	-0.02	0.03	-0.12
Log(Clegg)	0.64	1.00	-0.03	0.04	0.18	0.07	-0.05	**-0.67**	-0.03	-0.09	-0.13	0.10	-0.00
Grass length (mm)	0.06	-0.03	1.00	0.27	0.16	**-0.51**	-0.44	0.02	-0.19	-0.37	-0.13	0.32	0.34
Evenness (mm)	-0.06	0.04	0.27	1.00	-0.05	-0.34	-0.39	0.08	-0.23	-0.28	0.07	0.22	0.31
Grass cover (%)	0.55	0.18	0.16	-0.05	1.00	0.05	0.19	-0.34	0.20	0.25	-0.11	-0.20	-0.23
Bulk density (upper)	0.04	0.07	-0.51	-0.34	0.05	1.00	**0.74**	-0.29	0.44	**0.63**	0.20	-0.40	**-0.60**
Bulk density (lower)	0.12	-0.05	-0.44	-0.39	0.19	0.74	1.00	-0.20	0.32	**0.73**	0.17	**-0.55**	**-0.73**
Measured Vol MC	-0.55	-0.67	0.02	0.08	-0.34	-0.29	-0.20	1.00	-0.25	-0.32	-0.06	0.24	0.32
log coarse sand	-0.08	-0.03	-0.19	-0.23	0.20	0.44	0.32	-0.25	1.00	**0.55**	-0.12	-0.44	-0.45
Medium sand	0.04	-0.09	-0.37	-0.28	0.25	0.63	0.73	-0.32	0.55	1.00	0.18	**-0.83**	**-0.84**
log fine sand	-0.02	-0.13	-0.13	0.07	-0.11	0.20	0.17	-0.06	-0.12	0.18	1.00	-0.21	-0.26
log silt	0.03	0.10	0.32	0.22	-0.20	-0.40	-0.55	0.24	-0.44	-0.83	-0.21	1.00	**0.67**
log clay	-0.12	-0.00	0.34	0.31	-0.23	-0.60	-0.73	0.32	-0.45	-0.84	-0.26	0.67	1.00

Correlations (All pitches (SCL removed) WET)
Marked correlations are significant at p < .05000
N=193 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.10	-0.17	-0.30	**0.70**	0.15	0.18	-0.19	0.01	0.20	0.17	-0.20	-0.28
Log(Clegg)	0.10	1.00	-0.11	0.26	-0.17	0.19	-0.11	-0.16	0.17	-0.11	-0.19	0.09	0.12
Grass length (mm)	-0.17	-0.11	1.00	0.09	0.10	-0.26	-0.17	0.11	-0.12	-0.21	0.01	0.24	0.24
Evenness (mm)	-0.30	0.26	0.09	1.00	-0.38	-0.17	-0.33	0.15	-0.07	-0.33	-0.27	0.29	0.40
Grass cover (%)	0.70	-0.17	0.10	-0.38	1.00	0.01	0.18	-0.08	-0.06	0.13	0.14	-0.09	-0.24
Bulk density (upper)	0.15	0.19	-0.26	-0.17	0.01	1.00	0.49	**-0.64**	0.44	0.45	0.14	-0.39	-0.39
Bulk density (lower)	0.18	-0.11	-0.17	-0.33	0.18	0.49	1.00	-0.14	0.10	**0.70**	0.31	**-0.64**	**-0.64**
Measured Vol MC	-0.19	-0.16	0.11	0.15	-0.08	-0.64	-0.14	1.00	-0.31	-0.28	-0.13	0.30	0.24
log coarse sand	0.01	0.17	-0.12	-0.07	-0.06	0.44	0.10	-0.31	1.00	0.29	-0.17	-0.25	-0.19
Medium sand	0.20	-0.11	-0.21	-0.33	0.13	0.45	0.70	-0.28	0.29	1.00	0.17	**-0.90**	**-0.81**
log fine sand	0.17	-0.19	0.01	-0.27	0.14	0.14	0.31	-0.13	-0.17	0.17	1.00	-0.22	-0.22
log silt	-0.20	0.09	0.24	0.29	-0.09	-0.39	-0.64	0.30	-0.25	-0.90	-0.22	1.00	**0.75**
log clay	-0.28	0.12	0.24	0.40	-0.24	-0.39	-0.64	0.24	-0.19	-0.81	-0.22	0.75	1.00

Correlations (CLAY)
Marked correlations are significant at p < .05000
N=30 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.67	0.03	-0.28	0.81	0.01	0.24	-0.62	-0.04	-0.26	-0.06	0.35	-0.11
Log(Clegg)	0.67	1.00	0.03	-0.26	0.51	0.33	0.09	-0.67	0.19	0.06	-0.38	0.27	-0.07
Grass length (mm)	0.03	0.03	1.00	-0.12	0.04	-0.17	-0.01	-0.16	-0.08	-0.18	-0.03	0.10	0.11
Evenness (mm)	-0.28	-0.26	-0.12	1.00	-0.14	0.18	0.16	0.27	0.00	0.09	0.00	0.10	-0.13
Grass cover (%)	0.81	0.51	0.04	-0.14	1.00	0.02	0.51	-0.54	-0.30	-0.14	0.24	0.36	-0.35
Bulk density (upper)	0.01	0.33	-0.17	0.18	0.02	1.00	0.16	-0.11	0.64	0.32	-0.47	0.28	-0.30
Bulk density (lower)	0.24	0.09	-0.01	0.16	0.51	0.16	1.00	-0.19	-0.39	0.25	0.57	-0.08	-0.41
Measured Vol MC	-0.62	-0.67	-0.16	0.27	-0.54	-0.11	-0.19	1.00	0.02	-0.09	-0.02	-0.13	0.20
log coarse sand	-0.04	0.19	-0.08	0.00	-0.30	0.64	-0.39	0.02	1.00	-0.02	-0.76	0.15	0.19
Medium sand	-0.26	0.06	-0.18	0.09	-0.14	0.32	0.25	-0.09	-0.02	1.00	0.25	-0.26	-0.68
log fine sand	-0.06	-0.38	-0.03	0.00	0.24	-0.47	0.57	-0.02	-0.76	0.25	1.00	-0.41	-0.37
log silt	0.35	0.27	0.10	0.10	0.36	0.28	-0.08	-0.13	0.15	-0.26	-0.41	1.00	-0.32
log clay	-0.11	-0.07	0.11	-0.13	-0.35	-0.30	-0.41	0.20	0.19	-0.68	-0.37	-0.32	1.00

Correlations (CLAY dry)
Marked correlations are significant at p < .05000
N=20 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.66	-0.17	-0.18	0.79	0.54	0.04	-0.62	0.46	-0.20	-0.58	0.51	-0.12
Log(Clegg)	0.66	1.00	0.04	-0.26	0.43	0.64	-0.18	-0.71	0.53	0.11	-0.81	0.32	-0.04
Grass length (mm)	-0.17	0.04	1.00	-0.13	0.07	-0.03	-0.04	-0.15	0.01	-0.09	-0.15	0.14	0.07
Evenness (mm)	-0.18	-0.26	-0.13	1.00	0.10	-0.09	0.13	0.26	-0.31	0.08	0.33	0.10	-0.33
Grass cover (%)	0.79	0.43	0.07	0.10	1.00	0.60	0.34	-0.41	0.22	-0.13	-0.32	0.66	-0.40
Bulk density (upper)	0.54	0.64	-0.03	-0.09	0.60	1.00	0.14	-0.48	0.63	0.21	-0.54	0.37	-0.35
Bulk density (lower)	0.04	-0.18	-0.04	0.13	0.34	0.14	1.00	0.23	-0.22	0.32	0.52	0.04	-0.51
Measured Vol MC	-0.62	-0.71	-0.15	0.26	-0.41	-0.48	0.23	1.00	-0.51	-0.09	0.60	-0.28	0.10
log coarse sand	0.46	0.53	0.01	-0.31	0.22	0.63	-0.22	-0.51	1.00	-0.13	-0.65	0.08	0.21
Medium sand	-0.20	0.11	-0.09	0.08	-0.13	0.21	0.32	-0.09	-0.13	1.00	0.33	-0.27	-0.66
log fine sand	-0.58	-0.81	-0.15	0.33	-0.32	-0.54	0.52	0.60	-0.65	0.33	1.00	-0.42	-0.30
log silt	0.51	0.32	0.14	0.10	0.66	0.37	0.04	-0.28	0.08	-0.27	-0.42	1.00	-0.41
log clay	-0.12	-0.04	0.07	-0.33	-0.40	-0.35	-0.51	0.10	0.21	-0.66	-0.30	-0.41	1.00

Correlations (CLAY wet)
Marked correlations are significant at p < .05000
N=10 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.63	0.34	-0.23	0.64	-0.49	0.04	0.50	-0.37	-0.68	-0.43	0.85	0.39
Log(Clegg)	0.63	1.00	-0.29	-0.09	0.88	0.04	0.35	0.35	-0.31	-0.35	-0.11	0.49	0.17
Grass length (mm)	0.34	-0.29	1.00	0.00	-0.40	-0.31	-0.18	0.27	0.04	-0.52	-0.54	0.28	0.44
Evenness (mm)	-0.23	-0.09	0.00	1.00	-0.12	0.34	0.56	-0.35	0.08	0.11	0.03	-0.47	0.18
Grass cover (%)	0.64	0.88	-0.40	-0.12	1.00	-0.13	0.33	0.37	-0.33	-0.29	-0.16	0.54	0.12
Bulk density (upper)	-0.49	0.04	-0.31	0.34	-0.13	1.00	0.67	-0.38	0.50	0.74	0.56	-0.78	-0.66
Bulk density (lower)	0.04	0.35	-0.18	0.56	0.33	0.67	1.00	-0.29	-0.03	0.37	0.37	-0.33	-0.25
Measured Vol MC	0.50	0.35	0.27	-0.35	0.37	-0.38	-0.29	1.00	-0.02	-0.57	-0.75	0.49	0.40
log coarse sand	-0.37	-0.31	0.04	0.08	-0.33	0.50	-0.03	-0.02	1.00	0.45	0.01	-0.61	-0.61
Medium sand	-0.68	-0.35	-0.52	0.11	-0.29	0.74	0.37	-0.57	0.45	1.00	0.80	-0.82	-0.89
log fine sand	-0.43	-0.11	-0.54	0.03	-0.16	0.56	0.37	-0.75	0.01	0.80	1.00	-0.50	-0.70
log silt	0.85	0.49	0.28	-0.47	0.54	-0.78	-0.33	0.49	-0.61	-0.82	-0.50	1.00	0.59
log clay	0.39	0.17	0.44	0.18	0.12	-0.66	-0.25	0.40	-0.61	-0.89	-0.70	0.59	1.00

Correlations (CLAY LOAM)
Marked correlations are significant at p < .05000
N=55 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.74	-0.20	-0.03	0.46	0.03	-0.06	-0.51	-0.15	-0.28	0.05	0.24	-0.37
Log(Clegg)	0.74	1.00	-0.21	0.17	0.02	0.24	-0.06	-0.62	-0.16	-0.38	0.10	0.41	-0.34
Grass length (mm)	-0.20	-0.21	1.00	-0.09	0.03	-0.37	-0.23	-0.03	0.36	0.29	-0.09	-0.24	0.36
Evenness (mm)	-0.03	0.17	-0.09	1.00	-0.17	0.16	-0.13	-0.06	0.08	0.24	-0.03	-0.14	-0.15
Grass cover (%)	0.46	0.02	0.03	-0.17	1.00	-0.18	-0.04	-0.14	-0.01	0.01	-0.04	-0.03	-0.19
Bulk density (upper)	0.03	0.24	-0.37	0.16	-0.18	1.00	0.49	-0.45	-0.15	0.08	0.18	-0.02	-0.40
Bulk density (lower)	-0.06	-0.06	-0.23	-0.13	-0.04	0.49	1.00	0.09	-0.17	0.24	0.03	-0.21	-0.22
Measured Vol MC	-0.51	-0.62	-0.03	-0.06	-0.14	-0.45	0.09	1.00	-0.11	0.05	0.00	-0.14	0.40
log coarse sand	-0.15	-0.16	0.36	0.08	-0.01	-0.15	-0.17	-0.11	1.00	0.29	-0.55	-0.22	0.23
Medium sand	-0.28	-0.38	0.29	0.24	0.01	0.08	0.24	0.05	0.29	1.00	-0.07	-0.85	-0.18
log fine sand	0.05	0.10	-0.09	-0.03	-0.04	0.18	0.03	0.00	-0.55	-0.07	1.00	-0.13	-0.37
log silt	0.24	0.41	-0.24	-0.14	-0.03	-0.02	-0.21	-0.14	-0.22	-0.85	-0.13	1.00	-0.02
log clay	-0.37	-0.34	0.36	-0.15	-0.19	-0.40	-0.22	0.40	0.23	-0.18	-0.37	-0.02	1.00

Correlations (CLAY LOAM dry)
Marked correlations are significant at p < .05000
N=30 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Measured Vol MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.79	0.10	-0.19	0.48	0.05	-0.07	-0.83	-0.30	-0.34	0.18	0.32	-0.37
Log(Clegg)	0.79	1.00	-0.12	-0.07	0.10	0.15	-0.17	-0.83	-0.33	-0.58	0.23	0.56	-0.40
Grass length (mm)	0.10	-0.12	1.00	0.10	0.27	-0.55	-0.42	-0.02	0.47	0.27	-0.33	-0.20	0.30
Evenness (mm)	-0.19	-0.07	0.10	1.00	-0.10	-0.22	-0.43	0.07	0.12	0.24	0.08	-0.15	-0.03
Grass cover (%)	0.48	0.10	0.27	-0.10	1.00	-0.18	0.05	-0.37	0.09	0.02	-0.14	-0.04	-0.05
Bulk density (upper)	0.05	0.15	-0.55	-0.22	-0.18	1.00	0.71	-0.19	-0.36	0.05	0.23	-0.03	-0.39
Bulk density (lower)	-0.07	-0.17	-0.42	-0.43	0.05	0.71	1.00	0.02	-0.22	0.22	-0.02	-0.18	-0.30
Measured Vol MC	-0.83	-0.83	-0.02	0.07	-0.37	-0.19	0.02	1.00	0.25	0.19	-0.16	-0.24	0.59
log coarse sand	-0.30	-0.33	0.47	0.12	0.09	-0.36	-0.22	0.25	1.00	0.36	-0.52	-0.26	0.24
Medium sand	-0.34	-0.58	0.27	0.24	0.02	0.05	0.22	0.19	0.36	1.00	-0.12	-0.84	-0.18
log fine sand	0.18	0.23	-0.33	0.08	-0.14	0.23	-0.02	-0.16	-0.52	-0.12	1.00	-0.12	-0.36
log silt	0.32	0.56	-0.20	-0.15	-0.04	-0.03	-0.18	-0.24	-0.26	-0.84	-0.12	1.00	-0.07
log clay	-0.37	-0.40	0.30	-0.03	-0.05	-0.39	-0.30	0.59	0.24	-0.18	-0.36	-0.07	1.00

Correlations (CLAY LOAM wet)
Marked correlations are significant at p < .05000
N=25 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.56	-0.68	0.37	0.52	0.21	0.09	0.03	-0.19	-0.11	-0.12	0.15	-0.50
Log(Clegg)	0.56	1.00	-0.42	0.77	-0.17	0.61	0.38	-0.27	0.06	0.18	-0.16	-0.16	-0.24
Grass length (mm)	-0.68	-0.42	1.00	-0.27	-0.21	-0.26	-0.00	-0.06	0.30	0.31	0.19	-0.39	0.45
Evenness (mm)	0.37	0.77	-0.27	1.00	-0.24	0.41	0.22	-0.22	0.13	0.23	-0.19	-0.17	-0.28
Grass cover (%)	0.52	-0.17	-0.21	-0.24	1.00	-0.18	-0.18	0.12	-0.15	-0.02	0.10	-0.02	-0.38
Bulk density (upper)	0.21	0.61	-0.26	0.41	-0.18	1.00	0.19	-0.75	0.15	0.09	0.10	-0.05	-0.44
Bulk density (lower)	0.09	0.38	-0.00	0.22	-0.18	0.19	1.00	0.18	-0.03	0.25	0.09	-0.33	-0.08
Measured Vol MC	0.03	-0.27	-0.06	-0.22	0.12	-0.75	0.18	1.00	-0.48	-0.15	0.19	0.03	0.16
log coarse sand	-0.19	0.06	0.30	0.13	-0.15	0.15	-0.03	-0.48	1.00	0.26	-0.60	-0.15	0.21
Medium sand	-0.11	0.18	0.31	0.23	-0.02	0.09	0.25	-0.15	0.26	1.00	0.01	-0.96	-0.17
log fine sand	-0.12	-0.16	0.19	-0.19	0.10	0.10	0.09	0.19	-0.60	0.01	1.00	-0.20	-0.38
log silt	0.15	-0.16	-0.39	-0.17	-0.02	-0.05	-0.33	0.03	-0.15	-0.96	-0.20	1.00	0.13
log clay	-0.50	-0.24	0.45	-0.28	-0.38	-0.44	-0.08	0.16	0.21	-0.17	-0.38	0.13	1.00

Correlations (LOAMY SAND)
Marked correlations are significant at p < .05000
N=34 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	-0.30	-0.09	0.14	0.67	0.06	0.29	0.03	-0.38	0.24	-0.18	-0.27	0.08
Log (gmax)	-0.30	1.00	-0.09	0.23	-0.31	0.39	0.13	-0.26	0.39	0.06	-0.13	-0.19	-0.02
Grass length (mm)	-0.09	-0.09	1.00	0.17	0.38	0.15	0.09	0.21	0.37	-0.21	0.14	0.07	-0.05
Evenness (mm)	0.14	0.23	0.17	1.00	0.20	0.32	0.35	0.22	0.24	0.07	-0.05	-0.09	-0.21
Grass cover (%)	0.67	-0.31	0.38	0.20	1.00	0.00	0.21	0.23	-0.18	0.13	-0.12	-0.11	-0.01
Bulk density (upper)	0.06	0.39	0.15	0.32	0.00	1.00	0.41	-0.23	0.29	0.07	-0.21	-0.11	-0.15
Bulk density (lower)	0.29	0.13	0.09	0.35	0.21	0.41	1.00	0.32	-0.01	0.25	-0.09	-0.21	-0.40
Volumetric MC	0.03	-0.26	0.21	0.22	0.23	-0.23	0.32	1.00	-0.27	0.07	0.01	0.36	-0.09
log coarse sand	-0.38	0.39	0.37	0.24	-0.18	0.29	-0.01	-0.27	1.00	-0.27	-0.07	0.11	-0.09
Medium sand	0.24	0.06	-0.21	0.07	0.13	0.07	0.25	0.07	-0.27	1.00	-0.76	-0.64	-0.34
log fine sand	-0.18	-0.13	0.14	-0.05	-0.12	-0.21	-0.09	0.01	-0.07	-0.76	1.00	0.32	-0.11
log silt	-0.27	-0.19	0.07	-0.09	-0.11	-0.11	-0.21	0.36	0.11	-0.64	0.32	1.00	0.36
log clay	0.08	-0.02	-0.05	-0.21	-0.01	-0.15	-0.40	-0.09	-0.09	-0.34	-0.11	0.36	1.00

Correlations (LOAMY SAND wet)
Marked correlations are significant at p < .05000
N=29 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	-0.17	-0.43	-0.01	0.37	0.05	0.25	-0.15	-0.45	0.14	-0.02	-0.24	0.12
Log (gmax)	-0.17	1.00	0.04	0.29	-0.22	0.40	0.16	-0.21	0.38	0.11	-0.21	-0.23	0.03
Grass length (mm)	-0.43	0.04	1.00	0.16	0.16	0.17	0.04	0.17	0.50	-0.29	0.22	0.13	-0.07
Evenness (mm)	-0.01	0.29	0.16	1.00	-0.13	0.32	0.26	0.17	0.27	-0.00	0.02	-0.05	-0.21
Grass cover (%)	0.37	-0.22	0.16	-0.13	1.00	-0.11	0.01	0.09	-0.16	-0.17	0.23	0.03	-0.01
Bulk density (upper)	0.05	0.40	0.17	0.32	-0.11	1.00	0.41	-0.24	0.31	0.06	-0.22	-0.11	-0.13
Bulk density (lower)	0.25	0.16	0.04	0.26	0.01	0.41	1.00	0.32	-0.07	0.24	-0.06	-0.18	-0.39
Volumetric MC	-0.15	-0.21	0.17	0.17	0.09	-0.24	0.32	1.00	-0.26	0.02	0.08	0.41	-0.14
log coarse sand	-0.45	0.38	0.50	0.27	-0.16	0.31	-0.07	-0.26	1.00	-0.28	-0.08	0.13	-0.01
Medium sand	0.14	0.11	-0.29	-0.00	-0.17	0.06	0.24	0.02	-0.28	1.00	-0.75	-0.64	-0.38
log fine sand	-0.02	-0.21	0.22	0.02	0.23	-0.22	-0.06	0.08	-0.08	-0.75	1.00	0.30	-0.10
log silt	-0.24	-0.23	0.13	-0.05	0.03	-0.11	-0.18	0.41	0.13	-0.64	0.30	1.00	0.37
log clay	0.12	0.03	-0.07	-0.21	-0.01	-0.13	-0.39	-0.14	-0.01	-0.38	-0.10	0.37	1.00

Correlations (SAND)
Marked correlations are significant at p < .05000
N=179 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.13	0.09	-0.16	0.66	-0.09	0.04	-0.20	-0.12	0.12	0.03	-0.05	-0.21
Log (gmax)	0.13	1.00	-0.08	0.19	-0.12	0.24	0.03	-0.43	0.28	-0.08	-0.14	0.05	0.02
Grass length (mm)	0.09	-0.08	1.00	0.04	0.28	-0.28	-0.04	0.01	-0.30	0.17	0.00	0.04	-0.13
Evenness (mm)	-0.16	0.19	0.04	1.00	-0.31	-0.01	-0.05	-0.10	-0.04	-0.08	0.09	0.08	0.04
Grass cover (%)	0.66	-0.12	0.28	-0.31	1.00	-0.18	0.15	-0.05	-0.16	0.31	-0.09	-0.19	-0.32
Bulk density (upper)	-0.09	0.24	-0.28	-0.01	-0.18	1.00	0.28	-0.34	0.28	-0.02	-0.23	0.08	0.04
Bulk density (lower)	0.04	0.03	-0.04	-0.05	0.15	0.28	1.00	0.12	-0.03	0.42	-0.31	-0.25	-0.18
Volumetric MC	-0.20	-0.43	0.01	-0.10	-0.05	-0.34	0.12	1.00	-0.17	-0.03	0.12	0.11	0.06
log coarse sand	-0.12	0.28	-0.30	-0.04	-0.16	0.28	-0.03	-0.17	1.00	-0.19	-0.50	0.11	-0.00
Medium sand	0.12	-0.08	0.17	-0.08	0.31	-0.02	0.42	-0.03	-0.19	1.00	-0.58	-0.64	-0.42
log fine sand	0.03	-0.14	0.00	0.09	-0.09	-0.23	-0.31	0.12	-0.50	-0.58	1.00	0.23	0.10
log silt	-0.05	0.05	0.04	0.08	-0.19	0.08	-0.25	0.11	0.11	-0.64	0.23	1.00	0.28
log clay	-0.21	0.02	-0.13	0.04	-0.32	0.04	-0.18	0.06	-0.00	-0.42	0.10	0.28	1.00

Correlations (SAND dry)
Marked correlations are significant at p < .05000
N=70 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.39	0.22	-0.07	0.54	-0.10	0.22	-0.34	-0.10	0.04	0.01	0.08	-0.12
Log (gmax)	0.39	1.00	0.07	0.13	0.07	0.16	0.16	-0.61	0.03	0.04	-0.14	0.04	-0.01
Grass length (mm)	0.22	0.07	1.00	0.17	0.27	-0.31	-0.09	-0.30	-0.21	0.06	0.19	0.00	-0.31
Evenness (mm)	-0.07	0.13	0.17	1.00	-0.38	-0.12	-0.13	-0.11	-0.32	-0.23	0.40	0.13	-0.07
Grass cover (%)	0.54	0.07	0.27	-0.38	1.00	-0.14	0.25	-0.19	0.04	0.28	-0.14	-0.27	-0.31
Bulk density (upper)	-0.10	0.16	-0.31	-0.12	-0.14	1.00	0.42	0.01	0.11	-0.06	-0.13	0.17	0.11
Bulk density (lower)	0.22	0.16	-0.09	-0.13	0.25	0.42	1.00	0.04	-0.02	0.35	-0.35	-0.16	-0.21
Volumetric MC	-0.34	-0.61	-0.30	-0.11	-0.19	0.01	0.04	1.00	-0.06	-0.10	0.07	0.07	0.05
log coarse sand	-0.10	0.03	-0.21	-0.32	0.04	0.11	-0.02	-0.06	1.00	-0.16	-0.42	0.00	0.00
Medium sand	0.04	0.04	0.06	-0.23	0.28	-0.06	0.35	-0.10	-0.16	1.00	-0.62	-0.65	-0.42
log fine sand	0.01	-0.14	0.19	0.40	-0.14	-0.13	-0.35	0.07	-0.42	-0.62	1.00	0.30	0.02
log silt	0.08	0.04	0.00	0.13	-0.27	0.17	-0.16	0.07	0.00	-0.65	0.30	1.00	0.30
log clay	-0.12	-0.01	-0.31	-0.07	-0.31	0.11	-0.21	0.05	0.00	-0.42	0.02	0.30	1.00

Correlations (SAND wet)
Marked correlations are significant at p < .05000
N=109 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	-0.04	0.06	-0.26	0.71	-0.08	-0.08	-0.09	-0.16	0.19	0.04	-0.15	-0.25
Log (gmax)	-0.04	1.00	-0.04	0.12	-0.25	0.33	-0.07	-0.22	0.29	-0.07	-0.18	0.06	0.06
Grass length (mm)	0.06	-0.04	1.00	0.02	0.30	-0.28	-0.00	0.11	-0.31	0.20	-0.11	0.06	-0.03
Evenness (mm)	-0.26	0.12	0.02	1.00	-0.29	0.06	-0.00	-0.01	0.03	0.06	-0.11	0.04	0.14
Grass cover (%)	0.71	-0.25	0.30	-0.29	1.00	-0.20	0.08	0.03	-0.26	0.33	-0.07	-0.15	-0.32
Bulk density (upper)	-0.08	0.33	-0.28	0.06	-0.20	1.00	0.17	-0.59	0.38	0.01	-0.30	0.00	-0.01
Bulk density (lower)	-0.08	-0.07	-0.00	-0.00	0.08	0.17	1.00	0.20	-0.05	0.49	-0.27	-0.34	-0.16
Volumetric MC	-0.09	-0.22	0.11	-0.01	0.03	-0.59	0.20	1.00	-0.15	-0.04	0.18	0.15	0.04
log coarse sand	-0.16	0.29	-0.31	0.03	-0.26	0.38	-0.05	-0.15	1.00	-0.18	-0.56	0.18	0.01
Medium sand	0.19	-0.07	0.20	0.06	0.33	0.01	0.49	-0.04	-0.18	1.00	-0.56	-0.65	-0.44
log fine sand	0.04	-0.18	-0.11	-0.11	-0.07	-0.30	-0.27	0.18	-0.56	-0.56	1.00	0.18	0.15
log silt	-0.15	0.06	0.06	0.04	-0.15	0.00	-0.34	0.15	0.18	-0.65	0.18	1.00	0.27
log clay	-0.25	0.06	-0.03	0.14	-0.32	-0.01	-0.16	0.04	0.01	-0.44	0.15	0.27	1.00

Correlations (SANDY LOAM)
Marked correlations are significant at p < .05000
N=15 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.42	-0.60	-0.68	0.56	0.37	0.46	-0.23	-0.35	0.37	0.01	-0.02	-0.11
Log (gmax)	0.42	1.00	-0.17	-0.04	-0.14	0.15	0.28	-0.47	0.30	0.26	-0.13	-0.18	-0.33
Grass length (mm)	-0.60	-0.17	1.00	0.00	-0.17	-0.24	-0.02	-0.08	0.42	-0.20	-0.01	-0.10	0.01
Evenness (mm)	-0.68	-0.04	0.00	1.00	-0.57	-0.35	-0.57	0.17	0.19	-0.27	0.04	0.08	0.05
Grass cover (%)	0.56	-0.14	-0.17	-0.57	1.00	0.07	0.44	-0.23	-0.37	-0.22	0.30	0.37	0.45
Bulk density (upper)	0.37	0.15	-0.24	-0.35	0.07	1.00	0.44	-0.26	0.37	0.42	-0.38	-0.48	-0.49
Bulk density (lower)	0.46	0.28	-0.02	-0.57	0.44	0.44	1.00	-0.61	0.08	0.18	0.00	-0.14	-0.13
Volumetric MC	-0.23	-0.47	-0.08	0.17	-0.23	-0.26	-0.61	1.00	-0.47	-0.32	0.20	0.34	0.36
log coarse sand	-0.35	0.30	0.42	0.19	-0.37	0.37	0.08	-0.47	1.00	0.32	-0.67	-0.63	-0.59
Medium sand	0.37	0.26	-0.20	-0.27	-0.22	0.42	0.18	-0.32	0.32	1.00	-0.58	-0.89	-0.92
log fine sand	0.01	-0.13	-0.01	0.04	0.30	-0.38	0.00	0.20	-0.67	-0.58	1.00	0.69	0.67
log silt	-0.02	-0.18	-0.10	0.08	0.37	-0.48	-0.14	0.34	-0.63	-0.89	0.69	1.00	0.97
log clay	-0.11	-0.33	0.01	0.05	0.45	-0.49	-0.13	0.36	-0.59	-0.92	0.67	0.97	1.00

Correlations (SANDY SILT LOAM)
Marked correlations are significant at p < .05000
N=15 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.38	0.10	0.45	0.93	0.28	0.16	-0.30	-0.36	-0.49	0.43	-0.02	0.44
Log (gmax)	0.38	1.00	0.05	0.68	0.29	0.20	0.12	-0.52	0.36	0.24	0.57	-0.79	0.34
Grass length (mm)	0.10	0.05	1.00	-0.15	0.18	0.03	-0.26	-0.07	-0.27	-0.16	-0.03	0.07	0.24
Evenness (mm)	0.45	0.68	-0.15	1.00	0.34	-0.21	-0.08	-0.31	0.31	0.04	0.25	-0.42	0.22
Grass cover (%)	0.93	0.29	0.18	0.34	1.00	0.24	0.13	-0.28	-0.58	-0.63	0.47	0.17	0.42
Bulk density (upper)	0.28	0.20	0.03	-0.21	0.24	1.00	0.45	-0.64	-0.17	0.24	0.49	-0.22	-0.22
Bulk density (lower)	0.16	0.12	-0.26	-0.08	0.13	0.45	1.00	-0.06	0.13	0.47	0.27	-0.12	-0.53
Volumetric MC	-0.30	-0.52	-0.07	-0.31	-0.28	-0.64	-0.06	1.00	0.06	-0.11	-0.50	0.35	-0.09
log coarse sand	-0.36	0.36	-0.27	0.31	-0.58	-0.17	0.13	0.06	1.00	0.68	-0.23	-0.62	-0.19
Medium sand	-0.49	0.24	-0.16	0.04	-0.63	0.24	0.47	-0.11	0.68	1.00	0.10	-0.58	-0.66
log fine sand	0.43	0.57	-0.03	0.25	0.47	0.49	0.27	-0.50	-0.23	0.10	1.00	-0.51	0.08
log silt	-0.02	-0.79	0.07	-0.42	0.17	-0.22	-0.12	0.35	-0.62	-0.58	-0.51	1.00	-0.15
log clay	0.44	0.34	0.24	0.22	0.42	-0.22	-0.53	-0.09	-0.19	-0.66	0.08	-0.15	1.00

Correlations (SAND WET BD1)
Marked correlations are significant at p < .05000
N=19 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	0.56	-0.20	-0.38	0.52	-0.05	-0.39	0.06	0.12	-0.13	0.29	-0.02	-0.22
Log (gmax)	0.56	1.00	-0.21	-0.47	0.33	-0.24	-0.30	0.04	0.55	0.02	-0.04	-0.15	-0.18
Grass length (mm)	-0.20	-0.21	1.00	0.22	0.26	-0.07	0.27	-0.03	-0.58	0.36	-0.23	-0.02	-0.17
Evenness (mm)	-0.38	-0.47	0.22	1.00	-0.30	0.15	0.22	-0.26	-0.39	0.22	-0.08	-0.22	0.10
Grass cover (%)	0.52	0.33	0.26	-0.30	1.00	-0.19	0.16	0.01	-0.24	0.23	-0.15	-0.20	-0.19
Bulk density (upper)	-0.05	-0.24	-0.07	0.15	-0.19	1.00	-0.45	-0.70	-0.23	-0.10	0.02	-0.05	0.34
Bulk density (lower)	-0.39	-0.30	0.27	0.22	0.16	-0.45	1.00	0.41	-0.11	0.56	-0.50	-0.25	-0.37
Volumetric MC	0.06	0.04	-0.03	-0.26	0.01	-0.70	0.41	1.00	0.25	-0.14	0.21	0.46	-0.40
log coarse sand	0.12	0.55	-0.58	-0.39	-0.24	-0.23	-0.11	0.25	1.00	-0.13	-0.11	0.08	-0.06
Medium sand	-0.13	0.02	0.36	0.22	0.23	-0.10	0.56	-0.14	-0.13	1.00	-0.91	-0.83	-0.62
log fine sand	0.29	-0.04	-0.23	-0.08	-0.15	0.02	-0.50	0.21	-0.11	-0.91	1.00	0.76	0.43
log silt	-0.02	-0.15	-0.02	-0.22	-0.20	-0.05	-0.25	0.46	0.08	-0.83	0.76	1.00	0.33
log clay	-0.22	-0.18	-0.17	0.10	-0.19	0.34	-0.37	-0.40	-0.06	-0.62	0.43	0.33	1.00

Correlations (SAND WET BD2)
Marked correlations are significant at p < .05000
N=58 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	-0.04	0.15	-0.18	0.71	-0.09	-0.03	-0.42	-0.33	0.29	0.07	-0.19	-0.29
Log (gmax)	-0.04	1.00	0.09	0.08	-0.21	0.38	-0.03	-0.27	0.08	0.01	-0.07	0.05	-0.02
Grass length (mm)	0.15	0.09	1.00	-0.15	0.35	-0.11	0.04	-0.04	-0.27	0.14	-0.15	0.04	0.08
Evenness (mm)	-0.18	0.08	-0.15	1.00	-0.22	0.17	-0.05	0.09	0.09	0.08	-0.12	0.01	0.03
Grass cover (%)	0.71	-0.21	0.35	-0.22	1.00	-0.15	0.09	-0.21	-0.34	0.39	-0.06	-0.20	-0.37
Bulk density (upper)	-0.09	0.38	-0.11	0.17	-0.15	1.00	0.07	-0.34	0.27	0.07	-0.10	-0.03	-0.19
Bulk density (lower)	-0.03	-0.03	0.04	-0.05	0.09	0.07	1.00	0.23	-0.07	0.52	-0.29	-0.42	-0.20
Volumetric MC	-0.42	-0.27	-0.04	0.09	-0.21	-0.34	0.23	1.00	0.08	-0.06	-0.10	0.06	0.33
log coarse sand	-0.33	0.08	-0.27	0.09	-0.34	0.27	-0.07	0.08	1.00	-0.20	-0.50	0.26	0.12
Medium sand	0.29	0.01	0.14	0.08	0.39	0.07	0.52	-0.06	-0.20	1.00	-0.58	-0.66	-0.50
log fine sand	0.07	-0.07	-0.15	-0.12	-0.06	-0.10	-0.29	-0.10	-0.50	-0.58	1.00	0.16	0.07
log silt	-0.19	0.05	0.04	0.01	-0.20	-0.03	-0.42	0.06	0.26	-0.66	0.16	1.00	0.48
log clay	-0.29	-0.02	0.08	0.03	-0.37	-0.19	-0.20	0.33	0.12	-0.50	0.07	0.48	1.00

Correlations (SAND WET BD3)
Marked correlations are significant at p < .05000
N=32 (Casewise deletion of missing data)

Variable	Traction (Nm)	Log (gmax)	Grass length (mm)	Evenness (mm)	Grass cover (%)	Bulk density (upper)	Bulk density (lower)	Volumetric MC	log coarse sand	Medium sand	log fine sand	log silt	log clay
Traction (Nm)	1.00	-0.19	-0.09	-0.41	0.81	0.15	0.22	0.05	0.17	0.17	-0.27	-0.12	-0.19
Log (gmax)	-0.19	1.00	0.02	0.26	-0.33	-0.01	-0.34	-0.06	0.31	-0.31	-0.11	0.12	0.26
Grass length (mm)	-0.09	0.02	1.00	0.17	0.09	-0.33	-0.20	0.18	-0.01	0.21	-0.29	0.30	-0.12
Evenness (mm)	-0.41	0.26	0.17	1.00	-0.48	-0.28	-0.17	0.21	0.06	-0.11	-0.03	0.23	0.30
Grass cover (%)	0.81	-0.33	0.09	-0.48	1.00	0.08	0.26	0.07	0.07	0.29	-0.32	0.00	-0.30
Bulk density (upper)	0.15	-0.01	-0.33	-0.28	0.08	1.00	0.28	-0.33	0.04	0.08	0.13	-0.52	-0.07
Bulk density (lower)	0.22	-0.34	-0.20	-0.17	0.26	0.28	1.00	0.43	-0.39	0.42	0.25	-0.48	0.06
Volumetric MC	0.05	-0.06	0.18	0.21	0.07	-0.33	0.43	1.00	-0.41	0.20	0.14	0.03	0.27
log coarse sand	0.17	0.31	-0.01	0.06	0.07	0.04	-0.39	-0.41	1.00	-0.22	-0.70	0.05	-0.17
Medium sand	0.17	-0.31	0.21	-0.11	0.29	0.08	0.42	0.20	-0.22	1.00	-0.38	-0.42	-0.22
log fine sand	-0.27	-0.11	-0.29	-0.03	-0.32	0.13	0.25	0.14	-0.70	-0.38	1.00	-0.06	0.20
log silt	-0.12	0.12	0.30	0.23	0.00	-0.52	-0.48	0.03	0.05	-0.42	-0.06	1.00	-0.08
log clay	-0.19	0.26	-0.12	0.30	-0.30	-0.07	0.06	0.27	-0.17	-0.22	0.20	-0.08	1.00

Appendix XV; Macros used in PitchQual.

Wet conditions:

```
It's wet...
    Range("R12").Select
    ActiveCell.FormulaR1C1 = "w"

'   All have Grass Cover as first factor
    Range("C19").Select
    ActiveCell.FormulaR1C1 = "Grass cover %"

'   Draw the Grass Cover Box
    Range("E19").Select
    Selection.Borders(xlDiagonalDown).LineStyle = xlNone
    Selection.Borders(xlDiagonalUp).LineStyle = xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeRight)
```

```
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With

'   First Group - less than 1.00 Bulk Density
    If Range("F13").Value < 1 Then
        ' Traction
        Range("F19").Select
        ActiveCell.FormulaR1C1 = "Grass length mm"
        Range("H19").Select
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        With Selection.Borders(xlEdgeLeft)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
        With Selection.Borders(xlEdgeTop)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
        With Selection.Borders(xlEdgeBottom)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
        With Selection.Borders(xlEdgeRight)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
```

```
        ' Hardness
        Range("C24").Select
        ActiveCell.FormulaR1C1 = "Cannot predict"
        Range("E24:H24").Select
        Selection.ClearContents
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        Selection.Borders(xlEdgeLeft).LineStyle = xlNone
        Selection.Borders(xlEdgeTop).LineStyle = xlNone
        Selection.Borders(xlEdgeBottom).LineStyle = xlNone
        Selection.Borders(xlEdgeRight).LineStyle = xlNone
        Selection.Borders(xlInsideVertical).LineStyle = xlNone
        Selection.Borders(xlInsideHorizontal).LineStyle = xlNone

    End If

'   Second Group - equal to 1.00, less than 1.20 Bulk Density
    If Range("F13").Value >= 1 Then
        ' Traction
        Range("F19").Select
        ActiveCell.FormulaR1C1 = "Moisture Content %"
        Range("H19").Select
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        With Selection.Borders(xlEdgeLeft)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
        With Selection.Borders(xlEdgeTop)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
```

```
With Selection.Borders(xlEdgeBottom)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeRight)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With

' Hardness
Range("E24").Select
Selection.ClearContents
Selection.Borders(xlDiagonalDown).LineStyle = xlNone
Selection.Borders(xlDiagonalUp).LineStyle = xlNone
Selection.Borders(xlEdgeLeft).LineStyle = xlNone
Selection.Borders(xlEdgeTop).LineStyle = xlNone
Selection.Borders(xlEdgeBottom).LineStyle = xlNone
Selection.Borders(xlEdgeRight).LineStyle = xlNone
Selection.Borders(xlInsideVertical).LineStyle = xlNone
Selection.Borders(xlInsideHorizontal).LineStyle = xlNone
Range("C24").Select
ActiveCell.FormulaR1C1 = "Density Only"
Range("F24").Select
Selection.ClearContents
Range("H24").Select
Selection.ClearContents
Selection.Borders(xlDiagonalDown).LineStyle = xlNone
Selection.Borders(xlDiagonalUp).LineStyle = xlNone
Selection.Borders(xlEdgeLeft).LineStyle = xlNone
Selection.Borders(xlEdgeTop).LineStyle = xlNone
Selection.Borders(xlEdgeBottom).LineStyle = xlNone
Selection.Borders(xlEdgeRight).LineStyle = xlNone
```

```
        Selection.Borders(xlInsideVertical).LineStyle = xlNone
        Selection.Borders(xlInsideHorizontal).LineStyle = xlNone

    End If

'   Group Three - Greater Than or equal to 1.20 Bulk Density
    If Range("F13").Value >= 1.2 Then
        ' Traction
        Range("H19").Select
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        Selection.Borders(xlEdgeLeft).LineStyle = xlNone
        Selection.Borders(xlEdgeTop).LineStyle = xlNone
        Selection.Borders(xlEdgeBottom).LineStyle = xlNone
        Selection.Borders(xlEdgeRight).LineStyle = xlNone
        Selection.Borders(xlInsideVertical).LineStyle = xlNone
        Selection.Borders(xlInsideHorizontal).LineStyle = xlNone
        Range("F19:G19").ClearContents

        ' Hardness
        Range("C24:H24").Select
        Selection.ClearContents
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        Selection.Borders(xlEdgeLeft).LineStyle = xlNone
        Selection.Borders(xlEdgeTop).LineStyle = xlNone
        Selection.Borders(xlEdgeBottom).LineStyle = xlNone
        Selection.Borders(xlEdgeRight).LineStyle = xlNone
        Selection.Borders(xlInsideVertical).LineStyle = xlNone
        Selection.Borders(xlInsideHorizontal).LineStyle = xlNone
        Range("C24").Select
        ActiveCell.FormulaR1C1 = "Cannot predict"
    End If
```

```
    ' Close Off
    Range("E19").Select
End Sub
```

Dry conditions

```
It's dry...
    Range("R12").Select
    ActiveCell.FormulaR1C1 = "d"

'   All have Grass Cover as first factor
    Range("C19").Select
    ActiveCell.FormulaR1C1 = "Grass cover %"

'   Draw the Grass Cover Box
    Range("E19").Select
    Selection.Borders(xlDiagonalDown).LineStyle = xlNone
    Selection.Borders(xlDiagonalUp).LineStyle = xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeRight)
```

```
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With

'   First Group - less than 1.00 Bulk Density
    If Range("F13").Value < 1 Then
        ' Traction
        Range("F19:H19").Select
        Selection.ClearContents
        Range("H19").Select
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        Selection.Borders(xlEdgeLeft).LineStyle = xlNone
        Selection.Borders(xlEdgeTop).LineStyle = xlNone
        Selection.Borders(xlEdgeBottom).LineStyle = xlNone
        Selection.Borders(xlEdgeRight).LineStyle = xlNone
        Selection.Borders(xlInsideVertical).LineStyle = xlNone
        Selection.Borders(xlInsideHorizontal).LineStyle = xlNone

        ' Hardness
        Range("C24").Select
        ActiveCell.FormulaR1C1 = "Evenness mm"
        Range("E24").Select
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        With Selection.Borders(xlEdgeLeft)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
        With Selection.Borders(xlEdgeTop)
            .LineStyle = xlContinuous
            .Weight = xlMedium
```

```
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
End If

'   Second Group - equal to 1.00, less than 1.20 Bulk Density
If Range("F13").Value >= 1 Then
    ' Traction
    Range("F19").Select
    ActiveCell.FormulaR1C1 = "Moisture content %"
    Range("H19").Select
    Selection.Borders(xlDiagonalDown).LineStyle = xlNone
    Selection.Borders(xlDiagonalUp).LineStyle = xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .Weight = xlMedium
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
```

```
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeRight)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With

' Hardness
Range("C24").Select
ActiveCell.FormulaR1C1 = "Moisture content %"
Range("E24").Select
Selection.Borders(xlDiagonalDown).LineStyle = xlNone
Selection.Borders(xlDiagonalUp).LineStyle = xlNone
With Selection.Borders(xlEdgeLeft)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeTop)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeBottom)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeRight)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
```

```
        End With
        Range("F24").Select
        Selection.ClearContents
        Range("H24").Select
        Selection.ClearContents
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        Selection.Borders(xlEdgeLeft).LineStyle = xlNone
        Selection.Borders(xlEdgeTop).LineStyle = xlNone
        Selection.Borders(xlEdgeBottom).LineStyle = xlNone
        Selection.Borders(xlEdgeRight).LineStyle = xlNone
        Selection.Borders(xlInsideVertical).LineStyle = xlNone
        Selection.Borders(xlInsideHorizontal).LineStyle = xlNone
    End If


'   Group Three - Greater Than or equal to 1.20 Bulk Density
    If Range("F13").Value >= 1.2 Then
        ' Traction
        Range("F19:H19").ClearContents
        Range("H19").Select
        Selection.Borders(xlDiagonalDown).LineStyle = xlNone
        Selection.Borders(xlDiagonalUp).LineStyle = xlNone
        Selection.Borders(xlEdgeLeft).LineStyle = xlNone
        Selection.Borders(xlEdgeTop).LineStyle = xlNone
        Selection.Borders(xlEdgeBottom).LineStyle = xlNone
        Selection.Borders(xlEdgeRight).LineStyle = xlNone
        Selection.Borders(xlInsideVertical).LineStyle = xlNone
        Selection.Borders(xlInsideHorizontal).LineStyle = xlNone

        ' Hardness
        Range("C24").Select
        ActiveCell.FormulaR1C1 = "Evenness mm"
        Range("E24").Select
```

```
Selection.Borders(xlDiagonalDown).LineStyle = xlNone
Selection.Borders(xlDiagonalUp).LineStyle = xlNone
With Selection.Borders(xlEdgeLeft)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeTop)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeBottom)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeRight)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
Range("F24").Select
ActiveCell.FormulaR1C1 = "Grass cover %"
Range("H24").Select
Selection.Borders(xlDiagonalDown).LineStyle = xlNone
Selection.Borders(xlDiagonalUp).LineStyle = xlNone
With Selection.Borders(xlEdgeLeft)
    .LineStyle = xlContinuous
    .Weight = xlMedium
    .ColorIndex = xlAutomatic
End With
With Selection.Borders(xlEdgeTop)
    .LineStyle = xlContinuous
```

```
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
        With Selection.Borders(xlEdgeBottom)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
        With Selection.Borders(xlEdgeRight)
            .LineStyle = xlContinuous
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With
    End If

    ' Close Off
    Range("E19").Select

End Sub
```

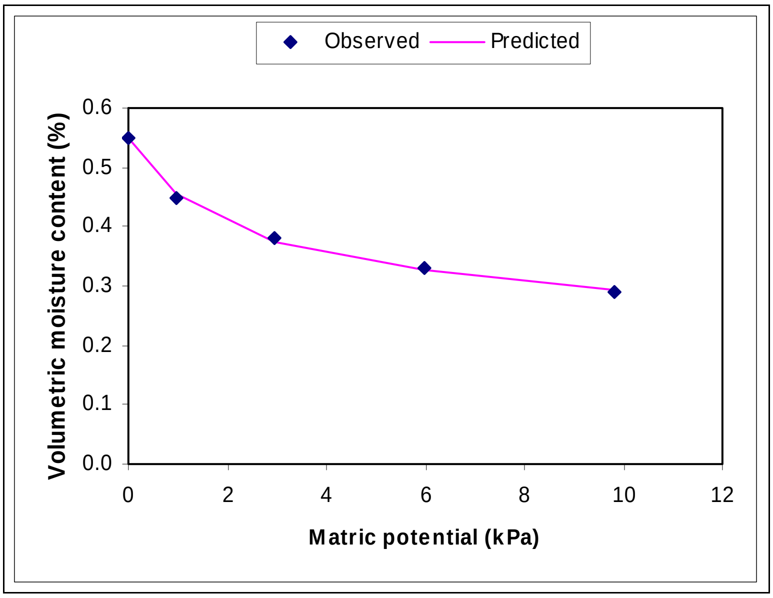
Appendix XVI; Rootzone modelling

Sunderland AFC Mansfield sand rootzone.

Theta sat	Theta res	Alpha	n
0.55	0.01	0.01156	1.223776

Tension kPa	Theta Measured	Theta estimated	(Difference)^2
0	0.55	0.55	0
0.98	0.45	0.45	0.000012
2.94	0.38	0.38	0.000018
5.98	0.33	0.33	0.000008
9.81	0.29	0.29	0.000018

5.65362E-05 Sum
0.007519058 sqrt (sum)



Solver function used to change Alpha and n to make D13 (sqrt (sum)) as close to zero as possible

Theta estimated generated using a rearranged van Genuchten (1980) formula

Original formula is:

$$\boxed{x = \left[\frac{1}{1+(\alpha\ f(x))^n}\right]^m}$$