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Reducing deep soil compaction through strain modification
under different wheel arrangements

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ABSTRACT

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Reducing deep soil compaction through strain modification under different wheel arrangements

New mechanisation methods associated with increasing loads have the potential to cause undesirable deep compaction, which is difficult, expensive and in some cases impossible to alleviate. Avoiding or reducing the risk of deep compaction seems to be the most straightforward solution to compaction management.

Previous research indicates that some benefits can be achieved through interactions between cultivation tines or other implements, in terms of the magnitude of forces and the extent of soil deformation. Interaction within wheel arrangements could have benefits for reducing deep soil compaction.

This study aimed to reduce the risk of deep soil deformation by locally modifying soil conditions through interactions in order to increase soil resistance and hence load support in the surface layers. To test the hypothesis, the research was based on soil mechanics theories and failure mechanisms related to bearing capacity in order to identify the major factors influencing load support and soil displacement. The nature of soil failure patterns, interaction behaviour, soil deformation and load/sinkage relationships were investigated under a wide range of dual and triple spaced footings/wheels configurations. Small-scale tests using rectangular plates were firstly conducted in a glass-sided tank. These initial tests were followed by larger-scale tests in a soil bin and in the field under different soil conditions using actual wheels, spaced and positioned as in the footing tests.

The results indicate that it is possible to reduce soil displacement at depth by increasing load support in the soil surface layers through the interaction between spaced wheel arrangements. It was shown that different interaction modes occurred under dual configurations depending on the spacing between them. A locally compacted zone was created between the wheels under dense interaction conditions, increasing surface support.

Surface support was increased further through a surcharging effect achieved by placing a third footing/wheel between and higher than the side wheels (triple arrangement). The central static interaction zone maximised the surface resistance locally under these configurations. Although single wide section wheels such as Terra tyres can tolerate higher loads at lower pressures, from a soil failure point of view, this is usually associated with large active and passive failure zones inducing deeper soil deformation. Triple spaced wheel arrangements with similar diameter wheels kept soil displacements shallower whilst carrying a similar load to a single very wide wheel with the same overall contact pressure. Reductions of up to 50% in the depth of soil displacement were achieved with the triple arrangements for the same load. These spaced arrangements can therefore be recommended as promising replacement for single wide wheel under heavy machinery application in practical situations.

Benefits from the spaced arrangements are achieved in two ways: firstly by increasing surface support through creating locally compacted zones and secondly by reducing the size of active and passive failure zones causing shallower deformations.

Stony soils provide more surface support than stoneless soils and also non-uniform soil with a denser layer at tillage depth can tolerate a greater load for a given sinkage compared with uniform homogenous soil.

A mathematical model was developed to predict the vertical force under interacting shallow footings and showed an acceptable level of agreement with the experimental results. The model can be used to estimate the extent of the rupture distance of the side passive planes to assist in identifying appropriate spacings and interaction modes for spaced wheel arrangements.

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“No success can be achieved without a patient and supportive wife”

Of course for a married man!!

God bless all

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Table A3.9. *Wheel sinkage in the firm field.....* A3-11

LIST OF SYMBOLS

(Unless otherwise stated in the text)

Q	Total vertical force	kN
Q_d	Vertical force per unit length	$kN.m^{-1}$
q	Surcharge stress	$kN.m^{-2}$
γ	Bulk unit weight	$kN.m^{-3}$
Z	Sinkage	m
w	Footing/wheels width	m
l	Length of the footing	m
L	Spacing between footings/wheels (horizontal)	m
n	Number of footings	-
$N_c, N_q \text{ \& } N_\gamma$	Dimensionless N factors	-
$N'_c \text{ \& } N'_q$	Meyerhof dimensionless N factors	-
φ	Angle of soil internal friction	deg
c	Soil cohesion	$kN.m^{-2}$
c'	Residual cohesion	$kN.m^{-2}$
r	Radius of the radial failure zone	m
r_0	Radius of the active wedge	m
f	Rupture distance at footing sides	m
θ	Angular position of the passive zones	deg
V	Vertical force on interacting wall	kN
V'	Vertical force on active wedge side	kN
H	Height of active wedge	m
L_t	Transitional spacing	m
σ	Bending stress	$kN.m^{-2}$
M	Bending moment	$kN.m$
I	Second moment of area	m^4
Y	Central distance	m

SF	Safety factor	-
τ	Shear stress	$kN.m^{-2}$
A	Area	m^2
V	Shear force	kN
D	Shaft diameter	m
Z	Section modulus	m^3
δ	Deflection	m
E	Modulus elasticity	$kN.m^{-2}$

Chapter 1. Introduction

1.1. Background

Soil compaction is a potential problem in many agricultural soils and world-wide interest has increased due to the severity of damage and the complication of the process. The increase in weight and size of machinery since 1948 in highly mechanised fields caused compaction to even greater depths. It has been reported that compaction has significant effects on four environmental issues, atmosphere, surface water, ground water and soil resources as well as crop productivity (Horn et al., 1995). The economic losses due to soil compaction were found to be very significant in the affected farms (Hakansson, 1994).

Compaction in the shallow upper soil layer can usually be removed by normal tillage operations. The major concerns and difficulties start when deformation occurs below the tilled layer in deeper layers. The operation to alleviate compaction in such a situation is a very high energy and expensive operation and needs considerable knowledge to perform effectively.

Numerous factors have been identified by researchers as the main reasons for causing deep compaction, including axle load, wheel shape and contact pressure (Abu-Hamed et al., 2000; Olsen, 1994; Soane et al., 1980). All agreed however that axle load was the dominant factor for causing deep compaction whilst contact pressure mostly affected the soil near the surface. This was also demonstrated and confirmed during field experiments by applying different ranges of loads and ground pressures (Smith and Dickson, 1990).

There have been some attempts and suggestions to provide maximum efficiency for deep compaction alleviation using subsoilers, although it is a difficult and expensive operation. Farmers still however in many countries are facing the problem and do not know how deep to operate, how long the subsoiling effect will last, how to make a precise assessment of the compaction severity in their fields and how to manage traffic to reduce the risk of damage (Adam and Erbach, 1995).

It was also indicated that subsoil deterioration could be persistent for a long time (Arvidsson, 2000) and could be alleviated only by natural process such as freezing/thawing, drying/wetting and biological activities (Hakansson, 1987).

Avoiding deep compaction or reducing the risk of it occurring seems, therefore, to be the most straightforward solution, as subsoiling has not been a long lasting, effective or easy operation. On the other hand due to increasing farm size, decreasing farm population, changing cropping systems and timeliness requirements, using heavier and larger machinery is unavoidable in many circumstances.

Soil ability to support or to fail under an applied static surface load is clearly related to its behaviour under the passage of a wheel. It has also been reported that a major concern for researchers in the agriculture sector as well as military, construction and other off-road equipment applications, has been to increase load support in the surface layer of soil (Soane et al., 1981 and Swanson, 1973). Such a condition in agriculture would allow greater loads to be tolerated on the shallower soil layers, reducing the risk of compaction at depth.

Experiments on soil loosening techniques (Spoor and Godwin, 1978) have indicated that the nature and direction of soil failure planes can be changed by altering soil properties locally before the main operation. Initial studies in a glass-sided tank (Answell, 1986) on plough presses also indicated possibilities for changing the extent of compaction by confining soil locally in relation to the actual press wheels.

Other researchers have indicated that some benefits could be achieved by inducing interaction or interference between tools.

This study intends to explore using interaction effects, possibilities for reducing soil displacement at depth by supporting more of the load in the shallower surface layer. Although increased compaction is likely to occur in the surface layer, this can be more easily alleviated during normal tillage operations than deep compaction.

In order to assist in understanding the complicated behaviour of soil and gain a fundamental knowledge of soil bearing capacity, failure patterns and soil deformation, plate-sinkage tests were arranged in the first phase of the project followed by large-scale and field tests.

Soane et al., 1981 reported that plate sinkage tests have played an important part in

the study of soil behaviour under vehicle loadings. The plates were successfully used recently to assess soil compactibility under load (Earl, 1997).

It has to be mentioned that there has been much research into the soil stress distribution caused by loads applied by tyres. Several models of soil compaction related to stress or stress-strain relationships have been developed (Bailey et al, 1986), although all have limitations. There have however been relatively few research projects investigating strain, displacement or soil deformation under tyres at depth. Lack of effective strain measuring and imaging techniques have been a major problem.

With the intention of avoiding deep compaction, this study took greater account of soil mechanics theories and failure mechanisms to increase soil bearing capacity and load support in the surface layers and decrease displacement at depth under different wheel arrangements and soil conditions. The failure patterns and displacement limits were monitored and measured during the experiments. Soil were prepared in two different layers with a dense bottom layer and looser top layer, simulating conditions common in field situations with a more compacted layer at tillage depth.

Although a model for interacting tines has been developed (Godwin et al. 1984) no model was found in the literature for predicting the resultant force under interacting shallow footings, which is one of the objectives of this research.

1.2. Aims

1. To evaluate the hypothesis that it would be possible to manipulate the direction and magnitude of soil strain and displacement by locally modifying soil conditions and hence increasing surface load support under multiple wheel arrangements.
2. To identify practical methods based on the above hypothesis, to avoid or reduce deep soil compaction through the development and selection of appropriate wheel arrangements.

2.1. Objectives

1. To identify the major factors influencing soil strain and surface load support under multiple wheel combinations.
2. To determine under vertical soil surface loading conditions, the nature of soil deformation, strain and density changes in the presence of discrete higher density zones of different shapes and depths.
3. To develop a predictive model to estimate the magnitude of the vertical soil support force generated under interacting wheel combinations.
4. To identify alternative practical wheel arrangements capable of developing optimum combinations of soil deformation and load support to cause the least soil displacement at depth.

2.2. Outline methodology

The work associated with the investigation can be categorised into four main areas of research. The areas are a) Small-scale tests, b) Large-scale tests, c) Field experiments and d) Development of a mathematical model.

A glass-sided tank will be developed to investigate a wide range of rectangular plate arrangements simulating wheels. The nature of soil deformations, failure patterns and load-sinkage relationships will be monitored and investigated under different dual and triple plates with varied spacings. The initial small-scale tests will allow a review of fundamental soil mechanics principles related to bearing capacity in order to identify major factors influencing soil strain and surface load support.

Soil will be prepared in two layers with a higher density in the bottom than in the top layer in all stages of this research, in order to be more equivalent to current field conditions than uniform homogenous soil.

Investigations will be followed by precise measurements of soil displacement limits under selected arrangements, which can optimise soil deformation and load support, using image analysis techniques in different soil conditions.

The most promising arrangements selected from the small-scale tests will be investigated in the soil bin using rigid rolling wheels as large-scale tests in order to provide a link between and confirmation of the results of small-scale tests.

Field tests will be then conducted to investigate the effect of varied spacings and therefore interaction behaviours between dual wheels in two different soil conditions.

A mathematical model will be developed based on bearing capacity theory in order to predict the vertical force under interacting multiple wheel arrangements. The model will be evaluated and compared with the experimental results.

Figure 1.1 provides a flow diagram of the work associated with this project.

It has to be mentioned that due to the nature of research undertaken at varied scales and under different conditions, the specific methodologies and techniques used will be described in the relevant chapters as well as under general methodology in chapter 3.

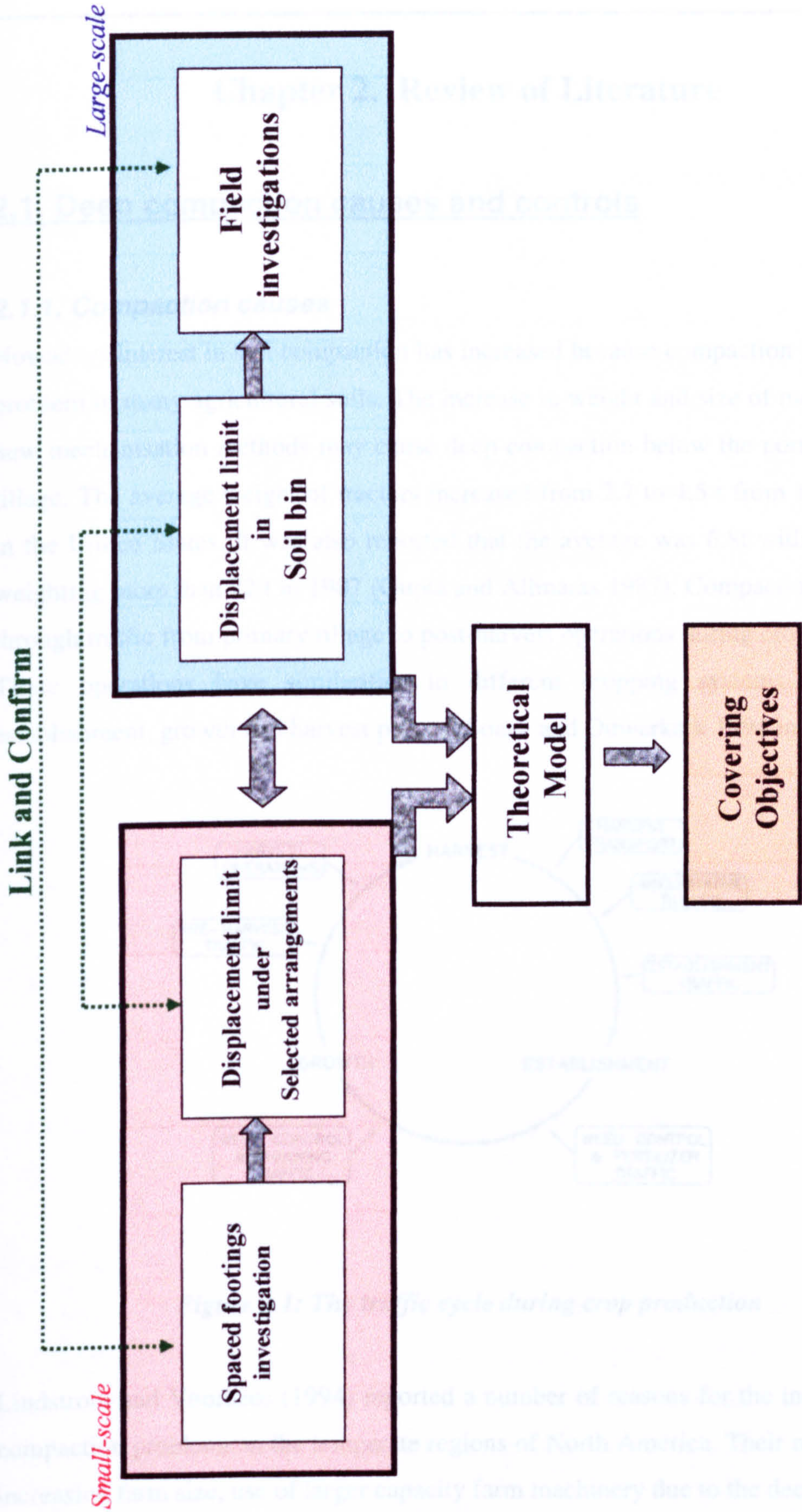


Figure 1.1. Flow diagram of the outline methodology

Chapter 2. Review of Literature

2.1. Deep compaction causes and controls

2.1.1. Compaction causes

Nowadays interest in soil compaction has increased because compaction is a potential problem in many agricultural soils. The increase in weight and size of machinery and new mechanisation methods may cause deep compaction below the normal depth of tillage. The average weight of tractors increased from 2.7 to 4.5 t from 1948 to 1968 in the United States. It was also reported that the average was 6.8t with larger units weighting more than 22 t in 1987 (Gupta and Allmaras 1987). Compaction may occur through traffic from primary tillage to post-harvest operations during crop production. These operations have similarities in different cropping systems through the establishment, growth and harvest phases (Soane and Ouwerkerk 1994 in Figure 2.1).

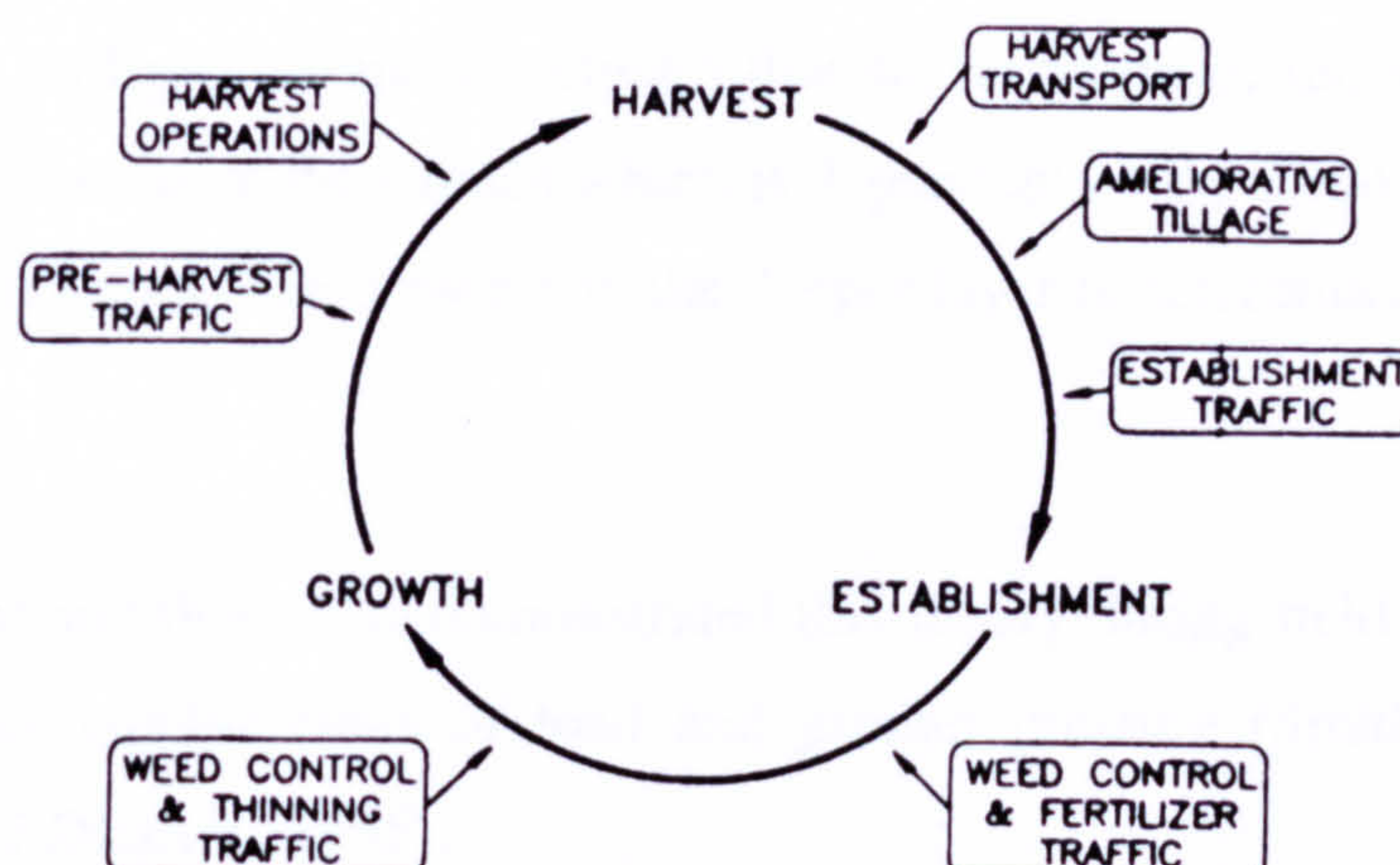


Figure 2.1: The traffic cycle during crop production

Lindstrom and Voorhees (1994) reported a number of reasons for the increasing soil compaction problems in the temperate regions of North America. Their reasons were: increasing farm size, use of larger capacity farm machinery due to the decreasing farm

population and change in cropping systems to a preponderance of row production resulting in more tillage activity and field traffic. A large combine harvester can have a loaded weight of 24 t or sugar beet trailers and grain carts can carry 20-30 t load on a single axle.

Arvidsson et al. (2000) reported that soil compaction effects soil strength and the movement of the water and gases and thereby most processes occurring in the soil. Subsoil compaction also can be persistent in the soil for a very long time and may be a threat to the long-term productivity of the soil.

Abu-Hamed et al. (2000) confirmed that the stress acting on the soil surface depended on a combination of several factors, such as static load, wheel shape and arrangements and soil conditions. The previous research showed that the total axle load is a much more significant factor in controlling deep compaction than the surface pressure.

Soehne (1958) investigated the effect of load and distribution of the loads on resulting pressure in the soil profile and concluded that the pressure in the shallow layer is determined by pressure at the surface which is dependent on the inflation pressure and the size of contact area. The pressure in the deeper layer is determined by the amount of load.

Smith and Dickson (1990) also demonstrated this theory during field experiments by applying various combinations of load and ground pressure (Smith and Dickson, 1984; Smith and Dickson, 1985).

Olsen (1994) noted three zones under the ground contact area. An upper zone where the vertical stress is nearly the same as the ground contact pressure, an intermediate zone where it decreases at a relatively high rate and depends on both ground contact pressure and wheel load, and a deep zone where the stress decreases very slowly with depth and depends almost exclusively on the wheel loads. He also mentioned that the

incidence of compaction in the topsoil is mainly determined by the ground contact pressure and in subsoil by the axle load.

Soane et al. (1980) concluded the most important factors and concerns for compaction were as follow:

1. Compaction under conventional pneumatic tyres is related to load, contact pressure, wheel slip, tyre dimensions, carcase construction, inflation pressure, forward speed and the number of passes. As vehicles become larger there is the need to reduce compaction by the adoption of new wheel design and operating conditions for pneumatic tyres.
2. To reduce the incidence of compaction, it would be desirable to reduce the average contact pressure of tyres in the field to below 200 kPa and ideally to below 100 kPa. However irrespective of the average contact pressure, vehicles with conventional wheel systems weighting more than about 120 kN are likely to cause appreciable compaction below the depth of normal cultivation.

Randall and Larry (1985) identified the wheel, as a primary cause of agricultural soil compaction. Based on the previous research, Cohron (1971) and Soane et al. (1980) listed three factors contributing to its effect as below:

1. The first wheel pass can result in up to 90% of the total compaction from multiple passes, depending on the initial strength of the soil (Raghavan et al. 1978; Taylor et al. 1982).
2. Traffic can compact soil below the depth of the conventional tillage (Raghavan et al. 1976), making mechanical alleviation of the problem economically and practically unrealistic in many cases. In assessing the state-of-the-art in soil compaction, Taylor and Gill (1984) identified the total axle load as the basic cause of deep compaction. The associated effect of tractive thrust can increase compaction 20% to 50% over the normal operating range by imposing shear stresses on the soil due to relative motion between the tyre and soil (Raghavan et al. 1977, 1978; Raghavan and Mckey 1977).

Soane and Ouwerkerk (1994) identified some options, which provide opportunity to reduce compaction problems. These options can be grouped into: (a) reduction of ground contact pressure, (b) reduction of axle load, (c) use of tracks, (d) use of zero-traffic systems. It seems however each will find application in different specific conditions.

Other factors that could help reduce the compaction capability of tyres are: 1) low inflation pressure, 2) low average ground pressure on a rigid surface, 3) small amount of loads, 4) low tyre stiffness, 5) radial tyres, 6) low wheel slip and 7) low lugs. Among these factors, inflation pressure and average ground contact pressure are the most important (Tijink 1994).

Chancellor (1977) noted that wheel ruts with low depth-to-width ratios tend to be associated with soil compaction near the surface and those with high depth-to-width ratios cause compaction at a comparatively greater depth. Reducing the ground contact pressure or increasing the intercasings contact area as solutions can be achieved by using wider section tyres or additional wheels and axles.

Janzen (1990) suggested that decreasing the ground pressure through the use of dual or high-flotation tyres can reduce compaction. But increasing the tyre size does not always improve its performance. For a given load, an increase either in diameter or in width of tyres, results in compressive stresses extending to deeper soil layers than for smaller tyres (Cooper and Reaves 1985; Soane et al, 1981).

Soane et al. (1980) reported that average contact pressure can be decreased by reducing load, increasing section width or decreasing inflation pressure and that the most effective way of reducing contact pressure was to combine all these effects. It was also pointed out that at a given level of contact pressure, stress within the soil will extend considerably deeper for the wide tyre carrying a high load than for the narrow tyre with a lower load. However increasing the width can not be advantageous without other accompanying factors. A commonly used relationship is that the zone of

maximum compaction occurs at a depth below the wheel rut equal to half the tyre width. Although there is evidence that such zones may occur after compaction of weak soils while not with stronger soils.

Trein (1995) measured the strain under different wheel arrangements and load applications to identify a system which causes least compaction. He concluded that tyres in tandem reduce the total sum of volumetric strains when compared with a single tyre. The intensity of volumetric strains produced were ranked as: a) highest with tyre combination of wide followed by narrow, b) intermediate with tyre combination of narrow-narrow, c) lowest with tyre combination narrow-wide.

Taylor and Gill (1984) tested two different tyre sizes, a standard agricultural tyre and a flotation tyre (wide section) carrying equal loads. Soil was prepared in two different ways, firstly with a uniform density profile and secondly with a simulated traffic pan with higher density at a depth of 0.3 m. The results showed a 22% increase of contact surface, hence reduced soil pressure under flotation tyre. But total axle load was the dominant factor in terms of soil pressure in the 0.18-0.5 m depth range.

Axle load has therefore been identified as a major cause of deep soil compaction. It was indicated that most of the compaction occurred to a depth of 0.3 m, at an axle load of 4 t, 0.4 m at 6 t and 0.5 m at 10 t. Still higher axle loads or very heavy tracked vehicles have caused compaction to 1 m depth. If deep ruts are formed in the soil, even lighter vehicle may cause subsoil compaction and the plough layer usually provides less protection (Hakansson and Petelkau 1994).

Alakukku (1996) investigated three treatments, one pass with heavy axle vehicle and with wheel tracks both completely covering the plot area, four repeated passes and a control without traffic. It was concluded that one and four passes with the high axle load compacted soils to a depth of 0.4-0.5 m. It was also found in the long term, that despite cropping and natural processes, changes in subsoil properties due to heavy loading were still measurable 9 years later. Moreover subsoil compaction had long

term effects on many important physical properties affecting soil workability, drainage and crop growth.

Many researchers noted that field traffic with an axle load greater than 9 t can compact soil to 0.5 m (Gameda et al. 1984; Blackwell et al. 1986; Voorhees et al. 1986; Lowery and Schuler 1991; Danfors 1994). Soil compaction under wheel traffic from normal farm operations can extend to 0.45 m (Voorhees et al. 1978) and under traffic by heavy machinery, to depths of 0.6 m (Eriksson 1982; Hakansson 1982).

Gameda et al. (1987) investigated subsoil compaction applying 10 and 20 t axle loads at 2 soil moisture contents in a clay soil. They concluded that soil moisture content during compaction significantly affected soil bulk density distributions under high axle load. In dry soil conditions, only the 20 t load significantly increased bulk density whilst in wet conditions both the 10 and 20 t axle loads had a significant effect on bulk density. Also fall tillage and overwintering removed the effect that soil loading had on topsoil under dry condition, but they were not as effective in reducing topsoil density under wet conditions.

Soil water content is another important factor to avoid deep compaction. Subsoiling on plastic soils below the critical depth may increase deep compaction locally rather than create loosening (Spoor and Godwin 1978).

Peters et al. (1982) concluded that subsoil with strong structure and structural porosity may not be affected by normal field operations but the porosity can be significantly reduced during the compaction process under wet conditions. It means, even when the soil moisture content on the surface is at an optimum for field operations, the subsoil can be at a moisture content where maximum compaction will occur.

2.1.2. *Compaction alleviation*

Taylor and Gill (1984) explained in their state-of-the-art research on management practices to control compaction, the following.

- Subsoiling was tried many years ago by farmers to relieve the problem of compaction. They realised it can be useful in some years but worthless in other years in the same fields. In that time the role of wheel traffic was poorly understood, as was the action of many tillage tools.
- Many researchers have suggested fewer trips over the field with wheeled vehicles for reducing soil compaction. Research showed almost a linear relationship between bulk density and the number of passes up to 10 passes (Raghavan et al. 1976). On the other hand, others have found that the first pass of a tyre is the critical one for a tilled soil. An investigation on three tilled soils and two dynamic loads indicated that 75% of the bulk density change and almost 90% of the sinkage measured during four passes of a tyre occurred on the first pass (Taylor et al. 1982). Therefore these results are not encouraging for those practicing fewer trips over the field.
- Some researchers have shown that using low ground pressure flotation tyres to support heavily loaded vehicles can be a solution.
- Using different tyre arrangements, shapes and sizes were also solutions to reduce soil compaction. Wide frame vehicles, spanning equipment and automated supported systems have been tried and tested in many countries.
- In addition natural behaviour due to freezing and thawing or weather and climate changes have been conducted to identify the causes of soil compaction.

Hakansson et al. (1987) reported that normal tillage operations cannot loosen the subsoil compaction and it should usually be alleviated by natural process such as freezing/ thawing, drying/wetting and biological activities.

Recent experience indicated that the efficiency of freezing in alleviating subsoil compaction was previously over-estimated (Hakansson and Petelkau 1994).

Farmers use deep tillage implements such as subsoilers to alleviate compaction. Although it is an expensive operation, it is not always effective or a long lasting solution. Moreover they do not know how deep to use these implements and how to manage the critical parameters of tractor and implement to operate more effectively (Adam and Erbach 1995).

There have been some attempts and suggestions for applying subsoilers to achieve the maximum benefits.

Lindstrom and Voorhees (1994) suggested that subsoiling can be an option but is a high-energy operation and improvements obtained have been inconsistent due to insufficient depth or recompaction of loosened soil or an actual deterioration of some soil properties by the operation.

For effective subsoiling soil must be relatively dry to allow shattering between the shanks. Moreover subsoiling is most effective when applied to air-dry soil, as the water content increases, the effectiveness of the subsoiling decreases (Larson et al. 1994).

Velykis (2000) concluded that the effect of subsoiling depends on the method of loosening and on the species of crop grown. A higher amount of productive moisture accumulated in soil loosened deeply, especially in the subsoil but subsoil bulk density decreased only when deep rooting crops were grown after subsoiling.

Johnson et al. (1989) showed improved soil physical properties by subsoiling in the fall below the normal ploughing depth when the soil was relatively dry. The benefits of this operation lasted for only one year, despite efforts to control post-subsoiling traffic. Also wheel traffic of normal tillage operations in spring recompacted soil loosened by subsoiling.

Hakansson and Petelkau (1994) summarised the main subsoil loosening points from their experience as: (a) it is better to avoid over-compaction of the subsoil by protecting it against mechanical overloading than to loosen it periodically, (b) loosening should not be undertaken without diagnostic evidence of detrimental compaction, (c) after loosening, the subsoil must be protected against mechanical overloading until the structure has stabilised.

Kooristra and Boersma (1994) noted that not only is deep loosening expensive, it can seldom ameliorate the compacted structure completely, but also the loosened soil is often recompacted within a couple of years with even worse physical properties.

Horn and Rostek (2000) noted that changes in physical soil properties due to wheeling underline the fact that parameters such as bulk density are not useful to predict subsoil compaction effects. This requires determination of pore continuity e.g. by air permeability measurements. It was concluded that subsoil compaction has to be considered as an irreversible process which neither freezing and thawing, wetting and drying nor biological processes can change back to the original site conditions.

Subsoil compaction often persists for a long time. In soil with clay content of 6-85 g per 100 g, the subsoil compaction is measurable 3-11 years after heavy loading (Voorhees et al. 1986; Gameda et al. 1987; Logsdon et al. 1992; Etana and Hakansson 1994).

Although topsoil compaction can be relatively alleviated through the tillage operation, subsoil compaction is not as easily corrected and is long lasting or may even be permanent (Hakansson et al. 1987). Since the effects of subsoil compaction are very persistent, the most straightforward solution is that it should be totally avoided. Van der Akker (1994) proposed that soil stresses should not exceed the strength of the subsoil.

Based on the literature it can be concluded that the available information from previous research and experience demonstrates a complicated compaction process involving machine, soil, crop and climate interaction. Some soil/machine relationships, were identified as major concerns to avoid or control undesirable soil compaction. The axle load was noted as a crucial factor influencing the depth of soil compaction, and wheel arrangement concerned with size and shape of the contact area was identified as a possible solution. However the researchers revealed that the most effective way is to avoid subsoil compaction occurring rather than alleviate it. This research aims to identify the most promising wheel arrangements to support more of the load in the surface layers in order to avoid deep soil compaction.

2.2. Soil displacement measurement and monitoring

There has been much effort and development to measure the stress under tyres in different conditions. In contrast, few attempts have been made to measure soil strain or displacement mainly because of the time-consuming procedure and complicated movement in the soil profile. There is still a lack of techniques to measure strain in-situ precisely.

In earlier research an X-ray method was used by Roscoe et al. (1963) to determine the displacement of lead markers in soil. The X-ray source was placed in front of the soil with a sensitive film behind. The lead markers, originally placed in a grid pattern, produced shadows on the film when displaced by a load from a wheel passing above.

Gill (1968) used another method in a glass sided tank by arranging small beads in the soil in a regular pattern using a template. The bead positions were marked with a coloured pen on a plastic transparent sheet. After applying treatments, the new bead positions were marked with a different colour on the sheet. Soil displacement could be calculated by measuring the distance between the original and displaced marks.

Adam (1985) used different markers to determine the soil flow and movement around the plough. String, chalk grids and beads were all used as markers and positioned in the soil. It was found that coloured 6 mm diameter beads offered the best method of recording the soil disturbance.

Randall and Larry (1985) used a cross-sectional soil profile grid pattern to characterise soil deformation. Modular sections of the bin were laterally removed to expose the cross-section after passes of a pneumatic tyre. The measured displacements of the grid points were converted to values of volumetric strain.

Wood and Wells (1985) measured soil deformation by using a modular bin, which could be filled or emptied. Five parallel lines of marble dust were placed 15 cm apart at the interface of each layer (15 cm thick). This appears as a grid 15*15 cm when digging a plane across the travel direction. The grid positions were identified after the test and compared with the initial positions from the other layer, which were assumed to be unaffected during the experiment.

Seig (1985) improved a technique used by Spoor and Fry (1983) and arranged plastic beads in a grid pattern, in different soil layers. A tank was used and three linear displacement transducers were mounted on a frame to measure bead position before and after the treatments. The pointer of an extension probe, linked to the linear transducers, was placed on the top of each bead so that X, Y and Z co-ordinates could be measured. The electric voltage output of all three transducers was transferred into a scanning data-logger and then on to paper tape. The voltage was converted into distances using a computer.

Weise (1990) introduced water marked technique to measure soil displacement. A spray bar was used for producing water marks on each soil layer. Soil profile then exposed and brushed showing the water points in the profile as small humps. These marked with pinheads to make them more detectable for soil displacement analysis.

Van der Akker and Stuiver. (1989) developed a photographed point grid to visualise and measure deformation and subsoil compaction. A pit 1.0 m deep by 1.2 m wide by 1.5 m long was dug in the field to place the points in the soil. A cross-section wall was exposed and smoothed, and plastic pins were inserted in the soil on a grid pattern of 50*50 mm. and photographed. The wall after wheel passes was re-photographed. The strain was calculated by comparing the co-ordinates of each pin before and after the treatment using a computer program. This procedure was very time-consuming.

Trein (1995) used a similar technique to markers for calculating the strain under different wheel arrangements. He prepared soil in 50 mm thick layers and added painted lines to each layer. The paint was placed in the slots made by a ridged roller and absorbed by the soil. Images were recorded before and after treatments and transferred to a computer. Strain was determined by calculating the difference between the original and final positions. Special software called Global Lab Image was used and a computer program developed during the analysis.

Erbach et al. (1991) introduced a soil strain gauge for measuring soil compaction under tyres. The deformation could be measured at several positions in the soil profile. The strain gauges were placed in the soil by an insertion tool with a helical endplate. Soil movement and the resulting strain were recorded and the elastic and plastic components of strain determined.

Strain gauges are widely used by the other researchers for measuring soil displacement and resulting compaction (Kinney et al. 1992; Way et al. 2000).

Also Wiermann et al. (1999) used a displacement transducer system developed by Kuhner (1997) to measure soil movement beneath a tyre. Total vertical strain, calculated as the engineering strain in the vertical direction, was determined.

Rohlf et al. (1994) used markers and a finite element method to identify the movements. A video imaging of markers that had been placed at known positions in

the soil profile before wheel loading was made. A finite element soil compaction model over-predicted vertical displacement directly beneath the centreline of the loaded wheel.

Many researchers also used different photographic techniques to identify and visualise the soil movement under treatments, these are explained below.

Hettiaratchi and Reece (1975) developed a technique to investigate the formation of boundary wedges in a glass-sided tank. They introduced two basic operation modes to visualise the blurred field. In mode “A” the camera was fixed to the translating interface and in mode “B” the camera was fixed to the soil tank, while the interface was translating. Although either mode can be used to trace both boundary wedges and rupture surface shapes, Mode “A” is particularly suitable for picking out, in sharp focus, the boundary zones in an overall blurred field.

Olson and Weber (1965) used a Wollensok WF17 movie camera that was equipped with two lenses. One lens was focused on a 0.38 m wide test section of the soil and a nonframing lens was directed toward an oscilloscope. The image obtained was projected on to a 0.9*1.2 m ground glass screen. Pencil tracing of the deformed grid coil could then be made by fastening tracing paper to the reverse of the glass.

Answell (1986) quantified soil flow and deformation under simulated furrow press wheels using spots of chalk. The chalk marks were placed against the glass at 20 mm intervals and each run was recorded by a video. The video recordings were played back on to a screen on which there was a grid of squares. The position of each spot initially was noted. The procedure was repeated for new positions and a picture was built up showing how the 20*20 mm squares moved.

Stafford (1987) used a cine camera mounted on a carriage to view the area of soil around experimental implements. He suggested use of a wide-angle lens and 8 kW photo-floods for illumination.

Godwin (1976) used long exposure photographs to show the lateral soil failure patterns of a tine using a glass-tank. The soil movement also was recorded using a video camera.

Wong and Reece (1966) reported that the exposure time for the photograph must be sufficient to give adequately long streaks. It was found that for a towed wheel, the sand in the background failing zone moves quite slowly and an exposure time of 0.5 s was required. For the driven wheels 0.2 s was sufficient.

Witney (1968) suggested that a shutter speed of 2 s was required at a penetration speed of 133 mm/min of a footing.

2.3. Influence of implement interaction

2.3.1. Tools and plates interaction

Previous research has indicated changes to soil deformation patterns and forces through interactions between implements or tools. It was considered that there was a significant difference in terms of energy requirement and soil disturbance by placing tools close to each other rather than operating as single tools. When two tools are placed close at an appropriate separation, the interference of one can overlap in the boundary of the other. It was found that this phenomenon of interaction can be used to increase the efficiency of a tillage system.

Rathje (1932) was one of the earliest researchers who used two 15 mm wide tines operated at different distances apart and towed simultaneously through sand. It was observed that a common soil compression wedge was formed when tines were working close together, similar to that in front of a single tine with equal total width. As the two tines were gradually moved apart, the draught resistance increased simultaneously for a given depth. On increasing tine spacing the compression wedge started to flow between the tines and the draught force increased. At this spacing the draught was only 10% higher than for a single tine working at the same depth. As the

tines were moved further apart the draught increased further and reached a maximum constant value. At this spacing both tines were acting independently without interaction. It was concluded that the draught was depended on the ratio of distance between the tines (L) to the working depth (D).

Zelenin (1950) investigated the influence of interaction tools, using two vertical tines each 7 mm wide in four different soils at various working depths and interacting positions. He observed four different situations in different soil conditions as follows:

1. Complete interaction took place for tine separations ranging from 20-30 mm. There was no soil movement and flow between the tines and the draught increased with increasing spacing.
2. When the tines were placed at spacings 50-100 mm the draught increased rapidly but the draught was found to be only 15-20% higher than that of the two tines working together at zero spacing. There was soil movement and flow between the tools in this phase.
3. With the tines spaced between 100-300 mm, the soil was not completely disturbed and two-upheaval areas were identified. The draught was found to increase gradually. When the tines were placed at spacings > 300 -400 mm, there was no interaction between them. The draught remained constant and was found to be twice that of the value of a single tine working at the same depth.

Zelenin also introduced a tool interaction by using teeth on a drag line scoop. It was found that teeth could reduce the draught by 22-25 %. He concluded that a minimum draught can be achieved at a spacing/tooth width ratio of approximately 2.5.

Ferguson (1970) measured the draught of several combinations of 203 mm wide scarifier shares on a dry sandy loam uncultivated soil at 100 mm working depth. The draught was decreased when the share was preceded by a disc coulter working immediately ahead at a depth of 75 mm. It was found that the tine interaction effect on draught ceased when the front shares were spaced 0.97 m apart.

Ghisholm et al. (1970) noted that the interaction between two or more tillage tools might affect the amount of energy required to till the soil to a given condition.

Two flat plates 19 mm thick were investigated in a loose cohesive soil in a soil bin. The results indicated that interference between the plates can have a large effect on force. Interaction between the tools could increase or decrease the draught force on one tool by over 25 % depending on the interaction tool position (Soomro 1977).

Harvey (1975) compared blade and tine shares in terms of draught and soil disturbance in a soil bin. It was indicated that tine interaction in multiple tine arrangements can reduce draught below that of a blade share with increased soil disturbance.

Spoor (1975) identified two failure zones with deep working tines. First above the critical depth where soil moves upward and second below the critical depth where it moves sideways. He indicated that by placing shallower working tines ahead of the deep tine the depth over which upward movement occurred could be increased.

Spoor (1976) compared the draught and soil disturbance caused by conventional and winged subsoiler tines with and without shallow tines working ahead in the field. It was indicated that shallow tines working ahead of the subsoiler increased the overall soil disturbance without increasing the draught. Also there were benefits from using wings on the subsoiler foot in terms of soil disturbance.

Godwin (1976) also reported that using wings on a subsoiler foot or shallow tines ahead of the subsoiler or both can produce better soil shattering. It was concluded that the effect of shallow tines causes a significant increase in disturbed soil without increasing total draught.

Brinco (1978) determined the effect of spacing deep tines and leading shallow tines on draught, soil disturbance and specific resistance. He claimed that the effect of

lateral interaction between two deep tines and two winged tines is determined by the depth of work and the spacing between the tines. It was concluded that the optimum effect of lateral interaction between two adjacent tines may be achieved where the crescent failure lines, intersect a few centimetres below the soil surface. He identified that the spacing between tines was a critical factor influencing the benefits.

Soomro (1977) and Godwin et al. (1984) reported some major effects on force, soil disturbance and specific resistance due to interaction. They indicated that shallow tines working at half the depth of deep tines are particularly efficient when spaced between 1.0 and 1.5 times the working depth of the deep tine. This increased the efficiency of disturbance 30-50% compared with single deep tines. The interaction between tines at the suggested separation left greater soil disturbance. Moreover combined interaction between the shallow and deep tines increase tillage efficiency further.

Answell (1986) reported that the interaction between furrow press feet both laterally and vertically caused changes in the mode of failure. He suggested that four distinct modes of failure between press feet occurred, these were identified as independent without interaction, interaction between the passive zones, passive flow around the active wedge and downward compressive failure.

2.3.2. Wheels interaction

There have also been many investigations on wheel or tyre interactions. It was indicated that some benefits in terms of carrying load, displacement and rolling resistance can be achieved through the interaction between the wheels.

McLeod et al. (1966) found less compaction occurred under low pressure and dual tyres compared with single tyres. Also it was reported that pressure from a conventional wheel-type tractor is greater than a tractor with dual rear wheels (Reaves and Cooper 1960; Brixius and Zoz 1976).

Kinney et al. (1992) identified soil strain under three tractor configurations, tractor with single rear wheel, dual rear wheel and steel track. Strain was measured using strain transducers installed at 100-150-200 and 300 mm depth. They concluded that the tractor with single-rear wheel produced more strain in the 100 to 440 mm soil layer than did equal-mass tractors with dual relationship rear wheels or with steel track.

Swanson (1973) investigated the effect of spacing on the performance of dual and tandem rigid wheels in sand. It was indicated that wheel spacing had a negligible effect on sinkage and resistance to motion for both dual and tandem towed wheels. Comparisons between single wheel and dual wheels confirmed for a given load two tyres are better than one but not twice as good.

Gee-Clough (1979) experimented with dual rigid wheels in sand at a range of spacings from zero to 3 wheel widths. It was noted that the coefficient of rolling resistance fell steadily as separation increased and at 3 wheel widths separation was 12% below that at zero separation. It was also mentioned that the wheels were not acting independently of each other even at 3 wheel width separation although in practice, the allowable separation will be less than this.

Rouch and Liljedahl (1967) tested driven 4*8 tyres in an artificial soils with varied slip values from 0 to 20 % and spacings up to 100 mm. They demonstrated that wheel sinkage and motion resistance of dual wheels decreased at close spacings because each wheel had a supporting effect on the other.

Mezler and Knight (1971) investigated 9*14 tyres at 20% slip in Yumma sand at a varied ratio of section width/spacing= 2-3.5. It was noted that dual tyres with zero spacing performed proportionately better than a single wheel with the same characteristics as each wheel of the dual wheel.

Two loaded wheels mounted close together (dual wheels) interact, and although they efficiently reduced topsoil compaction, they were less efficient in reducing subsoil compaction. However the more widely the wheels are spaced the less is the interaction. It was concluded that to avoid deep compaction in subsoil layers, heavy vehicles should have many wheels spaced widely apart (Hakansson and Petelkau 1994).

O'Sullivan et al. (1999) noted that using tandem axles on trailers caused less compaction in two types of soil but the differences were larger on the clay loam than on the sandy loam. They also concluded that subsoil compaction is likely to be greater with the single axle trailer.

It can be concluded that although there has been some research on wheel interaction, none of them investigated the soil movement pattern and different interaction behaviours under different wheel arrangements. Therefore there is still a lack of knowledge and information to identify the basic mechanics of failure under interacting treatments.

2.4. Bearing capacity and force prediction theories

This section discusses the soil mechanic theories on bearing capacity and failure pattern. Two major approaches, the first based upon shallow footings and second on wide blades were found to be most relevant to this research. These approaches also present models for predicting forces on a single footing as well as information on soil failure patterns.

2.4.1. Terzaghi Model

Terzaghi (1943) presented some definitions before developing his model. He called the area covered by the load the bearing area. The load required to produce failure of soil support was called the critical load or the total bearing capacity. The average

critical load per unit of area was called the bearing capacity of the soil. If the load acts on a very long strip footing of relatively narrow width, it was called a strip load in contrast to a load which acts on an area whose width is approximately equal to its length, such as a square, a rectangular or a circular area. The term shallow footing is applied to footings whose width is equal to or greater than the vertical distance between the surface of the ground and the base of the footing. The failure patterns under the plates used in this research are likely to follow the shallow footing definition. In this case, it is possible to neglect the shearing resistance of the soil located above the level of the base of the footing. In other words, it is possible to replace the surcharge term as $q = D_f \gamma$ (see Equation 2.1). Terzaghi divided the zone of plastic equilibrium ff_1e_1de (see Figure 2.2) into (1) a wedge-shaped zone located beneath the loaded strip, in which the major principal stresses are vertical, (11) two zones of radial shear, ade and bde_1 , emanating from the outer edges of the loaded strip, whose boundaries intersect the horizontal at an angle of $(45 + \phi/2)$ deg and $(45 - \phi/2)$ deg, zone (111) two passive Rankine zones. He also identified the failure zones under a strip for different situations (see b, c and d in Figure 2.2).

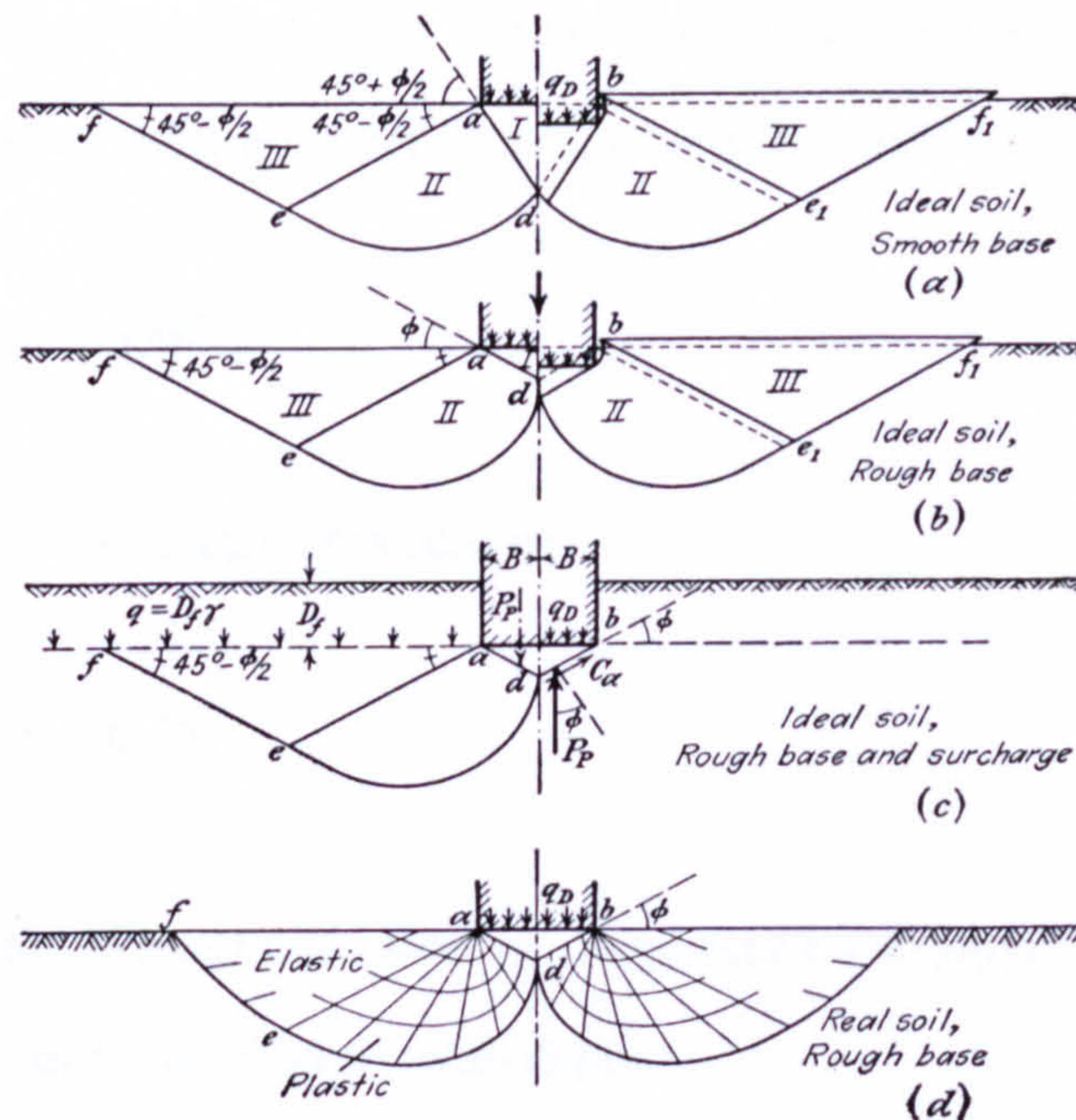


Figure 2.2: Bearing capacity and failure zones of a shallow footing in different situations

The results of his analysis using a logarithmic spiral technique was a general equation to predict force for bearing capacity under a shallow footing as below:

$$Q_D = 2B(cN_c + \gamma D_f N_q + \gamma B N_\gamma) \quad (2.1)$$

Where:

$2B$ = width of the strip (m)

γ = unit weight ($kN.m^{-3}$)

c = cohesion ($kN.m^{-2}$)

D_f = depth of sinkage (m)

N_c, N_q, N_γ = bearing capacity factors, depended on C and ϕ values

ϕ = angle of soil internal friction (deg)

Other researchers using this concepts and model, added some factors such as a footing shape factor to make it fit different situations.

Rosenak (1963) also reported work from Prandtl, that three zones are developed under shallow footings. Zone 1 is an active Rankine zone, zone 2 is a zone of radial shear and zone 3 is a passive Rankine zone. He concluded that the pressure q_f from the Terzaghi general equation for a square footing of size B would be:

$$q_f = 1.3cN_c + \gamma DN_q + 0.4\gamma BN_\gamma \quad (2.2)$$

and for circular footing of radius R would be:

$$q_f = 1.3cN_c + \gamma DN_q + 0.6\gamma RN_\gamma \quad (2.3)$$

He also from experience mentioned that N_c is greater for a square footing than for a long footing. It also increases slightly with depth.

Smith (1967 and 1981) derived the following equation for strip footings:

$$q = cN_c + \gamma Z(N_q - 1) + 0.5\gamma BN_\gamma \quad (2.4)$$

If Z is taken as 0 (footing at the surface) and ϕ is 0, $N_\gamma = 0$, $(N_q - 1) = 0$ and $N_c = 5.7$ then $q = 5.7c$. He suggested that for a rectangular footing width B , length L , friction at the ends of the footing must also be considered. The only variation will be to the bearing capacity coefficients N_c and N_γ which are multiplied by the following factors:

$$N_c \text{ (for rectangular footing)} = N_c \text{ (for strip footing)} \times \left(1 + \frac{0.2B}{L}\right)$$

$$N_\gamma \text{ (for rectangular footing)} = N_\gamma \text{ (for strip footing)} \times \left(1 - \frac{0.2B}{L}\right)$$

Coefficient N_q will be unchanged.

2.4.2. Meyerhof Model

The other common model using the same logarithmic spiral technique approach was developed by Meyerhof (1951). Scott (1963) has shown that this technique deviates only marginally from the more complex numerical solution of Sokolovski (1956).

Meyerhof has reported that the resultant force on a footing is relatively insensitive to the degree of mobilisation of shear stresses along the face af (see a in Figure 2.2). Therefore, shear stresses on this face are neglected. To meet this condition the angle $caf (\eta)$ must be $(45 - \phi/2)$ deg. In the case of a footing however, the angle $daf (\beta)$ between the face of the footing and the face (af) is a function of footing depth. Meyerhof found an equation to predict the resultant force under such a footing as :

$$Q = lw(cN'_c + qN'_q) \quad (2.5)$$

where: w = width of the footing (m)

l = length of the footing (m)

q = surcharge ($kN.m^{-2}$)

c = cohesion ($kN.m^{-2}$)

N'_c, N'_q = dimensionless factors

and for pressure:

$$q_f = cN'_c + qN'_q \quad (2.6)$$

The values of the factors N'_c, N'_q can be determined either from graphs (see Appendix 4, Figure A4-1) or expressions as follows (θ is the angle of dac in the Figure 2.2):

$$N'_c = C_o + \phi \left[\frac{(1 + \sin \phi) e^{2\theta \tan \phi}}{(1 - \sin \phi \sin(2\eta + \phi))} - 1 \right] \quad (2.7)$$

$$N'_q = \left[\frac{(1 + \sin \phi) e^{2\theta \tan \phi}}{(1 - \sin \phi \sin(2\eta + \phi))} \right] \quad (2.8)$$

In order to assess the value of approximate methods, he investigated a series of model experiments on square and rectangular footings on dry sand, at depths up to six times the footing width. It was concluded that the ultimate bearing capacity of a footing on the surface of dry sand agreed fairly well with the theoretical value for the failure condition and ultimate shear strength of soil.

2.4.3. Hettiaratchi Model

Hettiaratchi et al. (1966) developed a computer model with a minimising sub-routine to overcome the problem of lengthy trial solutions to determine the minimum passive force. This resulted in an expression known as the general soil mechanics equation:

$$P = \left[\gamma d N_\gamma + c d N_c + c_a d N_{ca} + q d N_q \right] w \quad (2.9)$$

where: P = passive force

d = depth(m)

γ = unit weight ($kN.m^{-3}$)

c = cohesion ($kN.m^{-2}$)

$c_a =$ adhesion ($kN.m^{-2}$)

$q =$ surcharge ($kN.m^{-2}$)

$w =$ width (m)

$N_\gamma, N_c, N_{ca}, N_q =$ dimensionless factors

The N factors can be obtained from a series of graphs and their values depend on the blade surface and soil condition (see Appendix 4). Hettiaratchi and Reece (1974) have shown that soil adhesion has only a very small effect on the passive force. They merged the adhesive term with that of cohesion, introducing the new dimensionless factor K.

Other researchers using the same concepts, developed models for wide tine (blade), narrow tines and very narrow tines, the particular model depended on the width/ depth ratio.

Payne (1956); O'Callaghan and Farrelly (1964); Hettiaratchi and Reece (1967) and Godwin and Spoor (1977) all used the theory successfully to describe the performance of narrow tines and very narrow tines. Osman (1964), Reece (1964), Siemens et al (1965) and McKyes (1985) described the performance of wide tines using the same approach.

The review of literature indicated that there is still need for further investigation and data on fundamental knowledge of failure patterns, bearing capacity, strain modification and interaction effects. Moreover it was revealed that avoiding deep compaction is the most straightforward solution, since subsoiling is not a easy and long lasting operation. This study therefore will take greater account of soil mechanic theories data on bearing capacity, failure mechanisms and soil displacement phenomenon under different wheel arrangements and soil conditions. It also aims that by modifying soil conditions locally under the tyres, it would be possible to increase load support in the surface to decrease soil displacement at depth.

Chapter 3. Methodology for preliminary soil tank tests

3.1. Introduction

Small-scale experiments were conducted in order to identify soil failure patterns, deformations and interactions under different treatments. This enabled the investigation of a wide range of simulated wheel arrangements under controlled conditions with reasonable accuracy and time-saving procedure. Plate/sinkage relationships were investigated at this preliminary stage to simulate different wheel arrangements. Hence a separate frame was built to place different plate sizes in a varied range of spacings both vertically and horizontally.

A glass-sided tank was designed and developed which allowed the recording of the static and dynamic images to identify and quantify the nature of soil movements.

A photographic technique was developed to obtain a clear image of the failure planes and strains occurring. The technique was improved following an initial evaluation and application of the different facilities during these initial tests.

Load and displacement transducers were calibrated and used to measure axial force and sinkage. A x-y plotter was also used to record load-sinkage relationships in order to identify the extent of interactions between the plates.

The small-scale tests in the glass tank provided data on failure mechanisms and plate interactions to identify the major factors influencing strain and load support under different arrangements.

3.2. Apparatus

3.2.1. Design and development of a glass- sided tank

A glass-sided tank was designed to enable the identification and development of soil failure patterns and movements under different plate arrangements. The dimensions of the tank were chosen to be 400mm wide by 600 mm deep and 1500 mm long in order to provide sufficient depth and length for a wide range of treatments. The calculations

for the major dimensions, forces and moments associated with the design are explained in the appendix 1. The built tank is shown in the Figure 3.1.

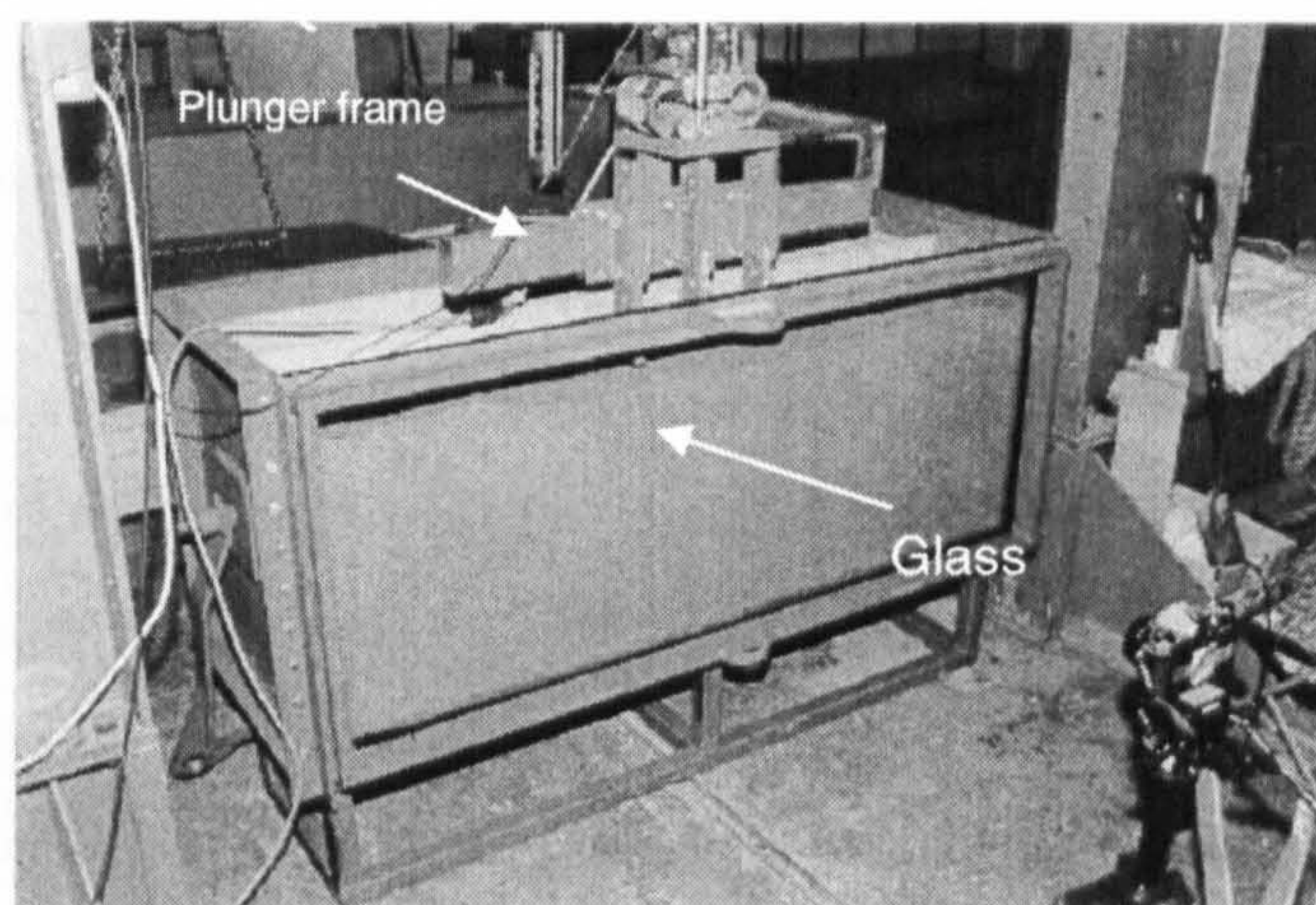


Figure 3.1. The Built tank with glass in front

3.2.2. Plunger frame

A frame was designed and built to hold the plungers for carrying the plates on one side and for attachment to a hydraulic ram on the other side. A long bar allowed the plungers to be located at a wide range of spacings. Each plunger had a bracket consisting of two metal plates and four bolts that provided free movement along the bar and varied horizontal spacing between the plungers as well as allowing vertical adjustment. Therefore for single, dual and triple plate tests one, two or three brackets could be used respectively. The plates were placed under the plungers and pushed into the soil to the appropriate depth (see Figure 3.1 and 3.4).

3.2.3. Rectangular plates

Plate sinkage test has played an important part in the study of soil behaviour under loading from vehicles (Soane et al., 1981). The plates were successfully used recently to assess soil compactibility under load (Earl, 1997).

There was no standard for choosing the plate size. Alexandrou and Earl (1995) used a circular plate with a diameter of 150 mm to investigate plate-sinkage relationships. They reported that plate dimensions had not been standardised and researchers have used many different shapes and sizes. Their choice was a compromise because a smaller size might not include many soil peds, and a larger size would require considerable force to impart sufficient stress to the soil.

There have been many attempts to derive fundamental sinkage parameters from plate-sinkage test for characterising soil behaviour under the wheel (Bekker 1969; Dwyer 1974). Bekker (1969) reported that there is a negligible difference between rectangular plates of high aspect ratio (length/width greater than 5 to 7) and circular plates to determine sinkage equation values.

Wills (1966) evaluated 7 different sizes of rectangular plate in different soil conditions. He used plates of 37.5, 50, 75, 100, 150, 200 and 250 mm width with aspect ratio of 6. He reported that it was impossible to determine the sinkage equation values with the sizes smaller than 50 mm.

Hegedus (1965) used 4 different sizes of rectangular plate with 25*112.5, 50*225, 75*337.5 and 100*450 mm sides as well as circular plates from 50 to 200 diameter. The objective was to use a small plate as a model to predict sinkage parameters for larger plates.

However the review of literature indicated that firstly, there has not been a plate dimension standardised and secondly most of the researchers, who suggested the minimum or aspect ratio of plates, were using the plates to determine sinkage equation parameter values such as K_c , K_ϕ , C or strength, traction and rolling resistance factors.

In this study 3 rectangular plates at different widths but same length were used to cover three wheel categories (see Figure 3.2). The rectangular plate allowed the failure planes against the glass on both plate edges to be seen.

- A) Very narrow, 40*150 mm
- B) Narrow, 70*150 mm
- C) Wide, 100*150 mm

Wooden model plates with different curvatures were also used to investigate the effect of curvature on the failure pattern and load-sinkage relationship. The plates were the same size as the wide category (100*150 mm) with different curvatures (simulating tyre with different inflation pressures) of 0, 5, 10, 20 and 27 mm. Figure 3.3 shows wooden model plates with different curvatures.

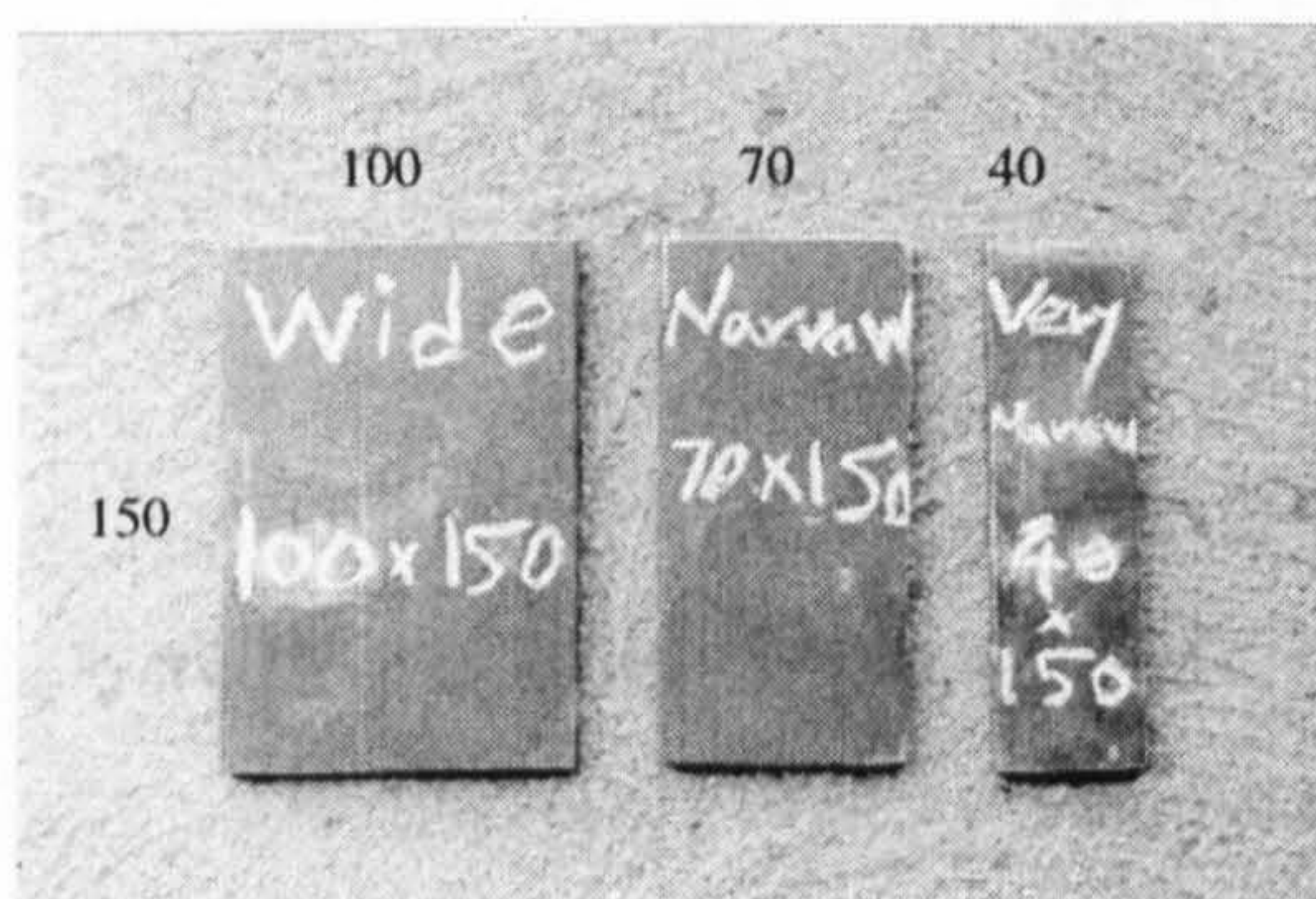


Figure 3.2. Different Rectangular Plate sizes

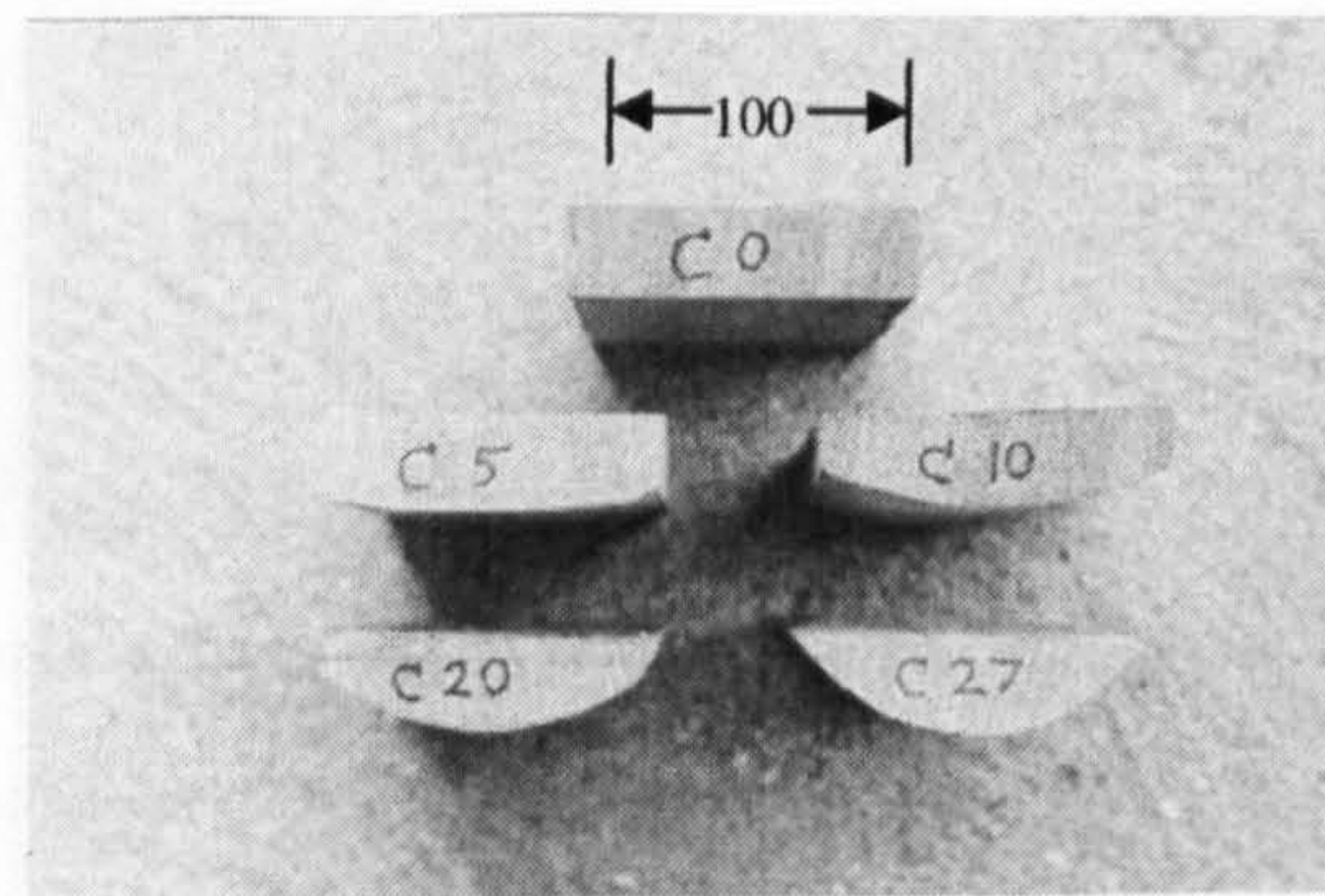


Figure 3.3. Wooden model with different curvatures

3.2.4. Hydraulic ram

A ram attached to a large anchor frame was used to push the plungers and plates into the soil. A hydraulic motor was used with two control valves enabling the ram to move downward and upward at selected speeds. The penetration velocity of the ram was adjustable by rotating the valves.

Graham (1987) used velocities ranging from 21 mm/s up to 810 mm/s and 50 to 370 mm/s respectively. The variability of the results was found not to be significant.

However lower velocities provided a better chance to record clear images and investigate the pattern of movement. Figure 3.7 shows the ram attached to the large anchor frame.

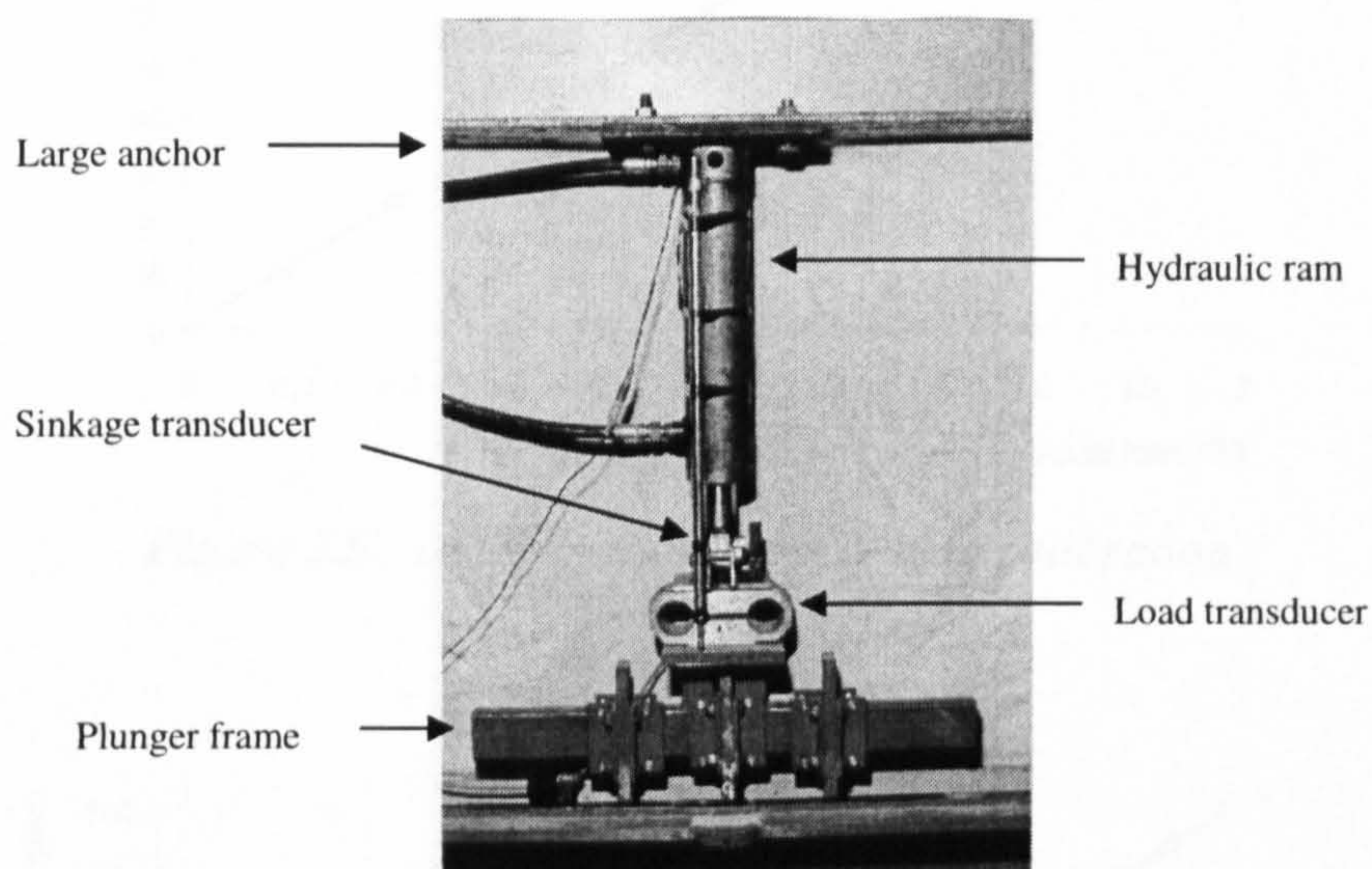


Figure 3.4. Hydraulic ram attached to the plunger frame and main frame at two ends

3.3. Instrumentation

3.3.1. Load

An octagonal ring transducer was used located between the ram and plunger frame to measure the vertical load (see Figure 3.4). The output of the transducer developed by Godwin (1975) was linear, being independent of the position of the load. The transducer has low hysteresis and cross sensitivity and meets the requirements of most tillage studies with two dimensional force systems. The transducer was calibrated by applying a series of weights. The result of calibration is given in Figure 3.5.

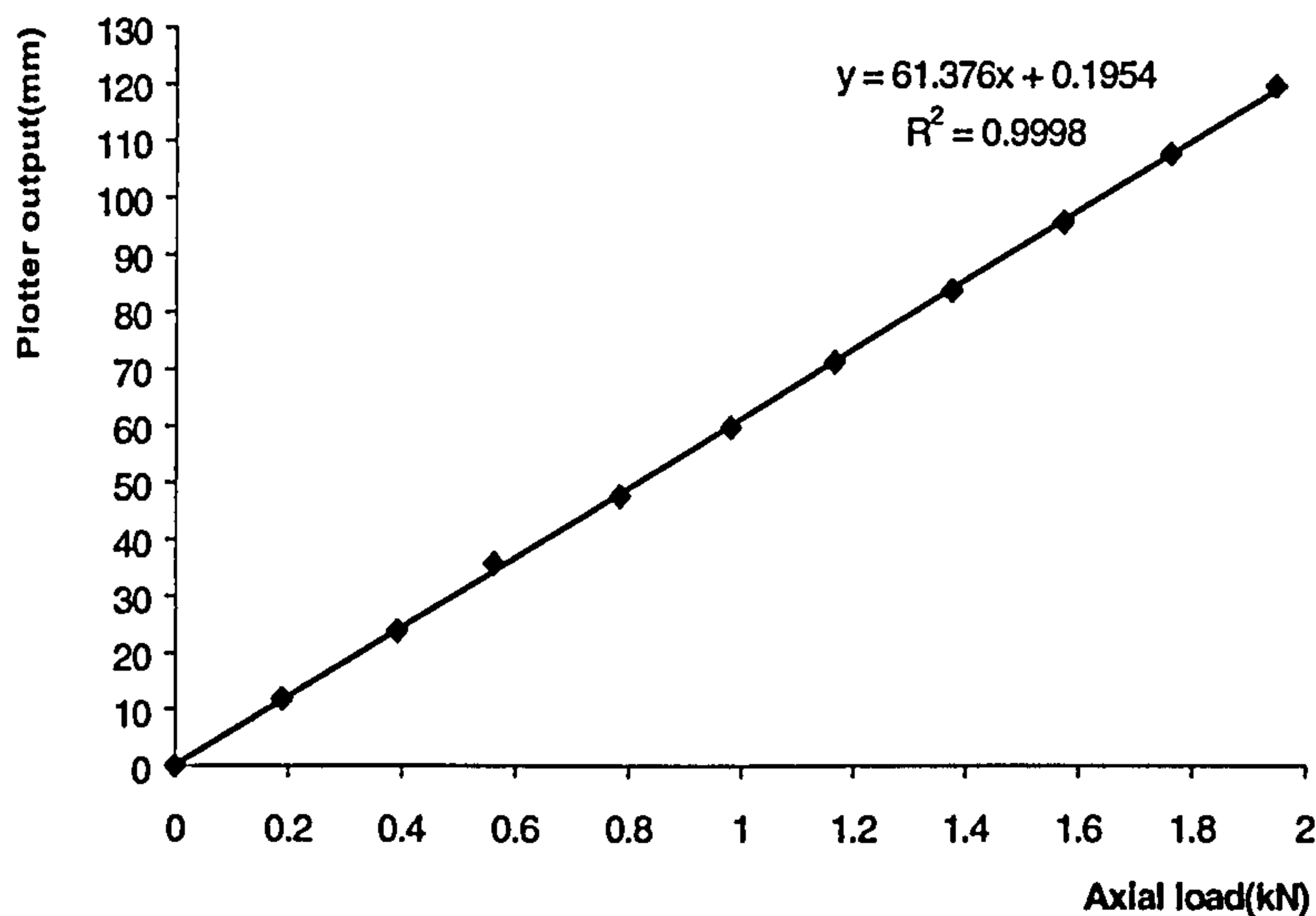


Figure 3.5. Octagonal transducer ring calibration

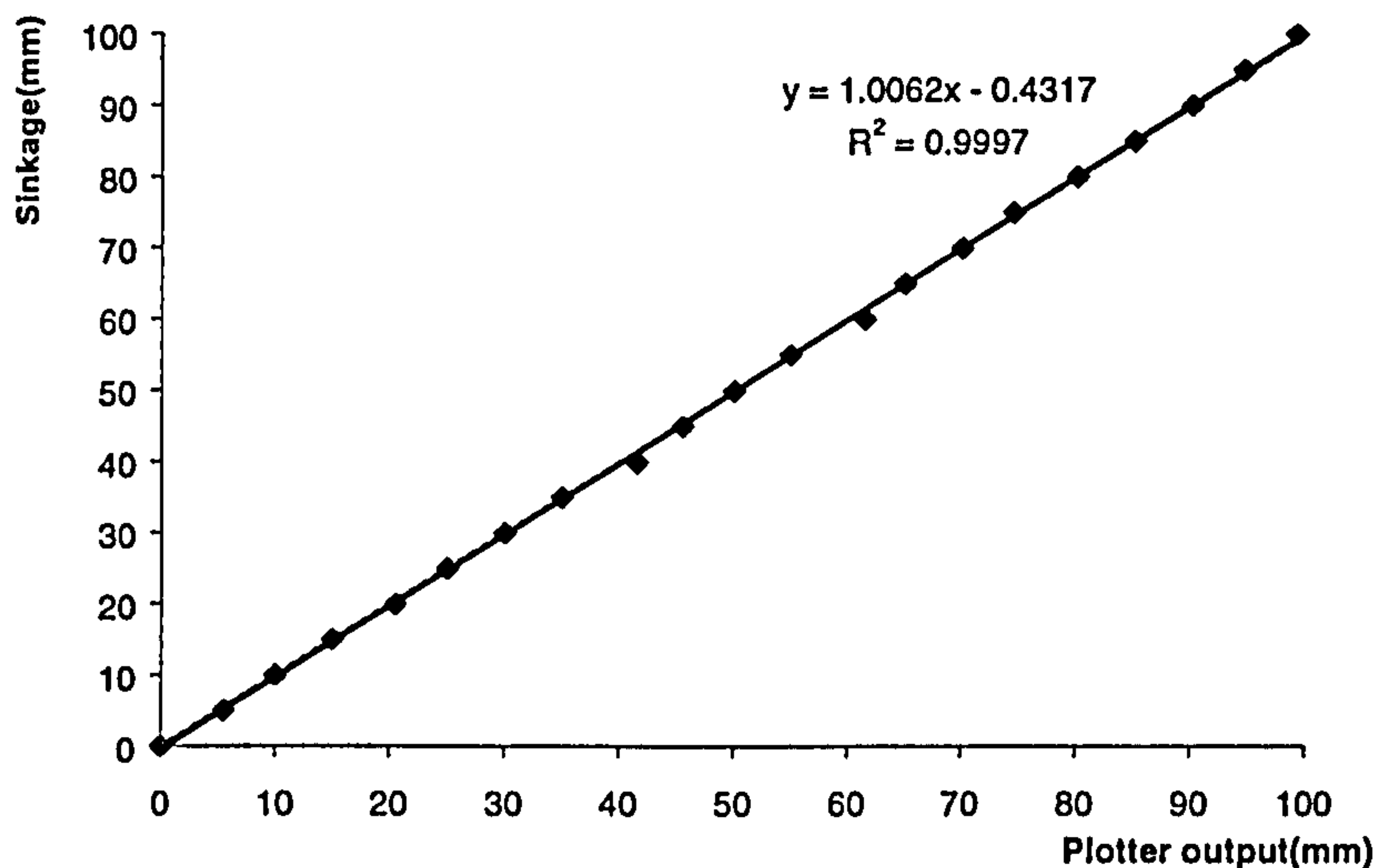


Figure 3.6. L.V.D.T. calibration

3.3.2. Displacement

The sinkage was measured by a Linear Variable Differential transducer or L.V.D.T. placed on the top of plunger frame (see Figure 3.4). The transducer was calibrated for a range of displacements before using. The result of calibration is given in Figure 3.6.

3.3.3. Load-sinkage relationship

A x-y plotter was used to plot the load-sinkage relationship. Both sinkage and load output from the transducers were connected to the x and y axes of the plotter respectively. Therefore the load-sinkage relationship could be monitored during the plate/sinkage tests under different plate arrangements. The sensitivity of plotter was chosen based on the size and number of plates used in each treatment.

3.4. Photographic technique

There have been some suggestions of techniques, facilities and type of illumination to be used in the photographic technique as explained in the literature review chapter (section 2.2).

The photographic facility was critical for identifying the soil particle movements and strain measurements. Some initial tests were therefore conducted to select the most appropriate technique. A still and a digital camera were used with ordinary light. Different exposure times of 1/10, 1/8, 1/6, 1/4, 1/3, 1/2, 2/3 and 1 sec. were checked to select the best speed. The results indicated that pictures taken by digital camera did not show the particle movements or the blurred field. This was a disadvantage since it would have been easy to transfer them to a computer for image or strain analysis. The quality of pictures taken by still camera were not as clear as the digital ones but it was possible to see the blurred field and particle movement by selecting appropriate shutter speeds. The best shutter speeds were found to be between 1/3 to 1 sec. The results also showed that the illumination of soil had to be through side lightening to avoid any effect of reflection.

Therefore a still camera can be used where the main objective is to reveal particle movement and the blurred field. The digital camera can be used where the main objective is transferring the picture to a computer for image and strain analysis. A video camcorder was also used to show continuous movements during the plate sinkage tests. Figure 3.7 shows the photographic facilities as used during the experiments.

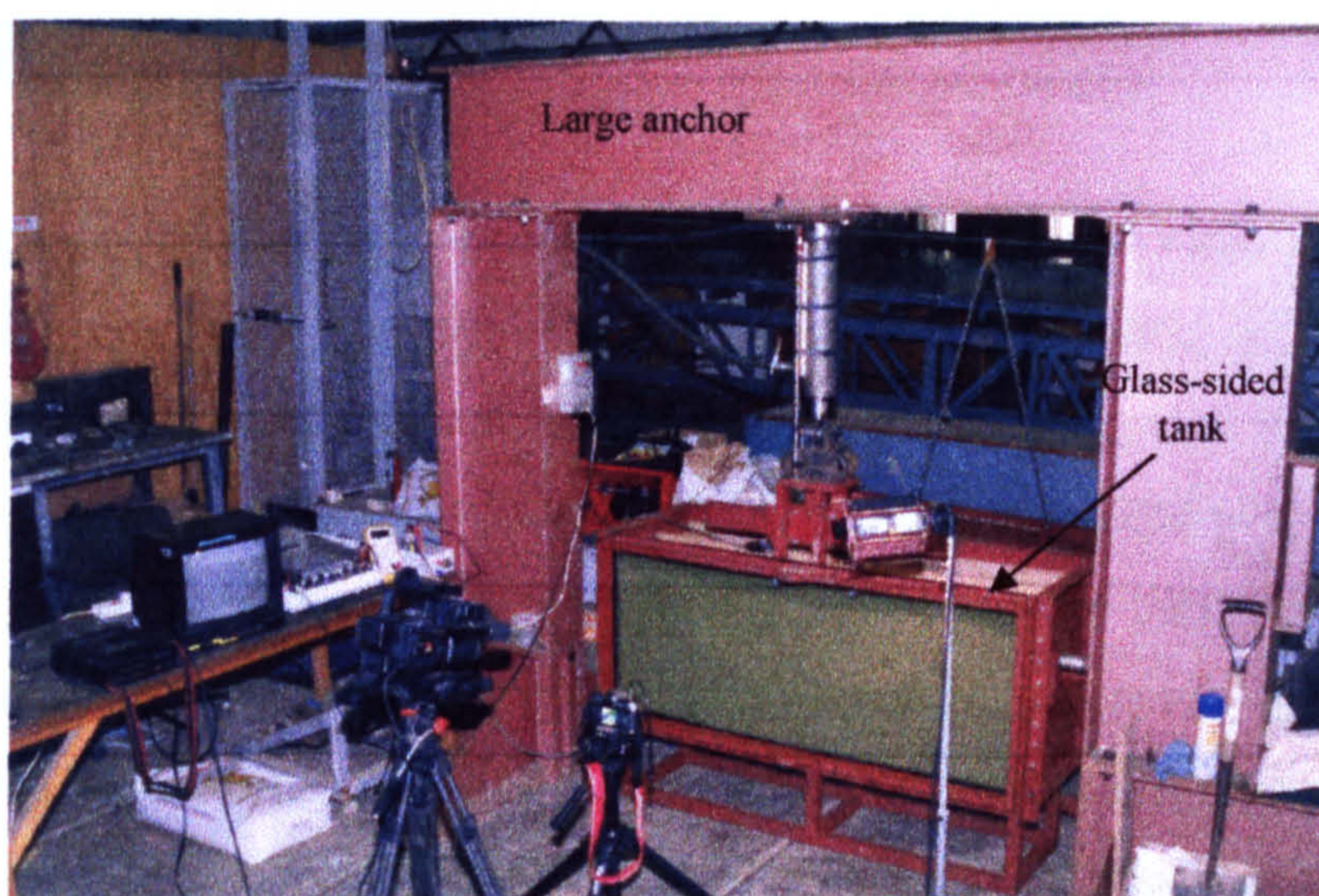


Figure 3.7. Photographic facilities in operation

3.5. Soil preparation

Soil was prepared to two different densities to simulate similar conditions in the field with a “traffic pan” of higher density at depth and a loosen layer above. The bottom layer of the tank was filled and compacted giving a 300 mm thickness. A 150 mm thickness loose layer was then placed on the top. The soil was re-prepared after each run to keep the condition the same for all treatments. The tank was filled to half capacity (half of width) to save time and avoid unnecessary soil processing.

From the literature review dry sandy soil was recommended for revealing the soil movement. Therefore in this research silica dried sand was used in the first stage, where the main objective was to reveal the failure mechanism movements under different plate arrangements. In the second stage a sandy loam soil was used to identify the maximum soil displacement limits by recording and transferring the digital image to a computer.

3.6. Summary

Plate-sinkage relationships are investigated in a glass-sided tank. In the first stage, different single, dual and triple arrangements will be tested at a wide range of horizontal and vertical spacings. This will allow identification of the failure patterns, interaction modes and the maximum affected depth under different treatments. Soil will be prepared in two layers with higher density in the bottom to simulate field conditions. A dry sandy soil will be used firstly to enable the nature of soil movements to be determined. A still camera with appropriate exposure time will be used as well as video recording to provide a picture of the soil blurred field and movements. The most promising arrangements selected from the first stage will be investigated in a sandy loam in the second stage of study. Soil marking method will be used to identify soil displacement limits at depth under promising treatment. Digital images will be recorded for further analysis using a computer. The results from these two stages could provide basic soil mechanics data and identify the major factors influencing strain and soil support to avoid deep compaction.

Chapter 4. Soil failure pattern and forces development under plates

4.1. Introduction

Plate–sinkage relationships are investigated under different plate arrangements in this chapter. A wide range of plate sizes and spacings were tested under the main categories of single, dual and triple configurations to identify soil failure patterns, interactions and displacements.

In the single tests, the soil behaviour and failure patterns were investigated for different plate widths and curvature patterns. Plates were arranged at a range of spacings in the dual tests to identify the beginning and the extent of the interaction between the failure planes. In the triple arrangements, the middle plate was placed in three different positions, firstly at the same level as the side plates, secondly higher and thirdly lower than the side plates. In each pattern, combinations with different vertical and horizontal spacings as well as plate sizes were investigated. These allowed comparisons of the failure patterns, interaction and force development under the varied configurations.

The results obtained from all single, dual and triple experiments, were analysed in two ways. Firstly the failure pattern was considered to identify the arrangements causing least displacement and secondly, the load-sinkage relationship was analysed to identify the promising arrangements for supporting greater loads. It was possible to estimate the approximate soil movement and displacement limits under different arrangements from the images taken during the tests. The main objective was to determine the arrangements most effective in both supporting greater loads on the surface and causing less strain at depth.

These experiments were followed by investigating failure pattern and force development changes induced by the stone content of soil. Simulated stones were placed in the soil in different patterns under a single plate, the results being compared with stone free soil.

The results of this chapter can provide more details on the bearing capacity phenomenon, failure patterns and force development to identify the major factors influencing load support at the surface and strain at depth.

4.2. Treatments

4.2.1. Single plate test

- a) Flat plates:* In this case all different plate sizes were investigated individually to identify active and passive failure zones formed under each size.
- B) Curved plates:* Wooden plates with different curvatures of 0, 5, 10, 20 and 27 mm were investigated to identify the effect of curvature on failure patterns. This aimed to simulate the tyre deflection behaviour with varied inflation pressures.

4.2.2. Dual plates test

A wide range of spacings between the plates in dual arrangements were investigated to determine the starting point and extent of interaction effects. The spacings were 600, 400, 300, 200 and 120 mm between the outer edges of the plates in order to identify the different modes of interaction. A similar procedure was followed for all three plate sizes (wide, narrow and very narrow).

4.2.3. Triple plates test

Triple arrangements were tested based on the soil movement patterns in the dual tests. The triple tests had the middle plate in three patterns:

- a) Pattern 1:* In this pattern, the side plates were placed at an appropriate separation to provide maximum interaction with a static zone forming in the middle. The third plate was placed in the middle at the same level as the side plates (see 1 in Figure 4.1).
- b) Pattern 2:* In this pattern, the side plates were placed at different separations to allow upward movement in the middle due to varied interaction modes. In this case the middle plate was placed higher than the side plates, being 35 and 20 mm

higher (see 2 in Figure 4.1). Different sizes of middle plate were applied to identify the most effective configurations.

- c) *Pattern 3*: In this pattern, the third plate was placed 35 mm lower than the side plates. This could investigate the possibility of the side plates providing surcharge on the upward movement of passive planes induced by the lower middle plate (see 3 in Figure 4.1).

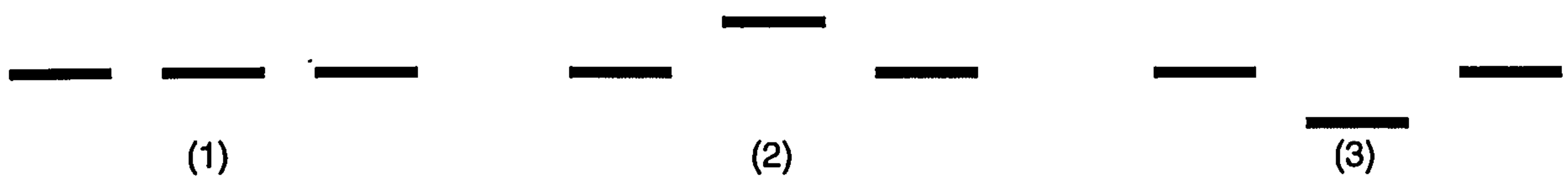


Figure 4.1. Triple tests, patterns 1, 2 and 3

4.3. Soil behaviour influenced by plate width and curvature

Soil behaviour was investigated in two ways, firstly failure patterns and secondly load-sinkage relationships under each plate size and curvature.

4.3.1. Flat plates

4.3.1.1. Failure pattern: The observed failure patterns for all sizes were the same as a bearing capacity failure under a shallow footing. An active soil wedge was formed directly under the plates with wedge zones of passive failure either side. The sketch of failures in Figure 4.2 shows that the size of active and passive zones depended on plate width. The wide plate had a greater effect on soil than the narrow and very narrow plates. Figure 4.3 indicates that there is a direct relationship between plate width and active zone. The active zone becomes greater with wider plates. Figure 4.4 also shows photographs of failure planes under narrow and wide plates.

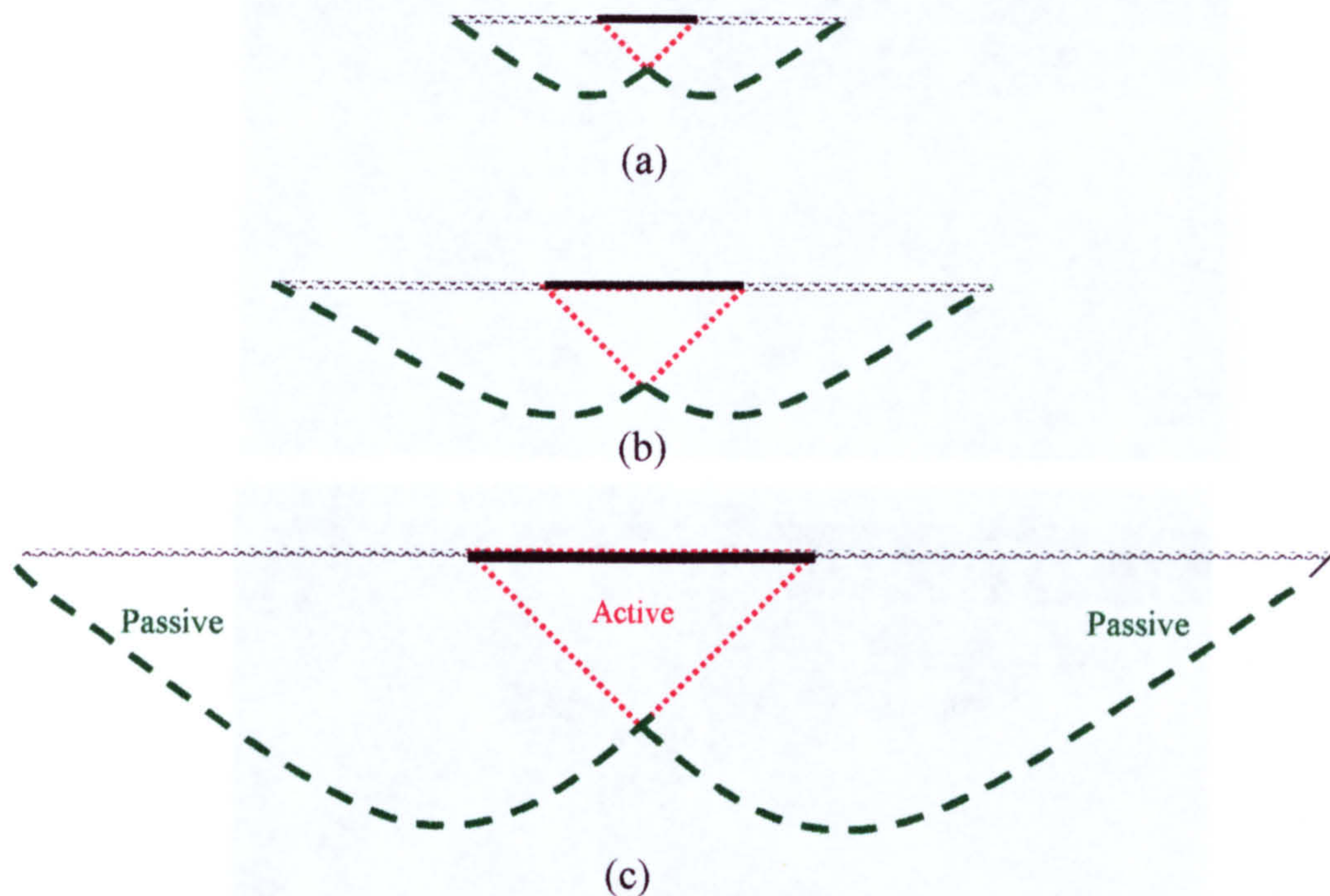


Figure 4.2. Active and passive zones under different plate width
 (a) Very narrow (b) Narrow (c) Wide

It is clear that the active wedge formed under the plates would cause vertical movements with maximum effect at depth, which is related to plate size (width).

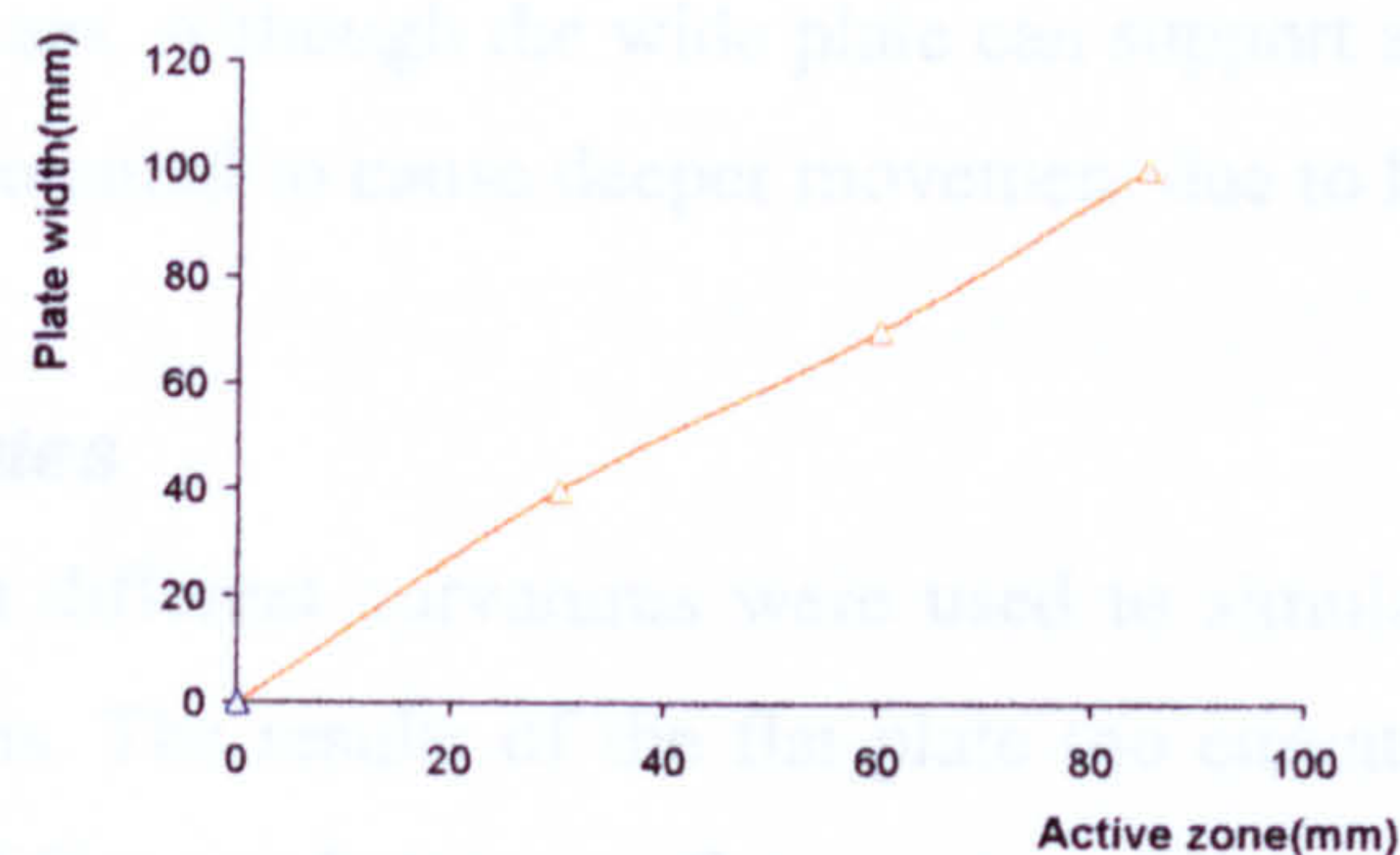


Figure 4.3. Relationship between plate width and active zone under the plate

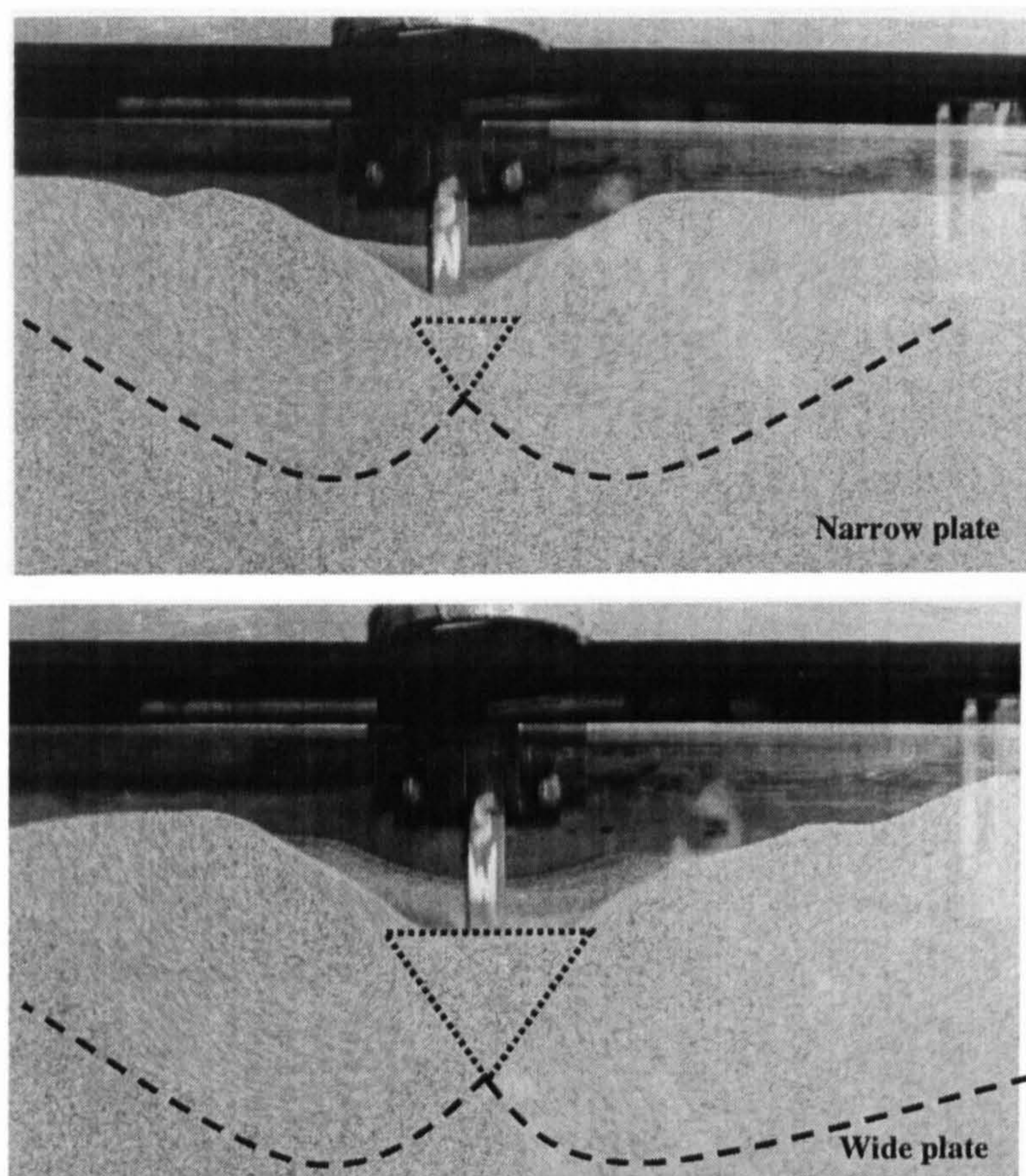


Figure 4.4. *The active and passive zones under two different plate sizes*

4.3.1.2. Load-sinkage relationship: A general shape of failure curve was identified for the load/sinkage relationship (see Figure 4.5). The results showed differences between the plate sizes. Although the wide plate can support a higher load for a given sinkage, it has the potential to cause deeper movement due to larger failure zones.

4.3.2. Curved plates

Curved plates with different curvatures were used to simulate varied tyre pressure and shape conditions. The results of the flat plate (no curvature) showed that, there was no significant difference between a flat wooden plate and a metal one in terms of both failure pattern and load-sinkage relationship (see C0 in Figure 4.6). The plate with 5 mm curvature (C5) acted very similarly to the flat one with a definite failure

point. As the curvature increased from 10 to 27 mm, the initial section of the load-sinkage relationship became more linear (see C10 and C27 in Figure 4.6). This change was due to a very small initial contact area, which initiated small active and passive zones giving considerable penetration for small loads. This contact area was representative of a high pressure tyre condition in contact with a surface. Moreover comparisons between the results of both flat and curved tests confirmed that in practice, tyres with low inflation pressure could support more load for a given sinkage than high pressure tyres.

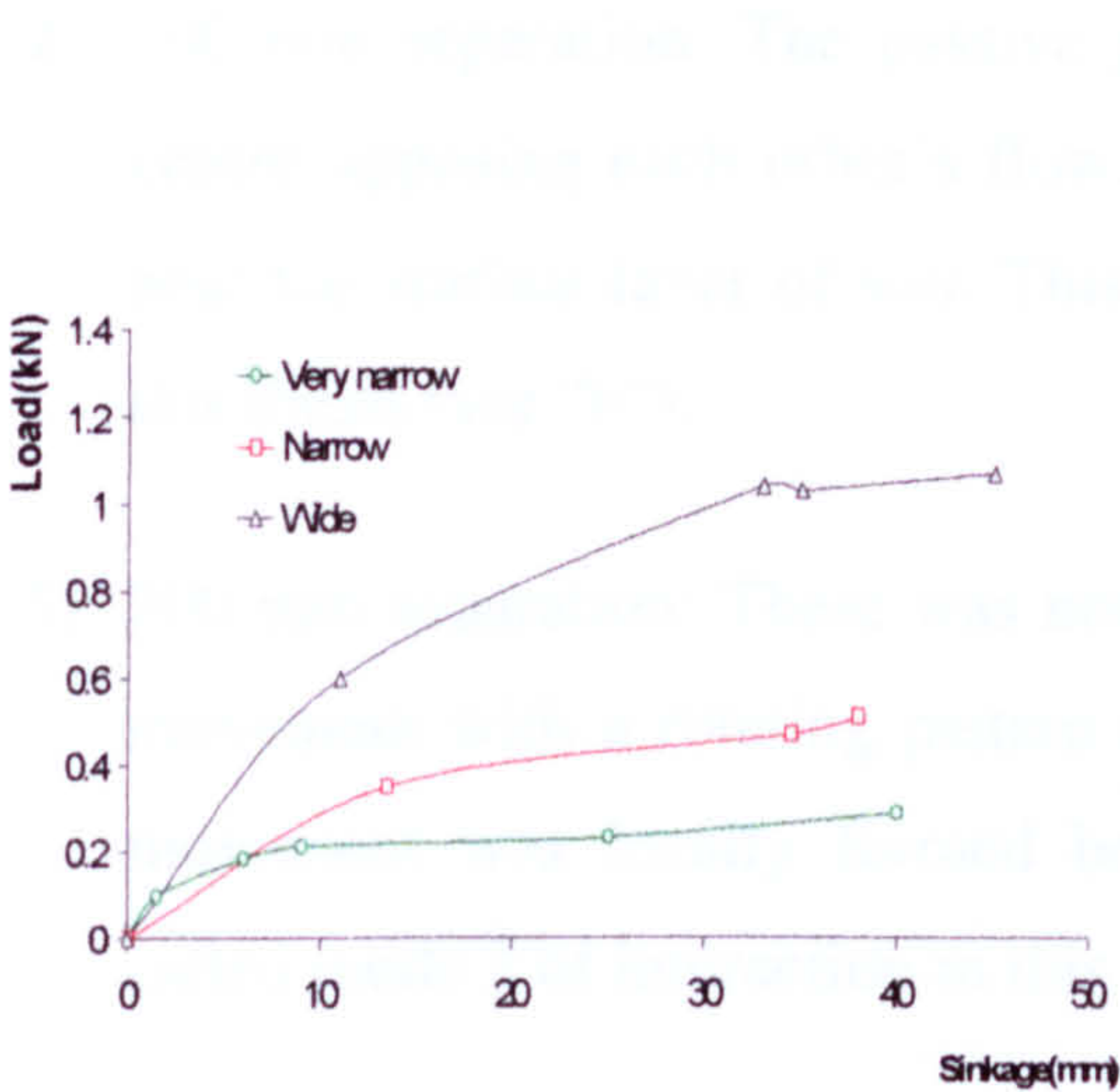


Figure 4.5. Load-sinkage relationships under different plate widths

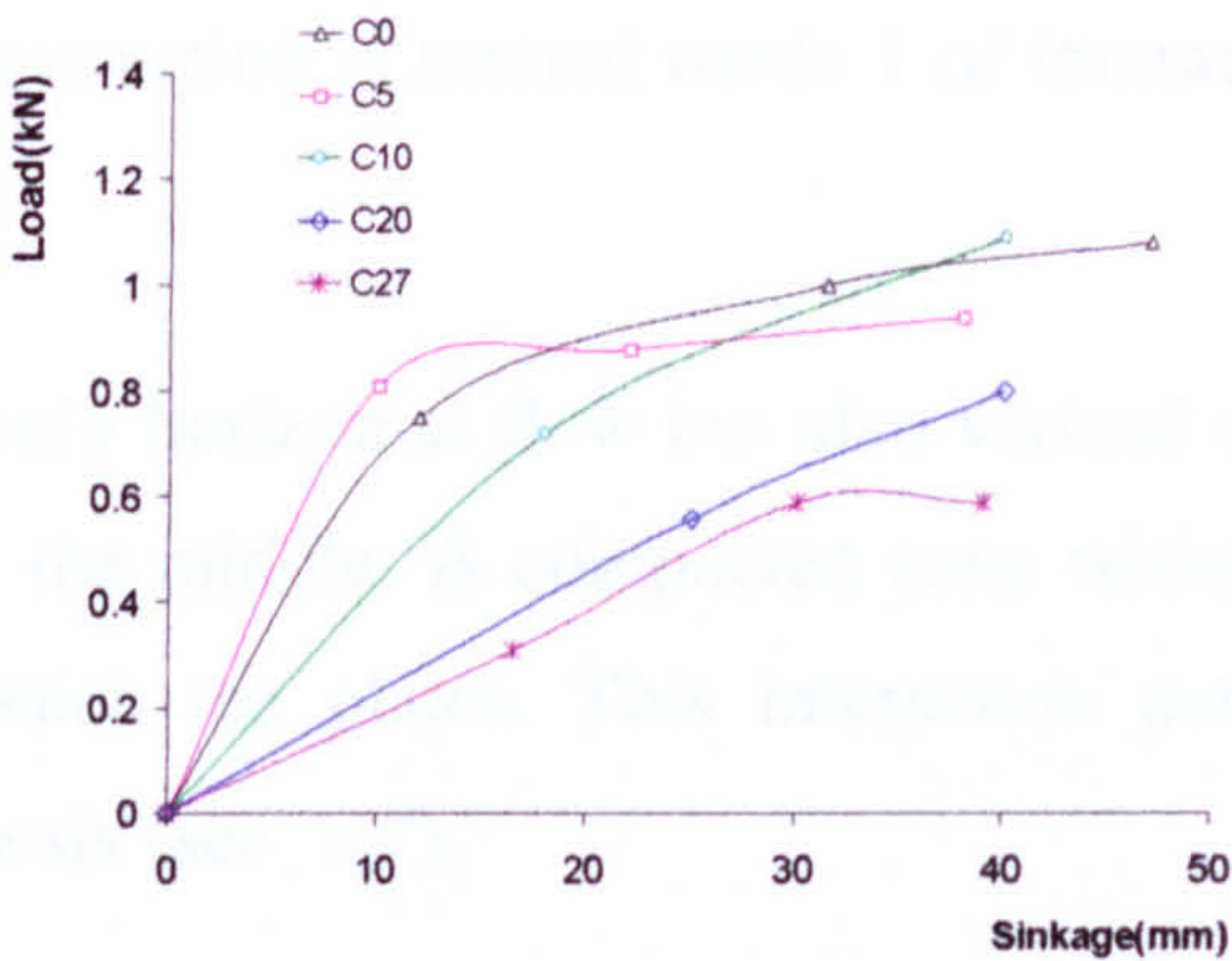


Figure 4.6. Load-sinkage relationships under different curved plates

4.4. Soil behaviour influenced by dual arrangements

The results showed similar fundamental behaviour for all three plate sizes in the dual arrangements. Therefore the results for the wide plates are explained below and the others are given as graphs and figures for comparison. The results were analysed for failure patterns and load-sinkage relationships.

4.4.1. Failure patterns

Reviewing the results and images revealed that there were different modes of interaction for each separation. Summaries of observations for the wide plates (100*150) at each distance are as followed (see sketch in Figure 4.7):

- 1) 600 mm separation: There was no interaction between the failure zones under the plates. Each active and passive zone acted individually. This is termed mode 0 of interaction in this thesis. The same pattern was also found for 400 mm separation. (see “a” in Figure 4.7)
- 2) 300 mm separation: The passive planes that flowed from each plate met in the centre opposing each other’s flow. There was a little rotating upward movement near the surface layer of soil. This interaction is termed mode 1 of interaction in this thesis (see “b”).
- 3) 200 mm separation: There was not only horizontal flow but also vertical upward movement with a rotating pattern in the middle. A compacted zone without any movement was locally formed between the plates. This interaction pattern is called mode 2 of interaction in this thesis (see “c”).
- 4) 120 mm Separation: The failure planes flowed mostly to the sides due to a very strong interaction with little rotating movement in the middle. There seemed to be deeper movement at the side than in the middle, meaning less vertical strain can occurred at depth in the centre. This interaction pattern is called mode 3 of interaction in this thesis (see “d”).

Comparing the interaction modes, revealed that somewhere between modes 2 and 3, where the compacted zone move slightly upward and downward respectively, the local compacted zone must become static without movement. This was identified as a transitional spacing between modes 2 and 3. Therefore it was possible to identify different modes of interaction under dual arrangements depended on the spacing between them. Photographs showing different modes of interaction under dual plates are given in Figure 4.8.

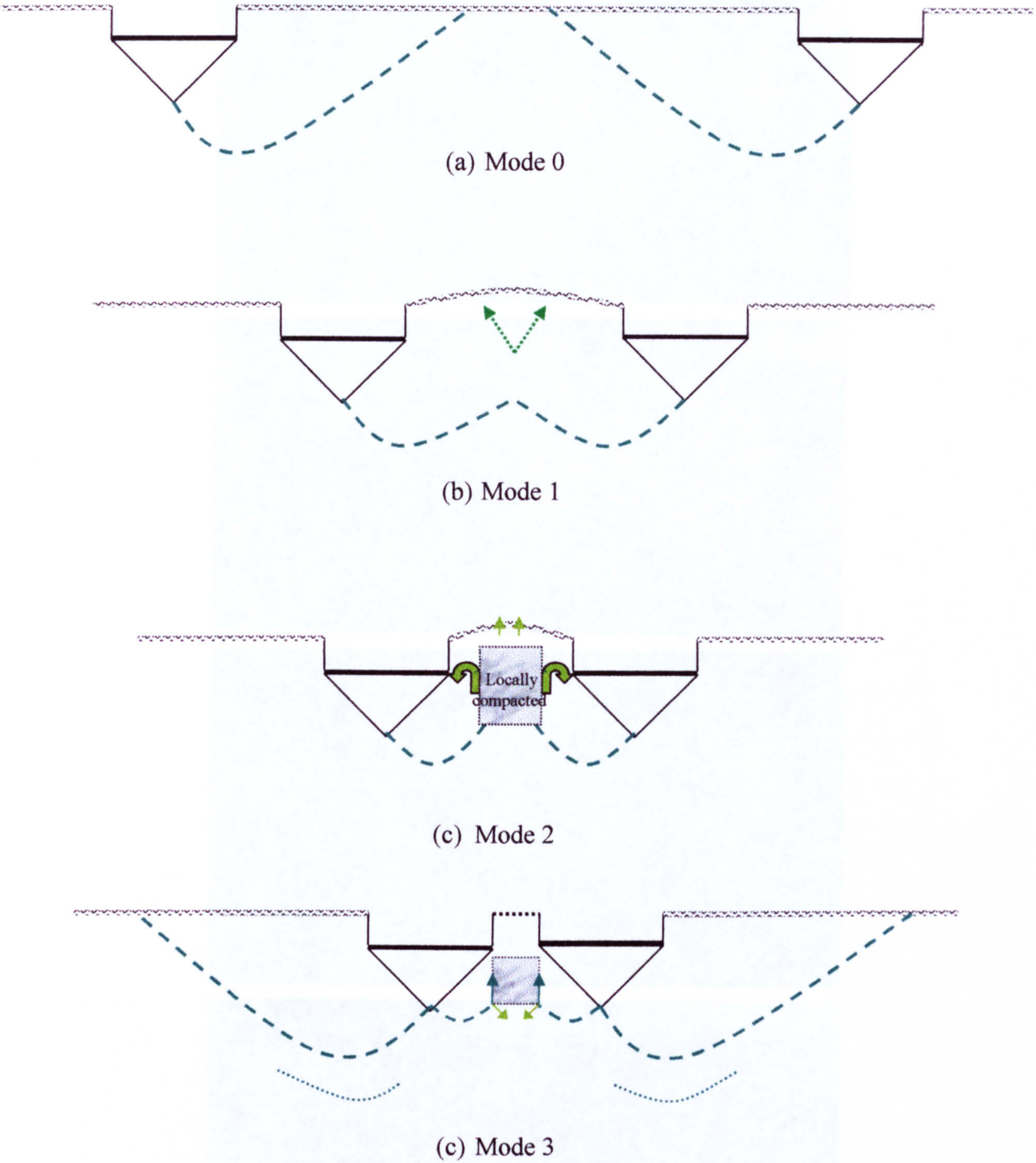
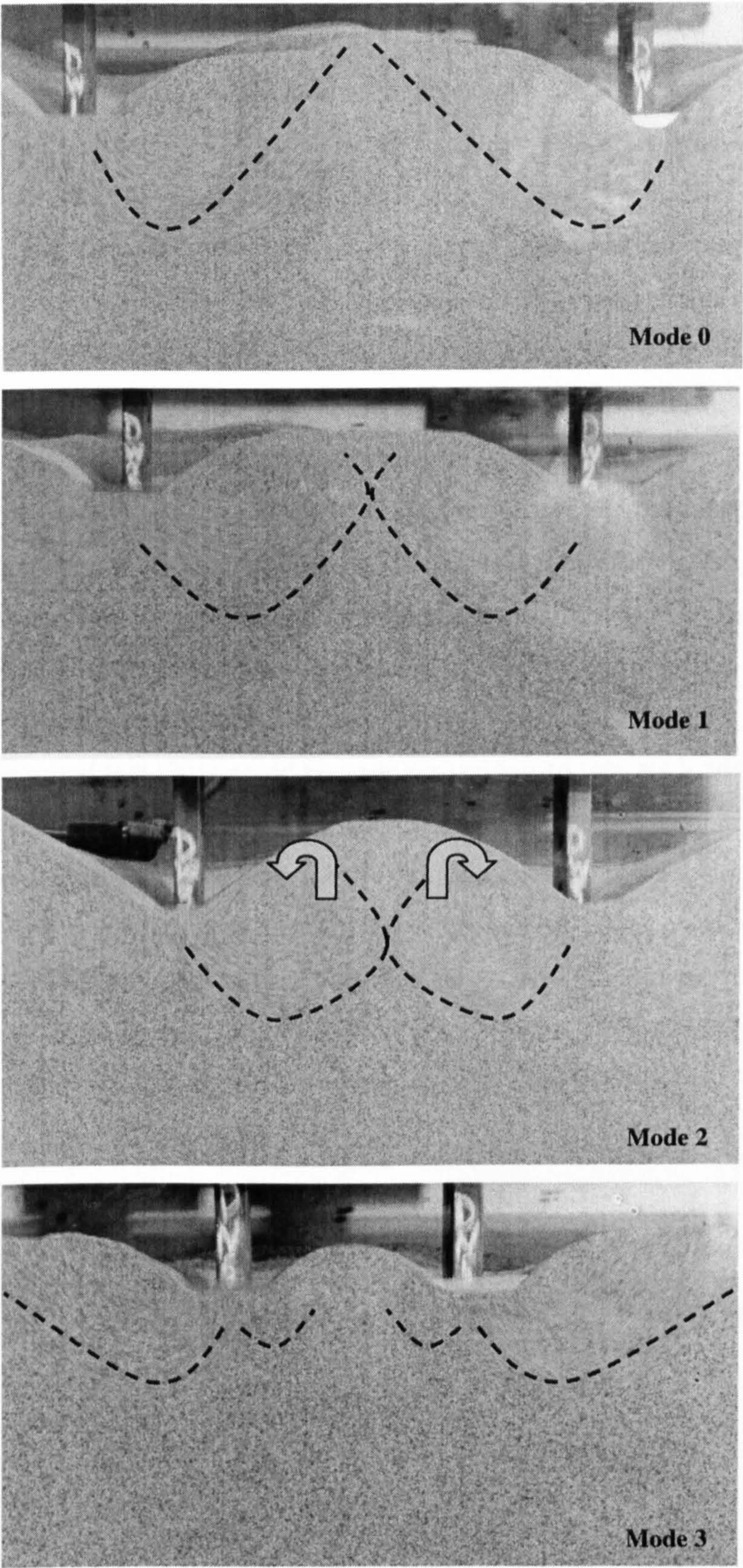


Figure 4.7. Failure patterns sketch and interaction modes under dual arrangements



4.8. Interaction modes identified during dual tests

4.4.2. Load-sinkage relationship

At 600 mm plate spacing (no interaction), failure zones were formed under each plate individually and the force was double that of the single plate test. The load-sinkage relationship was similar to the general pattern with a failure point. The pattern was similar for the 400 mm spacing [see (a) in Figure 4.9]. Interaction started from 300 mm separation where the slope of the first part of the load-sinkage curve (AB) increased uniformly [see (b) Figure 4.9]. At closer spacings of 200 and 120 mm, the slope followed the shape of the non interaction plates initially, but then suddenly changed. The change at B was due to interaction between the plates [see (c) and (d) in Figure 4.9]. The second part of the curves (BC) was found to be depended on the particular interaction mode, the slope of (BC) increased for closer spacings (stronger interaction). This meant that more load could be supported for a given sinkage under interacting plates [see (d)]. The tests confirmed that there is a definite relationship between the load-sinkage results and the interaction mode.

The results suggested that there could be stronger support to tolerate loads in modes 2 and 3 of interaction with less sinkage. It was also thought that there could be stronger support by placing a third plate in the middle as a triple configuration. The interaction in this case could provide strong support for third central plate, causing minimum movement at depth. The results for narrow and very narrow dual plates followed the same pattern as the wide ones but with interaction starting at closer spacings. The load-sinkage results for narrow dual plates are given in Figure 4.10.

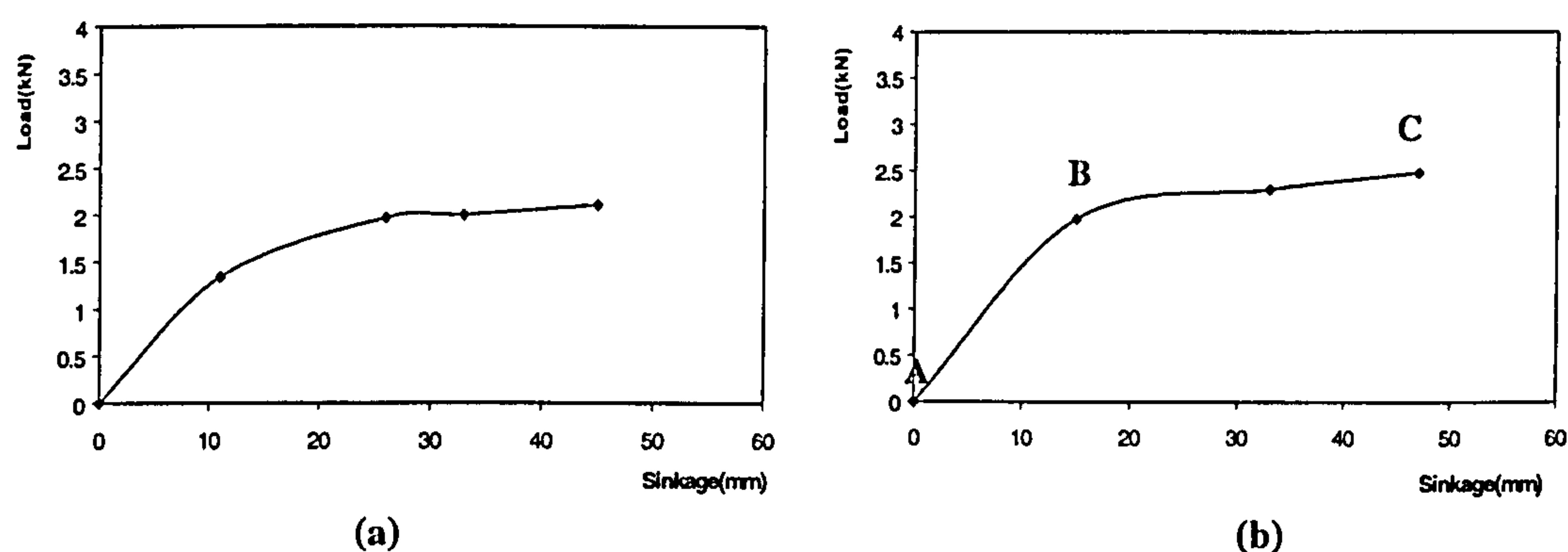


Figure 4.9.

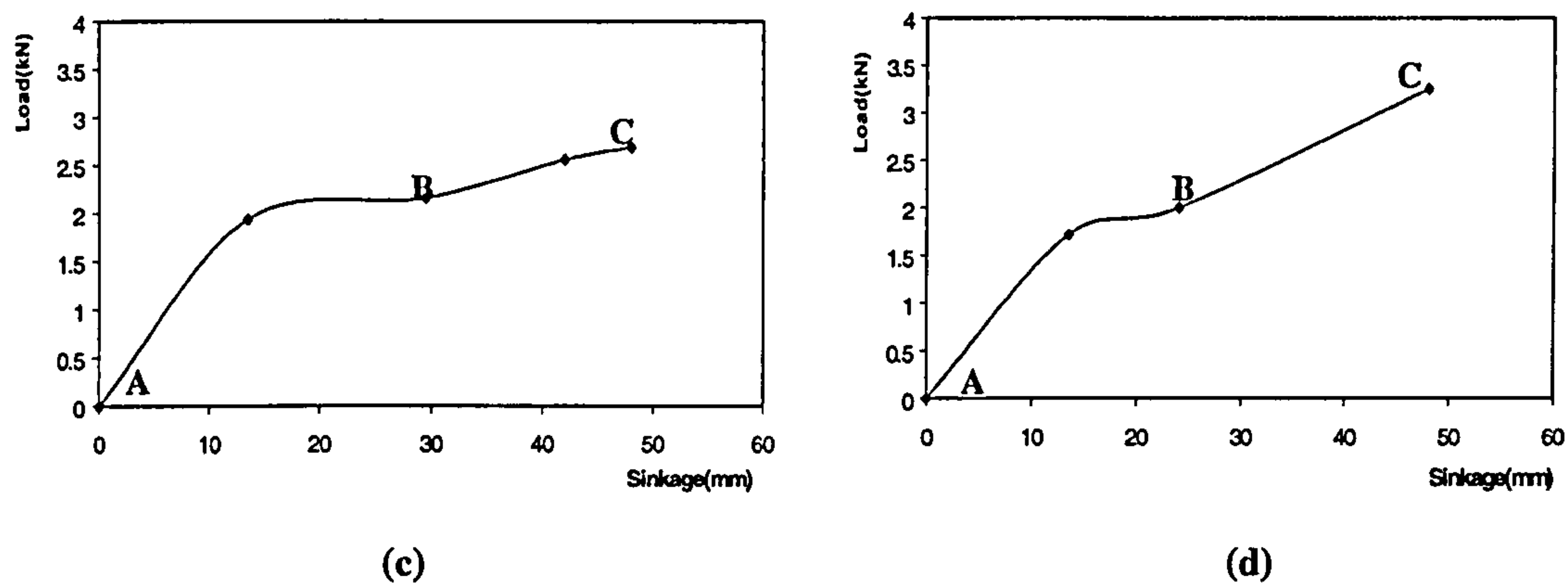


Figure 4.9. Load-sinkage results under dual wide plates at varied separations
(a) 400 mm (b) 300 mm (c) 200 mm (d) 120 mm

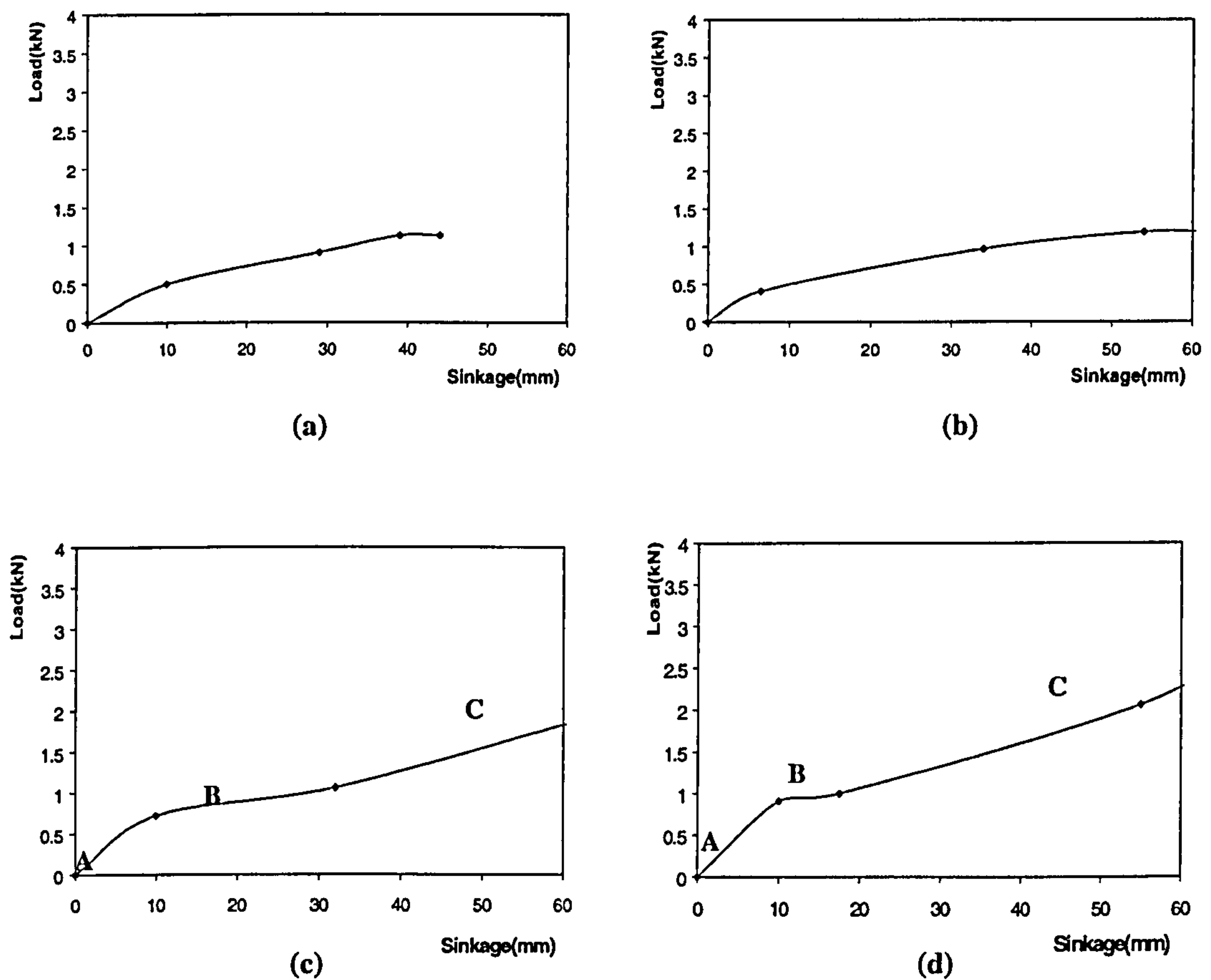


Figure 4.10. Load-sinkage results under dual narrow plates at varied separations
a) 400 mm b) 300 mm c) 200 mm d) 120 mm

4.5. Soil behaviour influenced by triple arrangements

4.5.1. Pattern 1, plates at the same level

Based on the dual test results, the side plates were placed at the closer spacing of 150 mm where there was considerable interaction, to assess the influence of the central third plate. The third plate was placed at the same level as the side plates. This left only 25 mm spacing between the wide plate sizes and 40 mm between the narrow (see Figure 4.11).



Figure 4.11. Triple tests, arrangement 1
a) Triple narrow b) Triple wide

The load-sinkage results showed that there was a significant difference between triple wide plates and triple narrow plates (see Figure 4.12). The improved relationship under triple wide was considered to be due to the smaller spacing and hence the greater interaction between them. Therefore it can be concluded that the spacing between the plates is a key factor in generating strong interactions and hence stronger load support. It was clear that more loads could be supported for a given sinkage under triple wide plates (compare load for 40 mm sinkage in Figure 4.12).

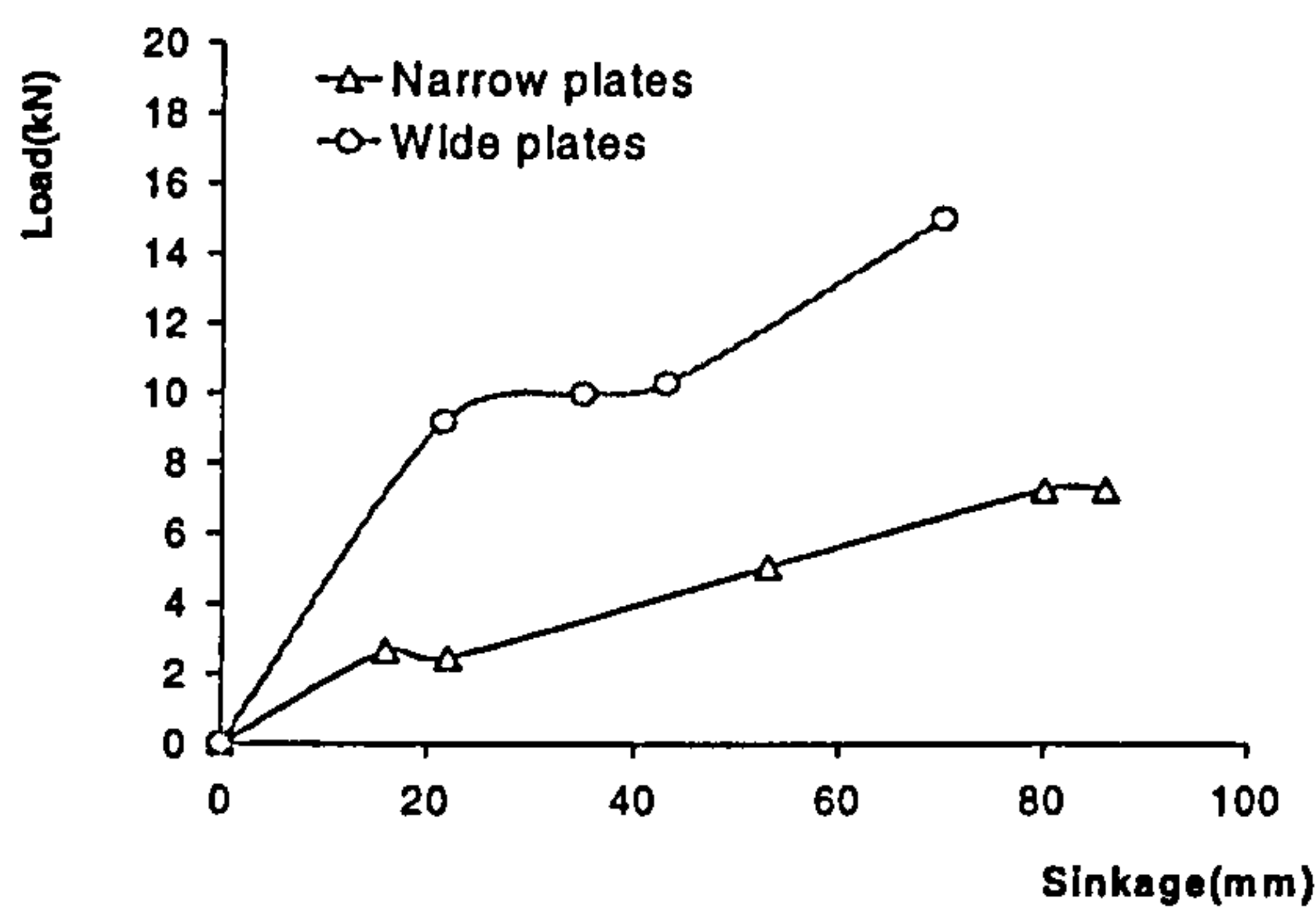


Figure 4.12. Load-sinkage results under triple pattern 1 for two plate sizes

The recorded images indicated however that deeper movement occurred under the triple wide plates. It was assumed that soil tended to move downward due to insufficient spacing between the plates to allow upward movement.

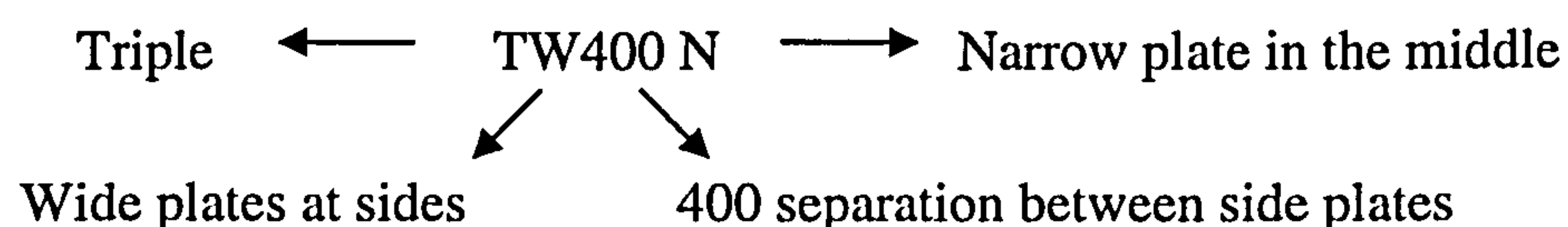
4.5.2. Pattern 2, raised middle plate

The dual test results showed that some upward movement could occur as well as blockage in the central area in both modes 2 and 3 of interaction. It was thought that by placing the third plate shallower than the side plates, it should be possible to provide stronger support due to interaction and the surcharge induced by the third plate. Therefore different sizes of third plate were tested being placed 35 mm and 20 mm higher than the outside plates.

a) **35 mm raised:** The side plates were placed at 400, 300, 200 and 120 mm separation to present different modes of interaction. Different ranges of third plate were placed in the centre, all at 35 mm higher than the side plates. Figures 4.13, 4.14 and 4.15 show the results for each dual set of wide, narrow and very narrow plates with varied spacings and different sizes of third plate in the middle. The labelling of each configuration is given by 4 characters, the first being the triple arrangement, the second the size of side plate, the third the spacing between side plates and the fourth the size of the middle plate.

W- Wide N- Narrow V- Very narrow *sizes of the middle plate*

Such as:



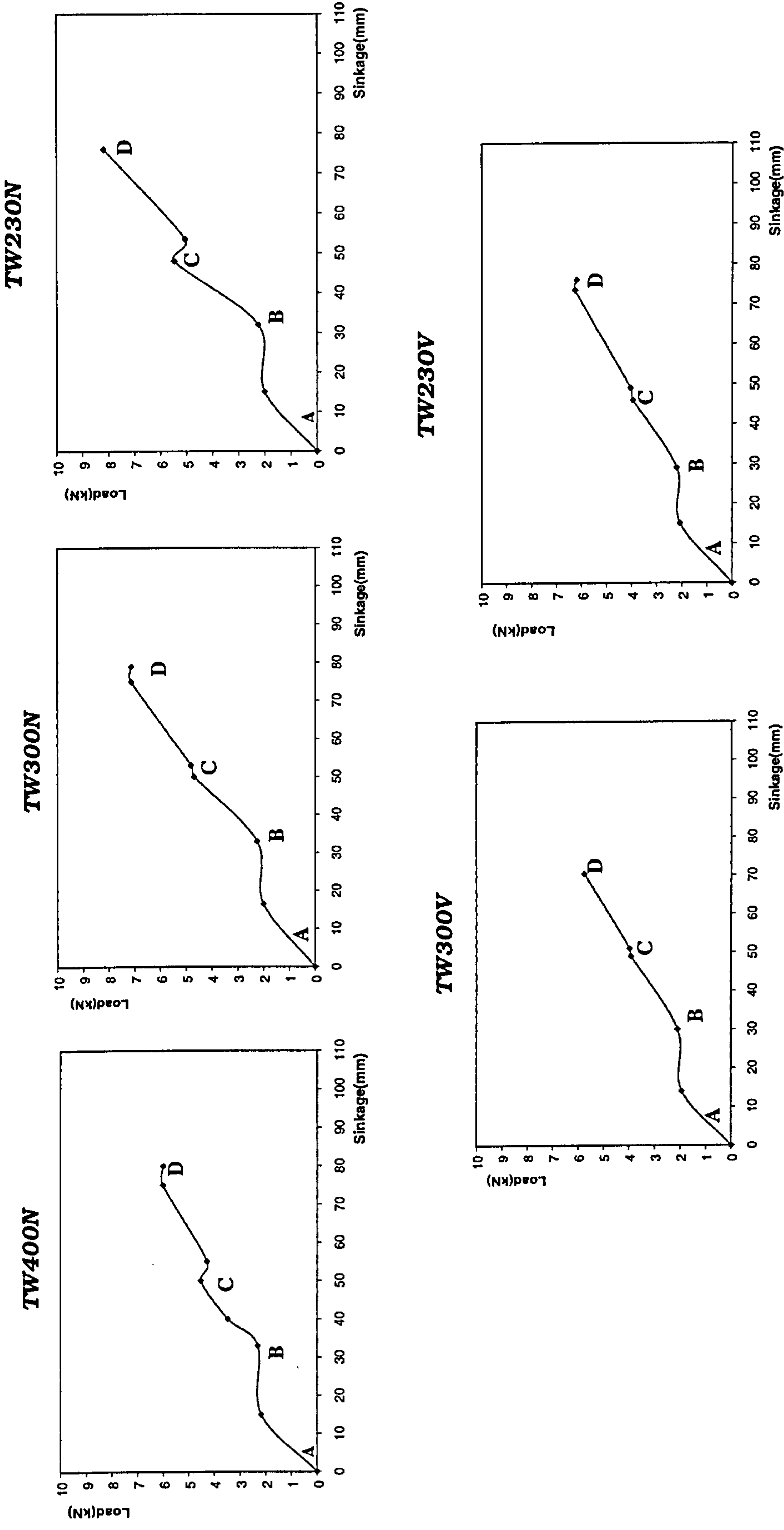


Figure 4.13. Triple tests, pattern 2 (35 mm raised middle plate), wide plate at different spacings at sides and also different sizes of middle plate

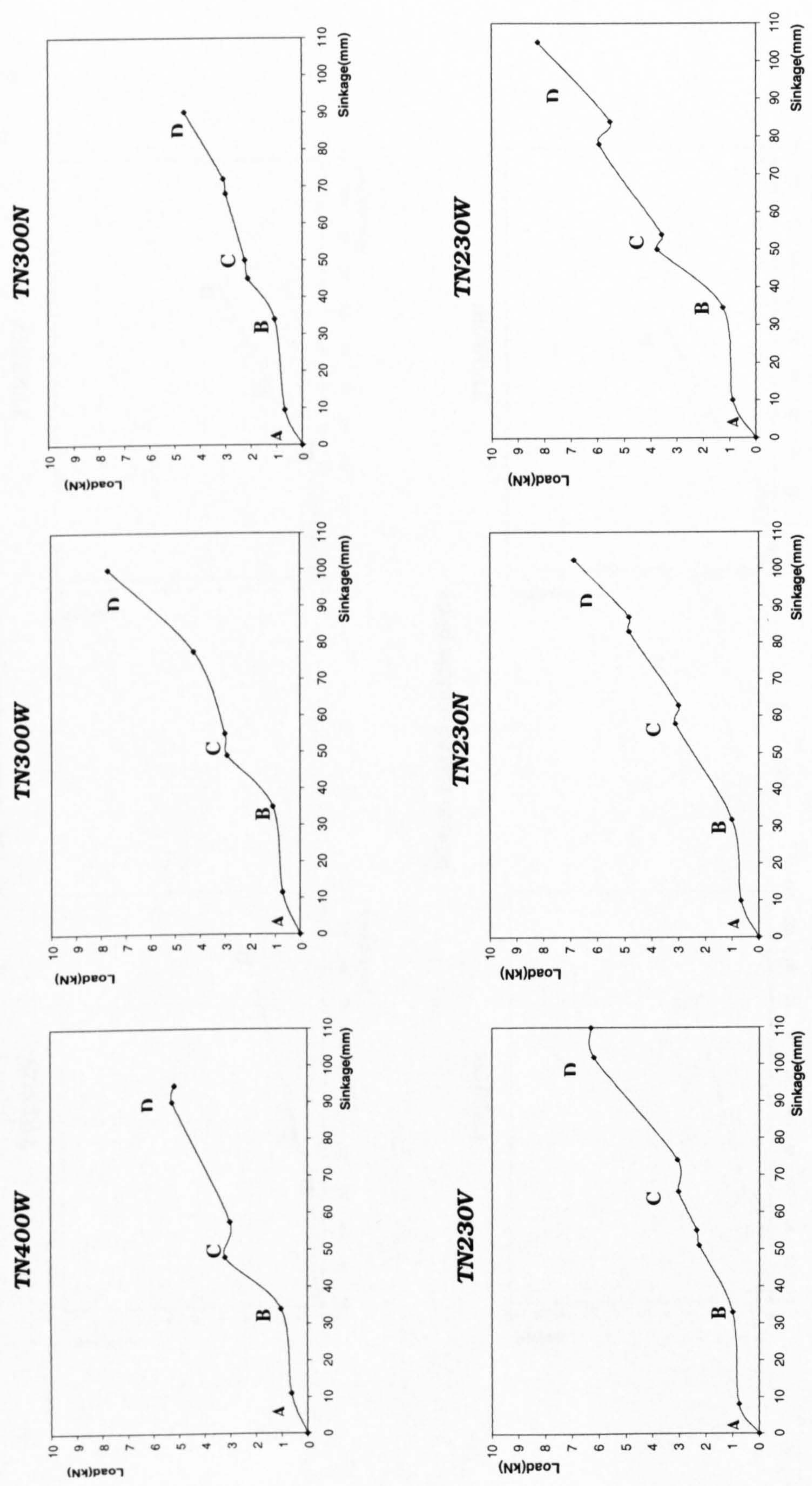
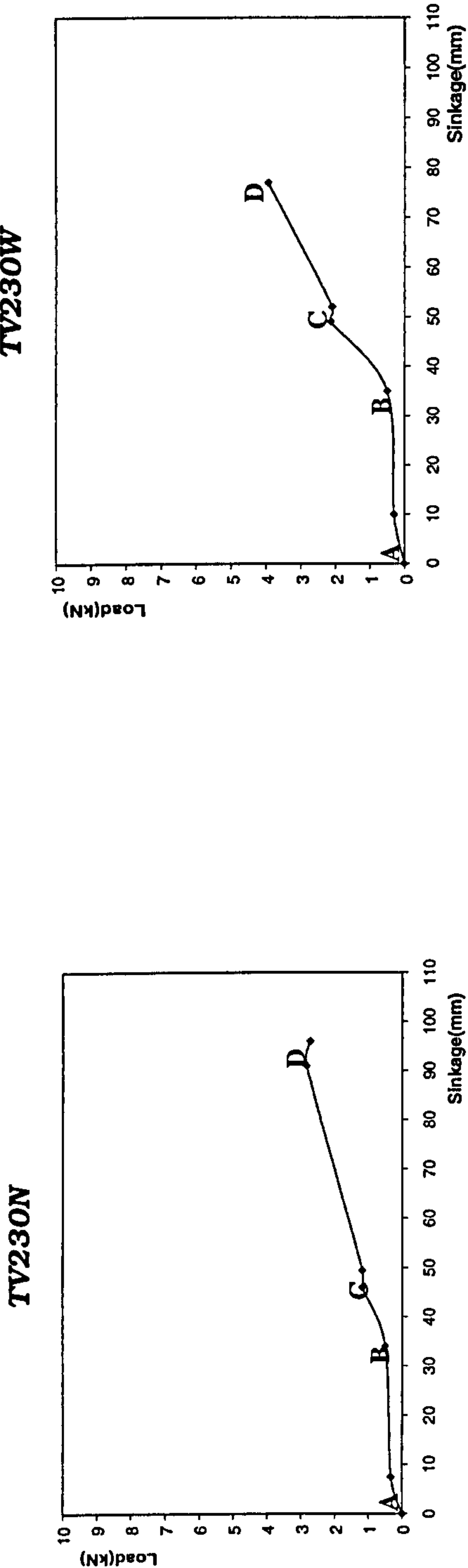


Figure 4.14. Triple tests, pattern 2(35 mm middle raised plate), narrow plate with different spacings at sides and also different sizes of the middle plate

35 mm raised middle plate



20 mm raised middle plate

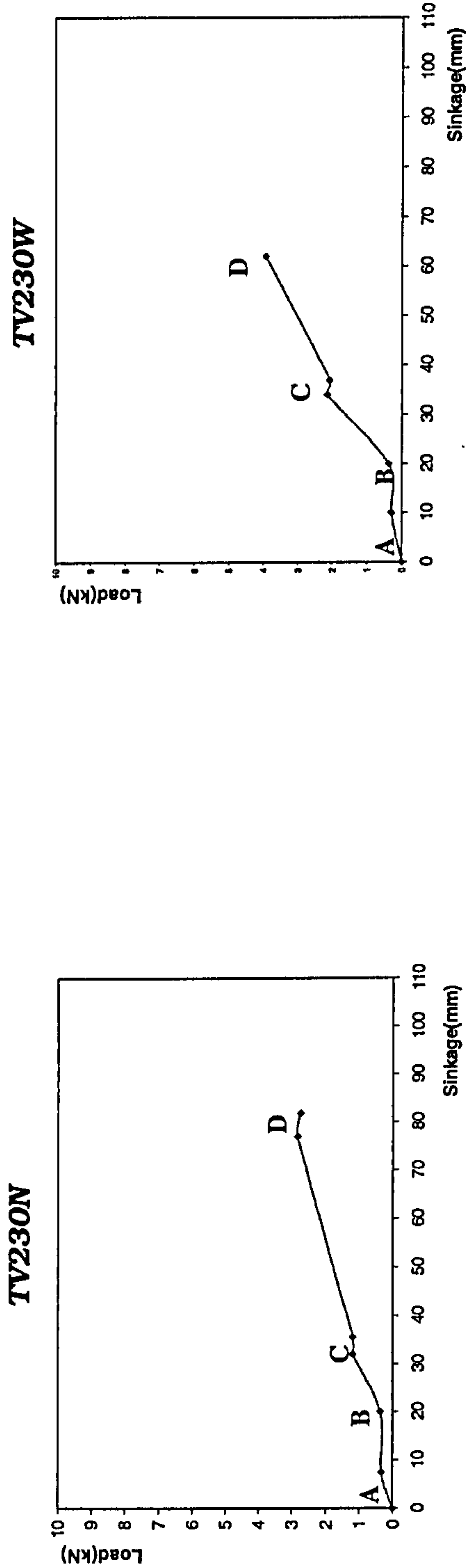


Figure 4.15. Triple tests, pattern 2, very narrow plate at sides with different sizes of middle one

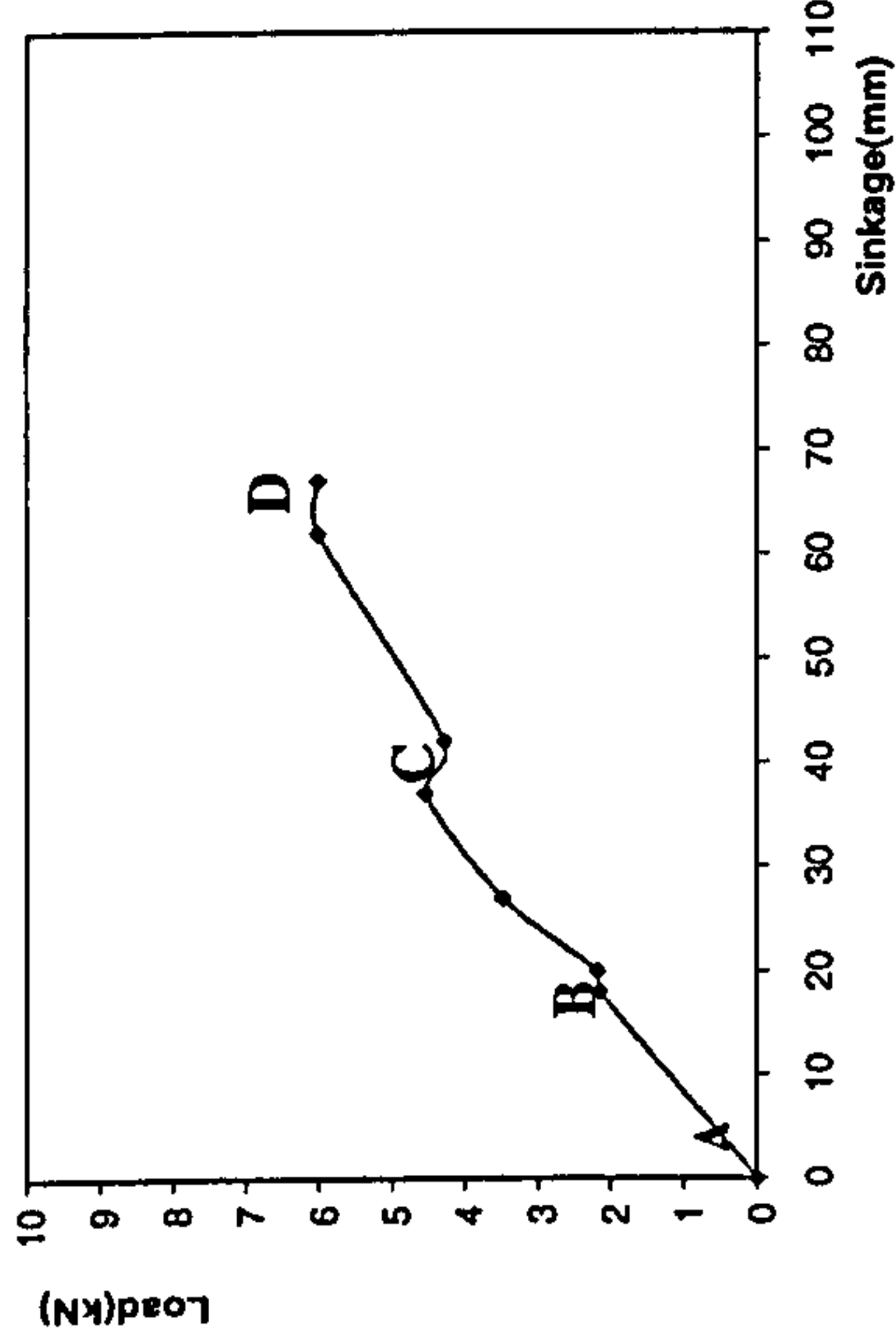
The load-sinkage relationships for all configurations indicated that:

- 1) The first part (AB) of the curves (35-40 mm sinkage) was the same as in the dual tests with similar plate sizes and separations.
- 2) The second part (BC) of the curve was affected by the third plate coming into contact with the soil. The slope of this part was related to the size of the third middle plate. The wider plate produced a greater curve slope, which meant a greater load could be tolerated for a given sinkage (compare TW300V having a very narrow middle plate with TW300N having a narrow middle plate in Figure 4.13).
- 3) The third part (CD) of the curve was due to the interaction of all plates, as well as the failure patterns developing within the dense layer of soil at depth. For closer distances of the side plates (mode 3 of interaction) the slope of the third part was increased which again means greater tolerated loads for given sinkages (compare TW400N with TW230N in Figure 4.13).

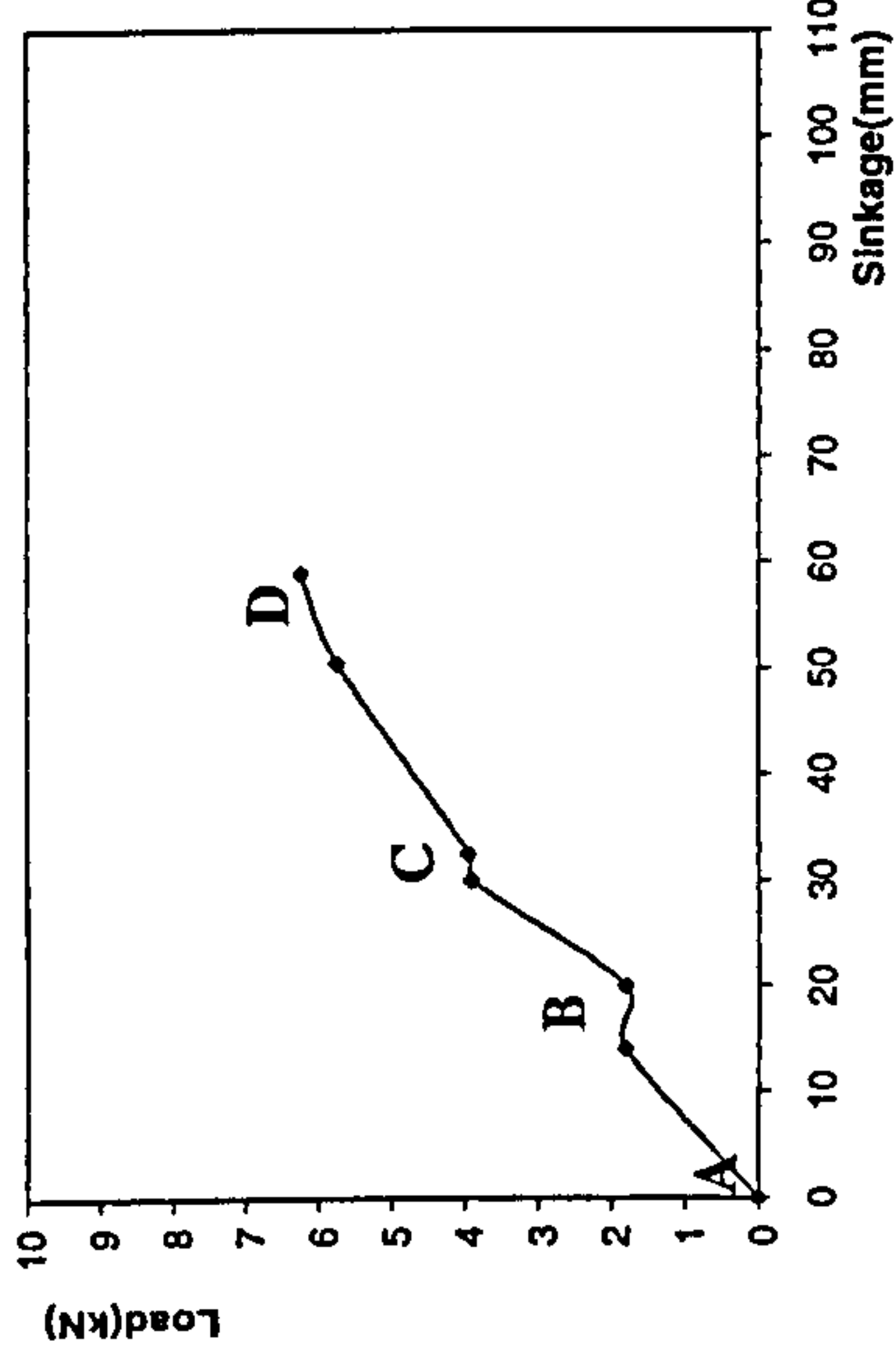
Reviewing the results for all configurations, the second part (BC) of the curve, which can offer more load for less sinkage, started after 30-35 mm sinkage. Moreover the horizontal section in the first part (AB) generates more sinkage without an increase in load. Therefore it was deduced that it should be possible to minimise or avoid this horizontal section by placing the third plate at a closer vertical distance. This would induce an earlier start of the second part avoiding any gap between the first and second parts, offering higher tolerated loads for a given sinkage. Hence configurations with a closer 20 mm raised middle plate were tested in the next set of experiments.

b) 20 mm raised: In this configuration the middle plate was placed 20 mm higher than the side plates. Figures 4.16 and 4.17 show the results for wide and narrow plates respectively. The results for the very narrow one are given in Figure 4.15 and can be compared with the 35 mm raised.

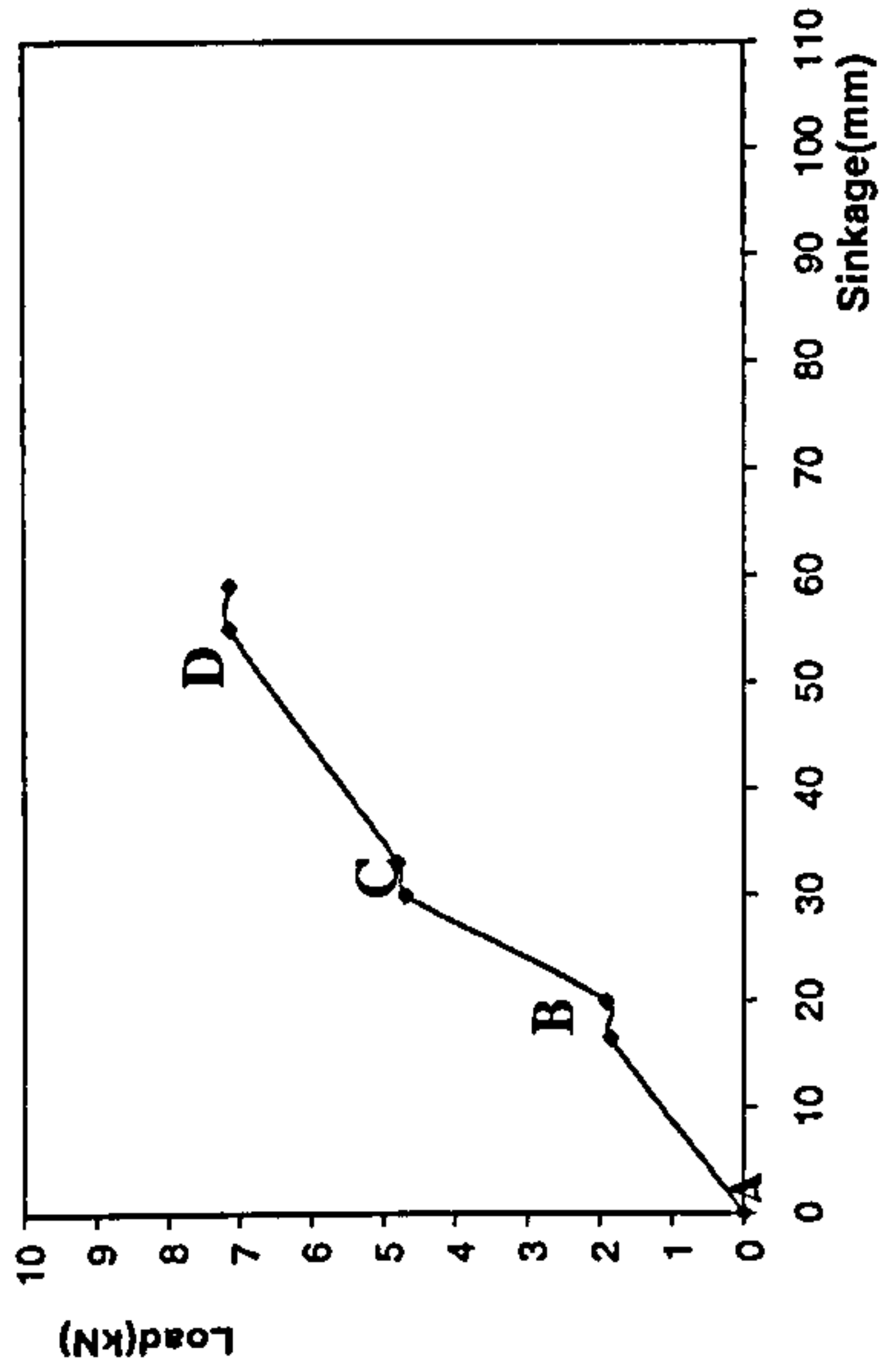
TW400N



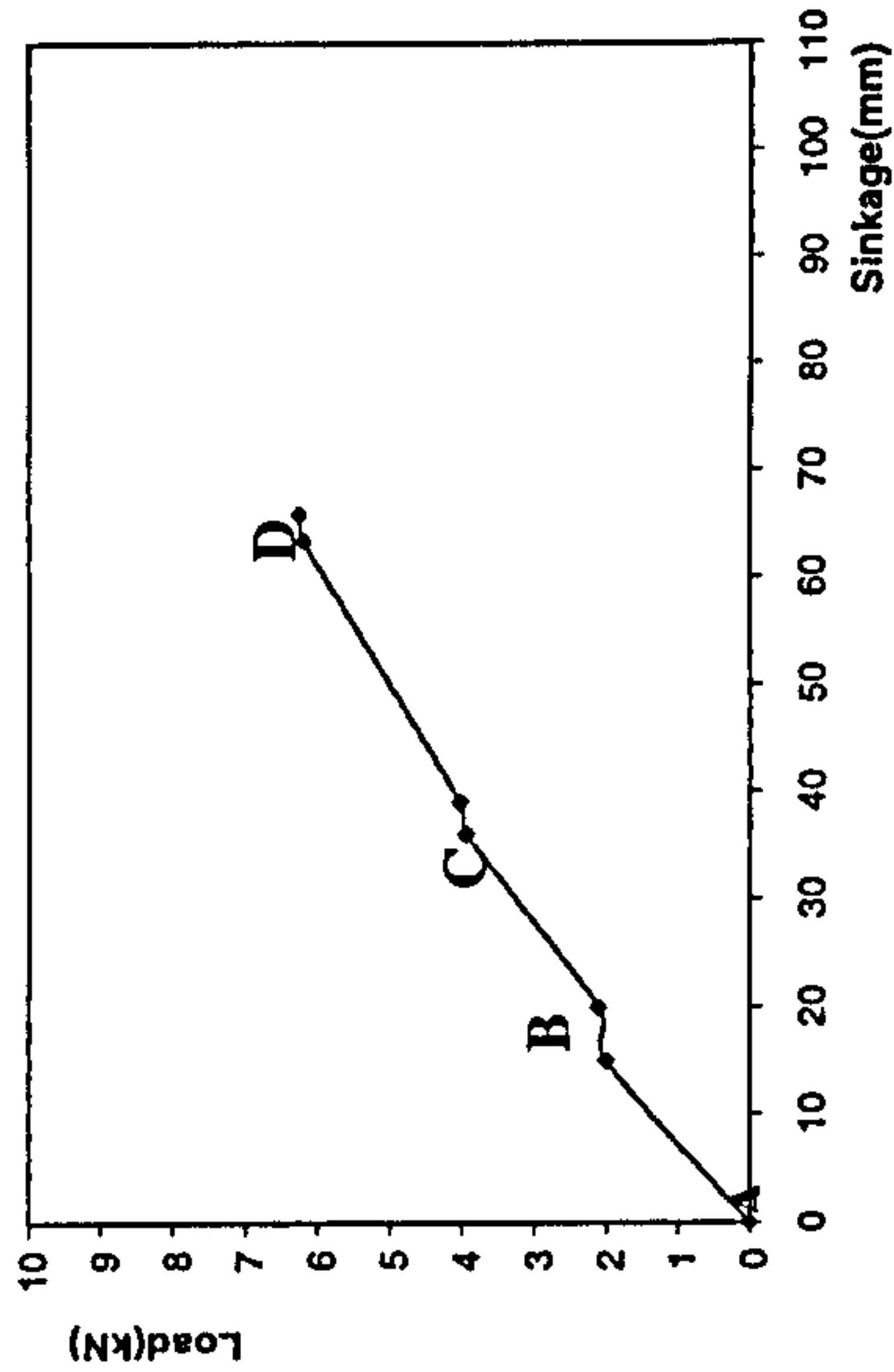
TW300V



TW300N



TW230V



TW230N

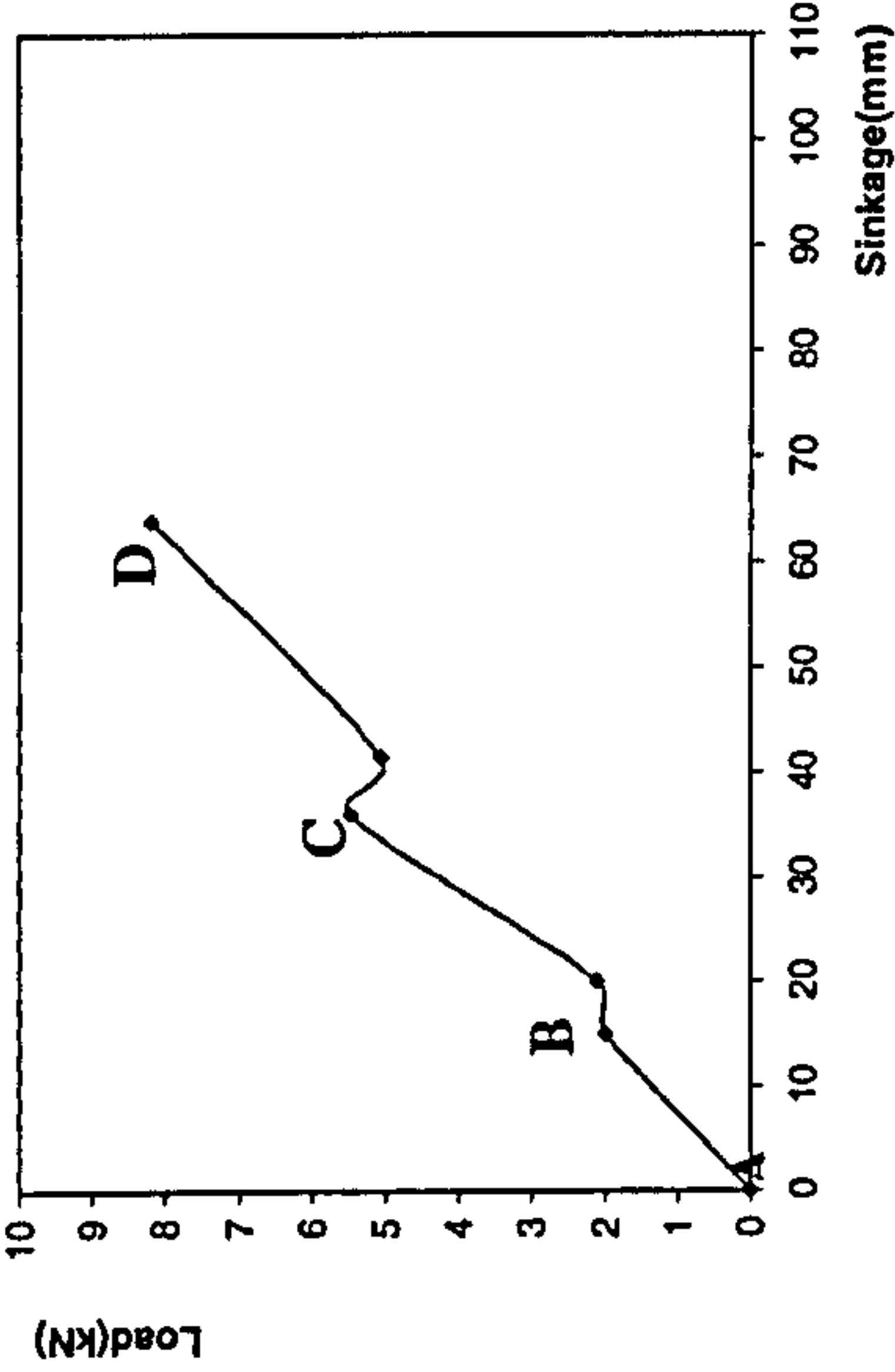


Figure 4.16. Triple tests, Arrangement 2-b (20 mm middle raised plate), wide plate with different spacings at sides and also different sizes of middle one

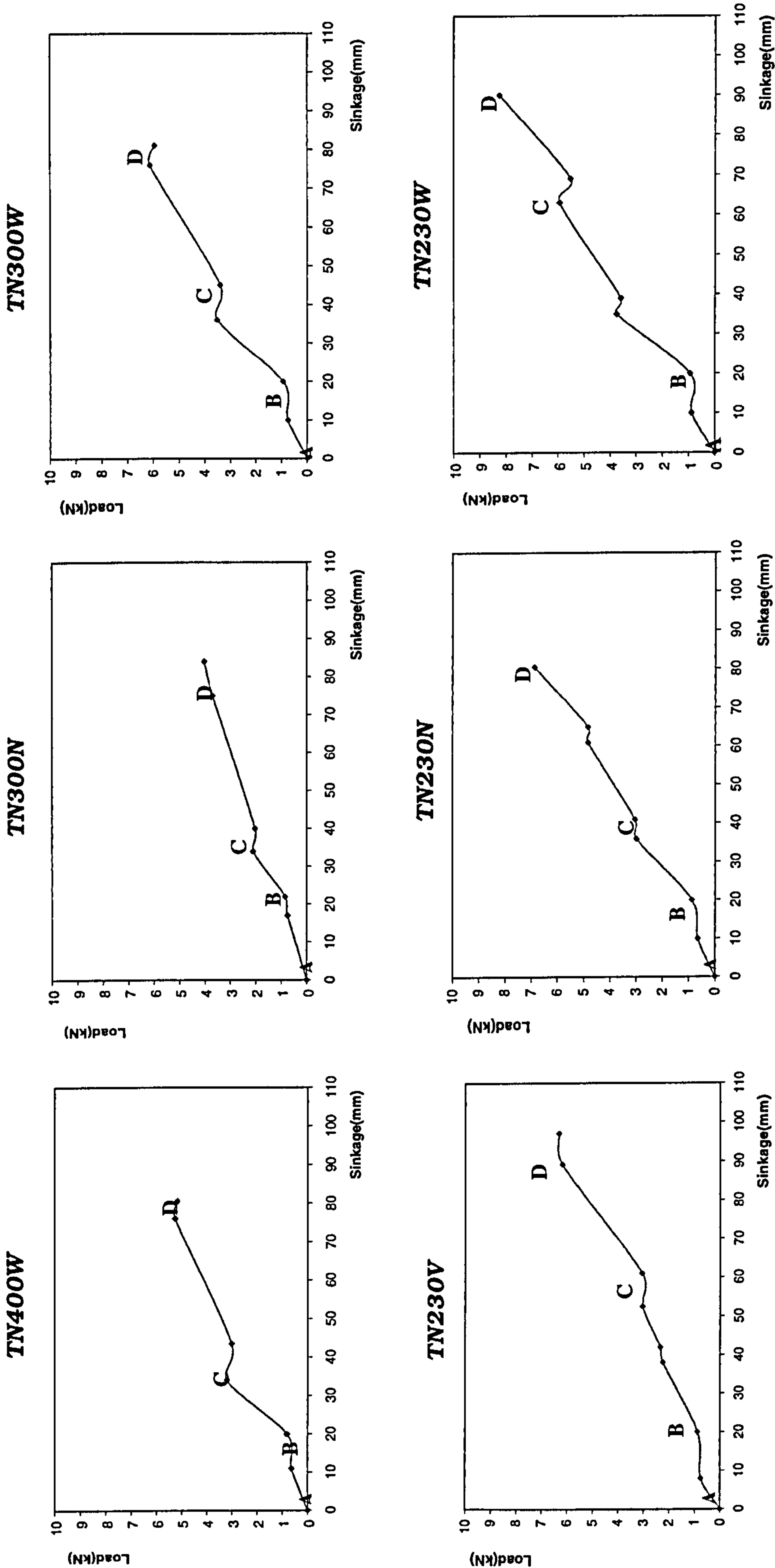
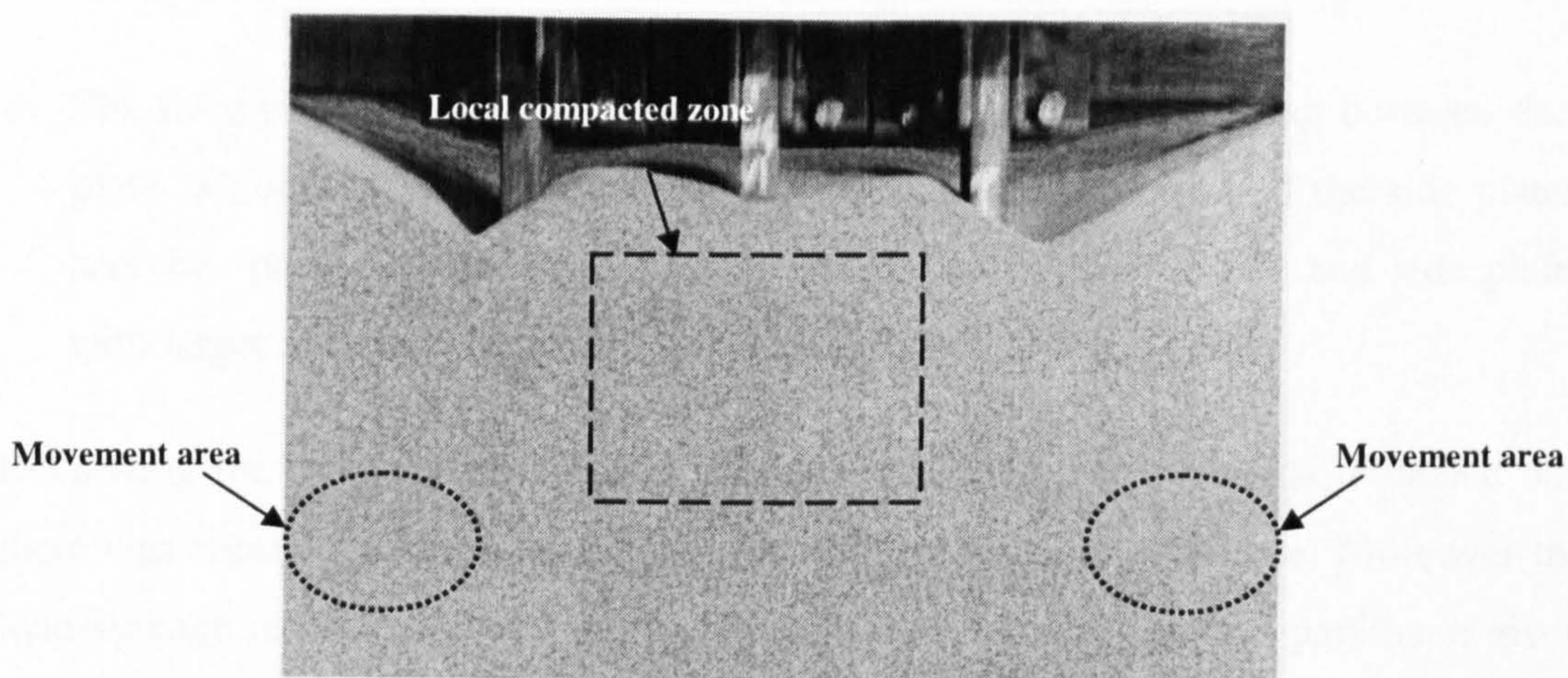


Figure 4.17. Triple tests, pattern 2-b(20 mm middle raised plate), narrow plate with different spacings at sides and also different sizes of middle one

The load/sinkage results in this case confirmed that:

- 1) The second part (BC) of curve started earlier (after 20 mm sinkage) reducing the extent of the horizontal section between the first and second parts.
- 2) There was an improvement in the load-sinkage relationship, with less sinkage occurring for a given load compared with the 35 mm raised one.

Reviewing the images of both the 35 and 20 mm raised distances indicated that a static zone formed between the plates when third plate started to penetrate (see Figure 4.18). The static soil zone supported the load in the centre without much soil movement immediately below at depth. Some deeper movements were identified at the sides. These were thought to be due to passive failure plane movements. In this case the strong interaction in the middle did not allow soil to move and hence most of the movements were transferred to the sides where the resistance for movement was less.



4.18. Photograph of triple raised plate showing movement and local compacted zone

4.5.3. Pattern 3, lower middle plate

In this pattern the middle plate was placed 35 mm lower than the side plates to investigate the effect of surcharge provided by the side plates. Figures 4.19 and 4.20 show the results of load-sinkage relationships for wide and narrow plates respectively. The results indicated that:

- a) The first part (AB) of the curve (0-35 mm sinkage) was depended on the size of the middle lower plate and confirmed the results of single plate tests.
- b) The second part (BC) of the curve was depended on the size of side plate as well as the size of middle plate. The wider side plates created a longer second part (compare TW300N with TN300N in the Figure 4.19 and 4.20). Also the wider middle plate created greater active and passive zones that could support the side plates more than the narrow one (compare TW300V with TW300N in the Figure 4.18).
- c) The horizontal or slightly reverse slope section between the second (BC) and third parts (CD) of curve was depended on the spacing between the side plates. The closer spacing gave the smallest horizontal part due to greater interaction (compare TW400N with TW300N in the Figure 4.19).
- d) The third part of curve was found to be dependent on the spacing between each plate, which was affected by the size of the middle plate, size of the side plates, and the spacing between the side plates. Hence smaller middle and side plates with larger spacings resulted in larger spaces between each plate.

Reviewing the images of the failure planes under these arrangements, revealed that there was significant strain at depth caused by the lower middle plate. Moreover the load-sinkage results indicated more sinkage could occur in the first part for a given load under this arrangement compared with the triple raised and the same level configurations. Therefore this pattern cannot be a promising configuration to reduce strain at depth and hence no further investigations were carried out.

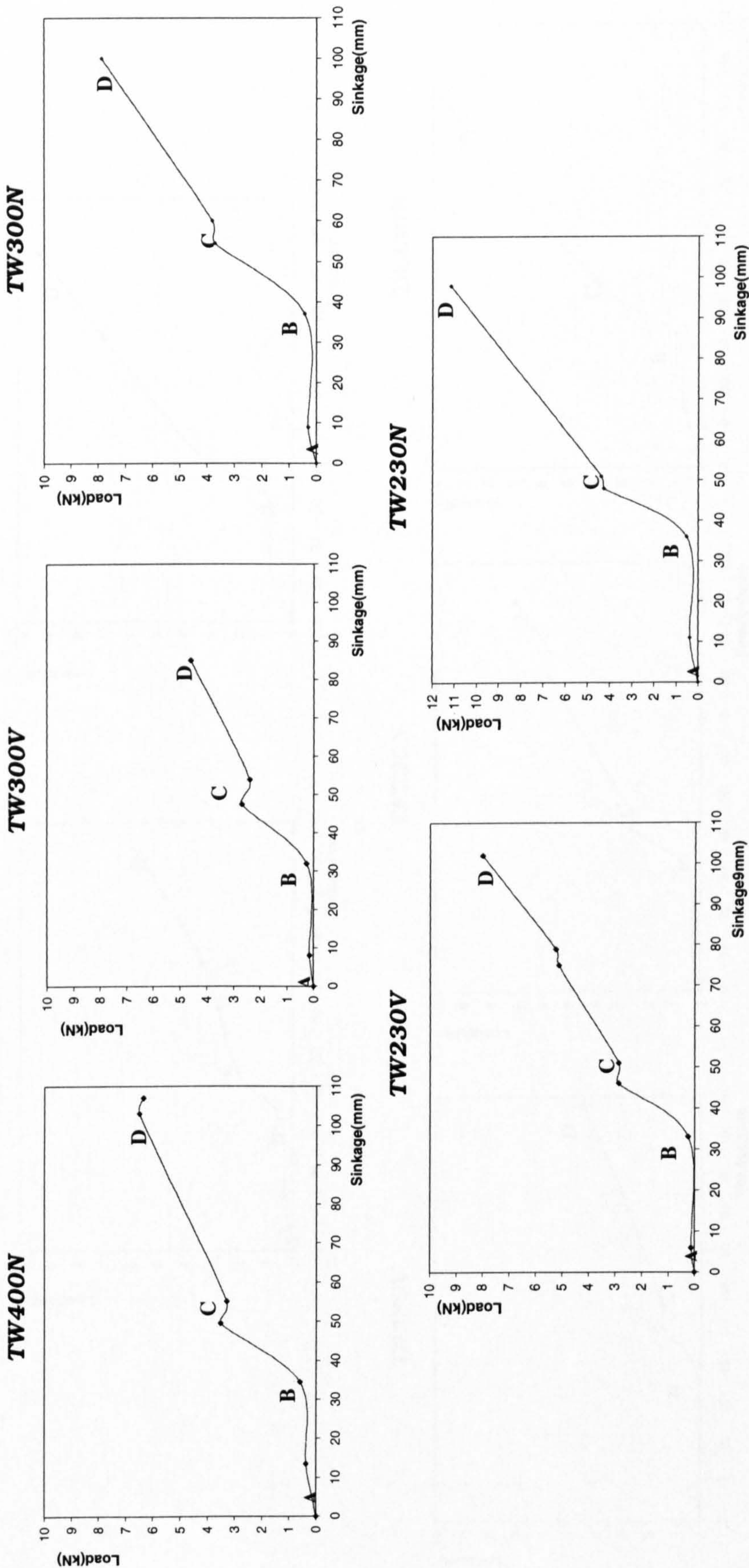


Figure 4.19. Triple tests, pattern 3 (35 mm lower middle plate), wide plate with different spacings at sides and also different sizes of middle one

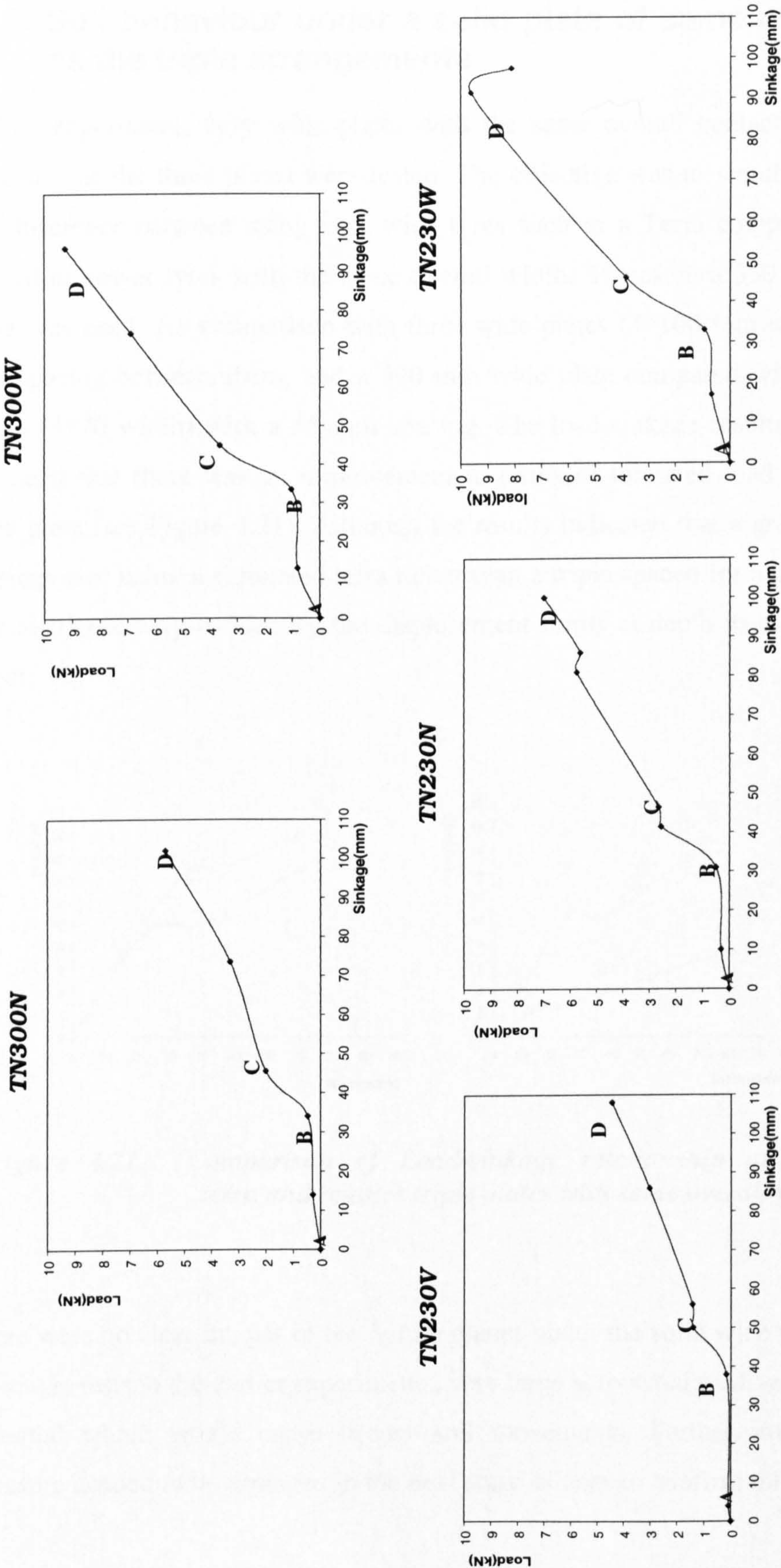


Figure 4.20. Triple tests, pattern 3(35 mm lower middle plate), narrow plate with different spacings at sides and also different sizes of middle one

4.6. Soil behaviour under a solid plate of same overall width as the triple arrangements

In this experiment, very wide plates with the same overall contact width (contact pressure) as the three plates were tested. The objective was to simulate and identify the difference between using very wide tyres such as a Terra compared with triple spaced narrower tyres with the same overall width. Therefore a 350 mm wide solid plate was used for comparison with three wide plates (3*100 mm width) with a 25 mm spacing between them, and a 320 mm wide plate compared with three narrow plates (3*70 width) with a 55 mm spacing. The load-sinkage results for both cases indicated that there was an improvement in terms of tolerated load under the solid wide plate (see Figure 4.21). Although the results indicated that a greater load could be supported using a simulated terra rather than a triple spaced for a given sinkage, it was also necessary to identify the displacement limits at depth to assess the overall effect.

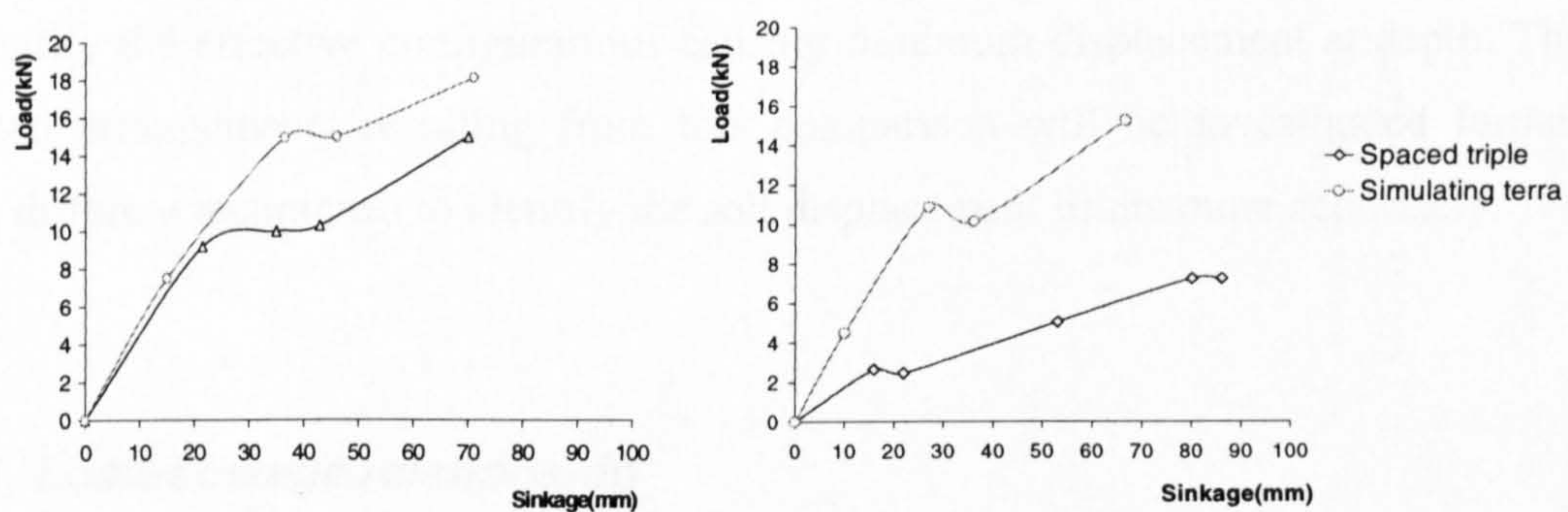


Figure 4.21. *Comparison of Load-sinkage relationship under simulating terra and relative triple plates with same overall width*

There were no clear images of the failure planes under the solid wide plates, but from the single tests in the earlier experiments, very large active and passive zones are to be expected which would cause deeper soil movements. Further investigation was therefore needed to be arranged in the next stage of tests to confirm this. However, the

difference between triple wide plates and the relative solid plate was smaller than the triple narrow plates and the relative solid one (compare the results in Figures 4.21). This was considered to be due to a greater interaction resulting from the smaller spacing between triple wide plates (25 mm) than with the triple narrow plates (55 mm).

It can be concluded therefore that the spacing between the plates, influenced by their sizes in different triple configurations, is a key factor inducing different interaction modes, which should be clarified giving optimum situation.

4.7. Overall comparison

All arrangements were compared to select the most effective configurations for supporting loads with least sinkage. The comparison was conducted in two steps, firstly the load-sinkage relationship was considered to identify the effective configurations for tolerating greater loads. Secondly the failure pattern was analysed to identify the effective configurations causing minimum displacement at depth. The selected arrangements resulting from this comparison will be investigated further using different techniques to identify the soil displacement limits more accurately.

4.7.1. Load-sinkage relationship

The tolerated loads were compared under different arrangements for two, 30 mm and 50 mm, sinkages (see table 4.1). The results showed that the solid wide plate (350 mm width) supported the greatest load for both given sinkages. The triple spaced one at the same level (pattern 1) was the second most effective arrangement. The triple spaced with 20 mm raised middle plate (pattern 2-b) came in third place. The dual plates at the closest spacing were shown to be the next effective arrangement. The triple spaced with 35 mm raised middle plate (pattern 2-a) claimed the fifth place.

Finally the triple spaced one with 35 mm lower middle plate (pattern 3) was shown to be the least effective arrangement.

Table 4.1. Load for given sinkages under selected configurations

Configurations	Load(kN)	
	30 mm Sink age	50 mm Sinkage
Very wide(Terra)	13.1	15.25
Triple, pattern 1(the same level)	9.9	11.5
Triple, pattern 2-b (20 mm raised)	4.2	6.1
Dual arrangement, 120 mm spacing	2.4	3.3
Triple, pattern 2-a (35 mm raised)	2	5.47
Triple, pattern 3(35 mm lower)	0.85	4.2

Therefore based on the results shown in table 4.1, it is possible to rank the most effective configurations in terms of their **load-sinkage relationships** as follows (load for 30 mm sinkage was considered):

- 1) Very wide (solid) as a Terra tyre with the same overall width as the triple spaced
- 2) Triple spaced, pattern 1, with three plates at the same level
- 3) Triple spaced, pattern 2-b, with 20 mm raised middle plate
- 4) Dual plates, at closest spacing with maximum interaction
- 5) Triple spaced, pattern 2-a , with 35 mm raised middle plate
- 6) Triple spaced, pattern 3, with 35 mm lower middle plate

4.7.2. Failure patterns and displacements

The failure and interaction patterns under selected arrangements from each category of single, dual and triple were compared to identify the most effective configurations causing least soil displacement at depth.

Sketches of the failure patterns made from reviewing the images are shown in Figure 4.22. A summary of each treatment is explained below. The line under each arrangement shown in the sketch indicates the approximate depth of affected soil, which is termed the displacement line in this section.

a) Triple spaced, pattern 1: This treatment with three plates at the same level also showed a promising load-sinkage relationship. The images indicated that three individual failure zones were formed under the plates (see 4.22-a). The relatively small active wedge under each plate caused shallower vertical movement. There was a strong interaction between the passive planes due to the small spacing. This created mostly side movement in the space around the outer plates as well as little downward movement between the plates. It was clear that dividing a very large active wedge formed under a wide plate into three small wedges formed under the triple spaced one, should cause significantly less movement at depth. Moreover the interaction between the passive planes should provide reasonable load support. The displacement line appeared to be shallower than the solid very wide one.

b) Triple spaced, pattern 2-b: Although this arrangement with raised 20 mm middle plate was not as effective as above triple arrangement in terms of load-sinkage, but it caused minimum movement at depth. It was however supported more loads compared with dual arrangements. The images showed that interaction with upward movement between the side plates provided strong support for the third plate when it started to penetrate (see 4.22-b). A static block area in the middle appeared as soon as the third plate entered the soil and most of the subsequent movements were to the side (shown also in Figure 4.18). This pattern could change the direction of movement mostly horizontally to the sides rather than vertically to depth. The displacement line appeared to be the shallowest.

- c) Triple spaced, pattern 3: This arrangement with 35 mm lower middle plate was the least promising in terms of strain at depth as well as load-sinkage. The images showed that the lower middle plate caused deep displacement (see 4.22-c). This was thought to be due to the middle plate acting as a single plate without any interaction or resistance below. Moreover the interaction with the side plates after some sinkage could create extra pressure on the middle plate that would cause more movement at depth. Although the displacement line appeared to be deeper than the other triple arrangements it was still shallower than the very wide (Terra).
- d) Solid very wide as a Terra: Although this treatment claimed to be the most effective configuration in terms of load-sinkage relationship, it appeared from the single test results to create a large active wedge and passive planes (see 4.22-d). The large active wedge could move soil particles beneath the plate vertically at depth. The images recorded by camera and video revealed that a deeper layer of soil was affected under this arrangement and the displacement line is shown to be deep.
- e) Dual arrangements: The failure pattern and interaction sketch was discussed previously in section 4.4 under different spacings between the plates in the dual test results.

Therefore based on the failure pattern considering displacement limits, it is possible to rank the most promising arrangements causing minimum **displacement** at depth as follows:

- 1) Triple spaced, pattern 2-b, with 20 mm raised middle plate
- 2) Triple spaced, pattern 1, with three plates at the same level
- 3) Triple spaced, pattern 3, with 35 mm lower middle plate
- 4) Very wide plate as a terra with the same overall width as triple spaced

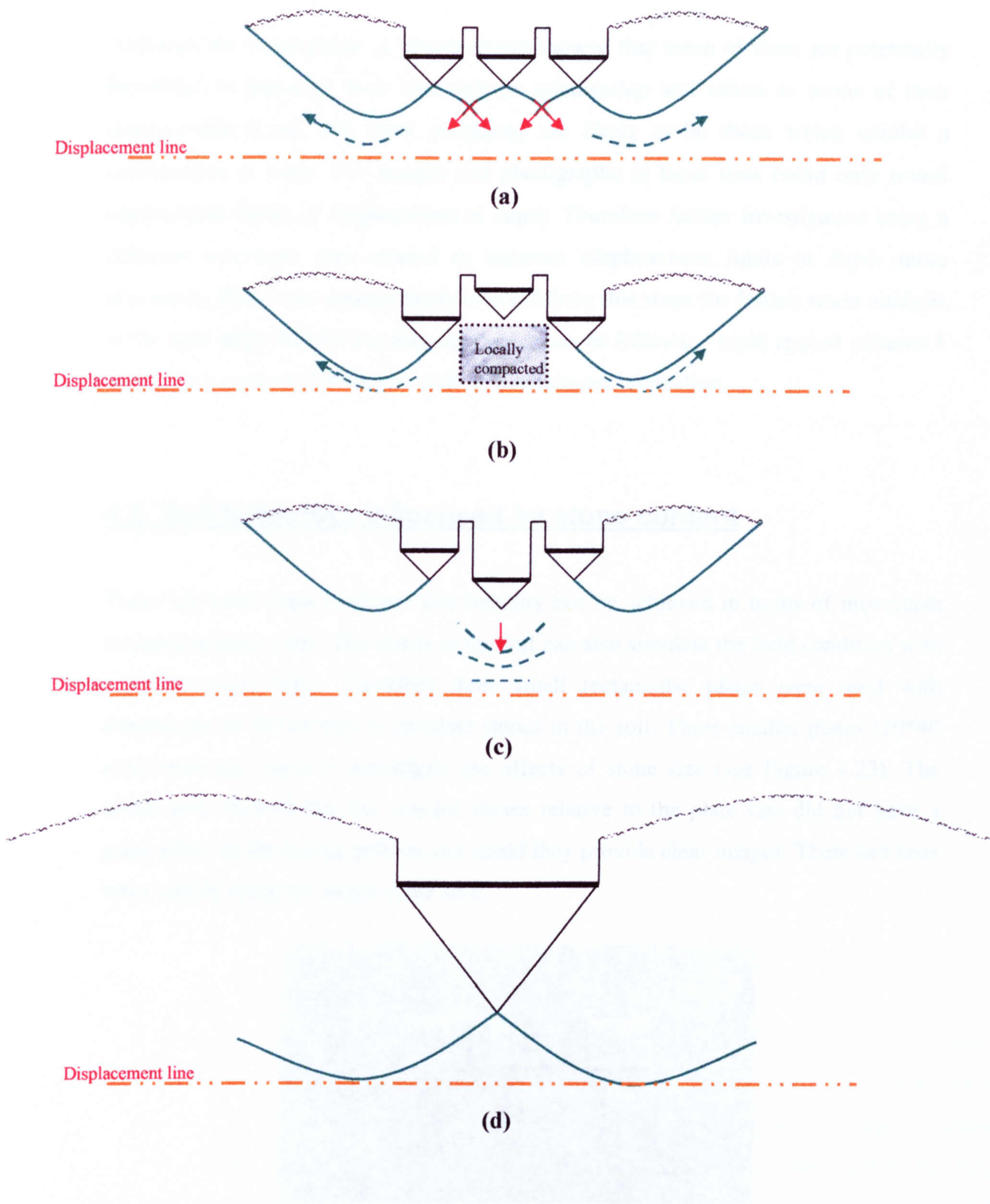


Figure 4.22. Failure pattern and displacement comparison under selected arrangements

4.7.3. Summary of discussions

Although the comparison of arrangements showed that some of them are potentially beneficial in terms of their load-sinkage relationship and others in terms of their displacement limits, the most promising are likely to be those which exhibit a combination of both. The images and photographs in these tests could only reveal approximate limits of displacement at depth. Therefore further investigation using a different technique was needed to measure displacement limits at depth more accurately. Hence the arrangements selected from this stage for further strain analysis at the next stage will be the four configurations as follows: triple spaced patterns 1 and 2, very wide as a Terra and dual with maximum interaction.

4.8. Soil behaviour influenced by stone content

There has been some evidence that benefits can be achieved in terms of movement changes in stony soils. The stones in the soil can also simulate the field condition with a limited hard layer. Therefore three small rectangular plates were used with dimensions of 40*40 mm to simulate stones in the soil. Three smaller plates (20*40 mm) were also used to investigate the effects of stone size (see Figure 4.23). The initial tests showed that the smaller stones relative to the plate size did not have a great affect on the failure pattern, nor could they provide clear images. Therefore tests were carried using the larger stone sizes.

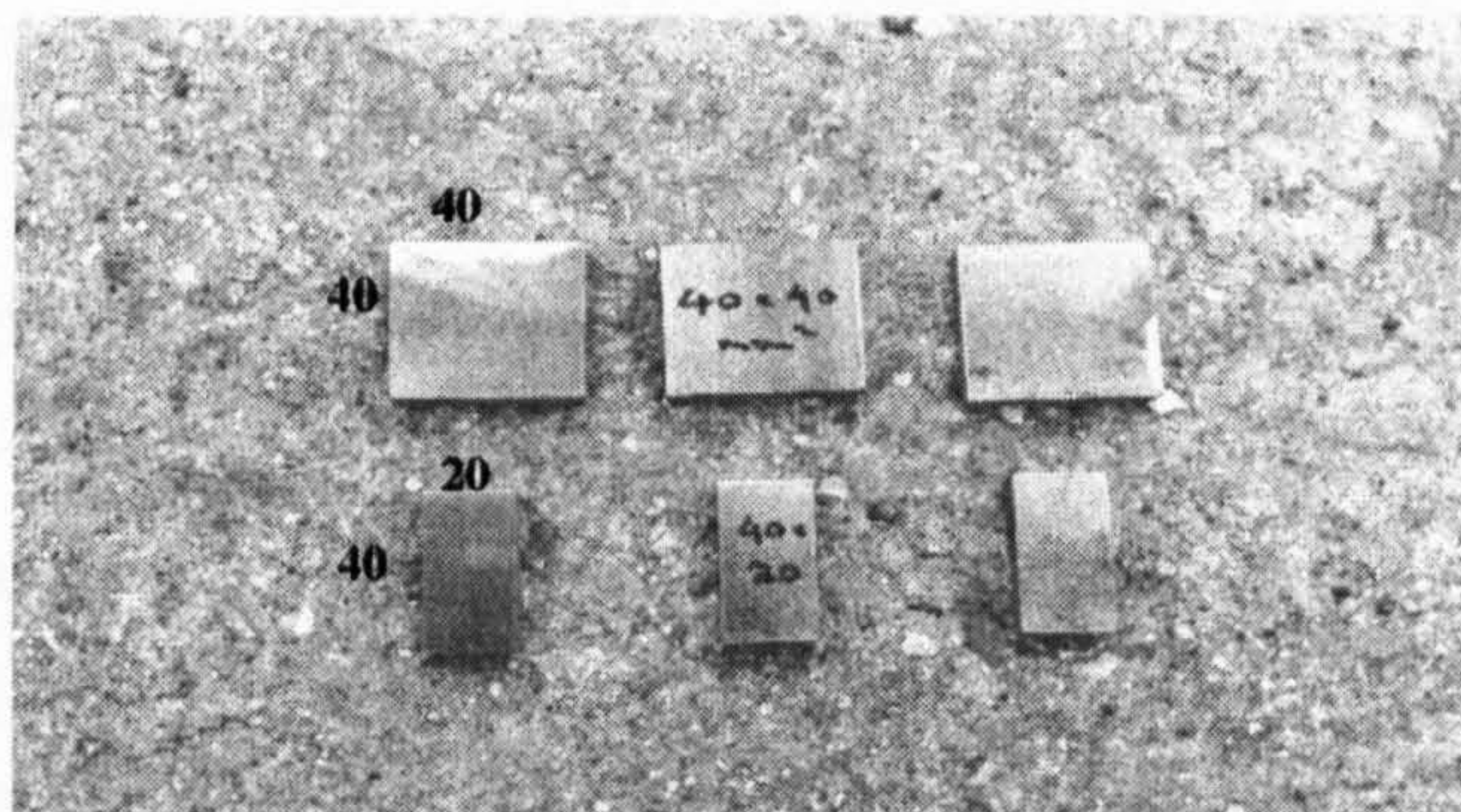


Figure 4.23. Simulating stones of two different sizes

A plate with the same dimension as the wide category (100*150 mm) was used to simulate a wheel with 2/5 aspect ratio to the width of the stones. The failure pattern changes, soil movements and load-sinkage relationships influenced by the stones were recorded using the same technique as described previously. The stones were placed in three different patterns in the soil as follows:

- 1) In this pattern, stones were placed at the same depth, 100 mm under the plate (see “a” in the Figure 4.24). The middle stone was placed under the centre of the plate.
- 2) In this pattern, the middle stone was placed 20 mm higher than the others (see “b” in the Figure 4.24).
- 3) In this pattern, the middle stone was placed 20 mm lower than the others (see “c” in the Figure 4.24).

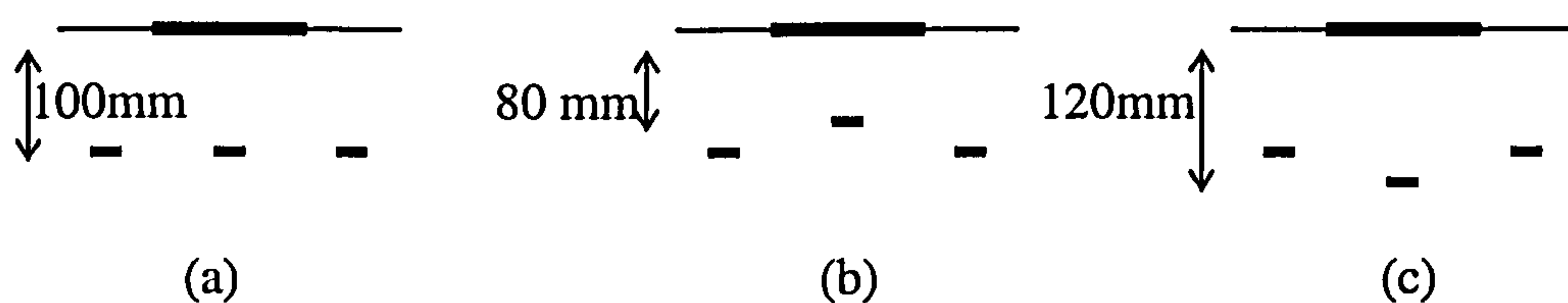


Figure 4.24. Different stone arrangements in the soil

The soil behaviour and failure patterns under each pattern are explained below.

4.8.1. Pattern 1, same level stones

The photographs indicated that as soon as the active wedge under the plate reached the middle stone, extra resistance was generated for further penetration (see Figure 4.25). By pushing the plate further into the soil, the small active and passive zones formed under the middle stone continued to develop increasing the support resistance further. This was due to the stone acting as a small footing that generating an increase in soil deformation resistance.

Comparing the load-sinkage results of the stone content tests with stone free soil indicated that the stones generated a greater slope in the second part of graph AB (compare “a” and “d” in Figure 4.26). This means that the load support capacity for a given sinkage can be increased in stone content soil.

4.8.2. Pattern 2, raised middle stone

The images showed that in this pattern the active wedge hit the middle stone for less sinkage than in pattern 1 causing the footing failure under the stone to be generated earlier (see Figure 4.25). The resistance due to side stones could influence the movement of the passive planes. The middle stone was pushed down by the plate until it reached the same level as the side stones. Soil behaviour then became the same as in pattern 1 after this point.

The load-sinkage results indicated an extended first part (AB) compared with pattern 1 and stone free soil. This was thought to be because of the earlier resistance of the middle stone whilst the plate was penetrating and pushing the stone down. As soon as the middle stone reached the same level as the others, the second part (BC) became similar to pattern 1 (see Figure 4.26).

4.8.3. Pattern 3, lower middle stone

Reviewing the photographs in this case revealed that there was no resistance under the plate due to the stones until the passive planes met the side stones (see Figure 4.25). The side stones would then tend to be moved largely horizontally. This means their effective footing width would be very small and hence the additional soil resistance would be small. The resistance became stronger when the active wedge hit the middle stone which would be moved downwards, giving effectively a larger footing width. In this situation an extra resistance could be generated for the passive planes moving upwards against the upper side stones. The load-sinkage results confirmed a similar

relationship in the first part (AB) to that in the stone free soil. The slope of the second part (BC) was found to be slightly greater than the other patterns (see Figure 4.26).

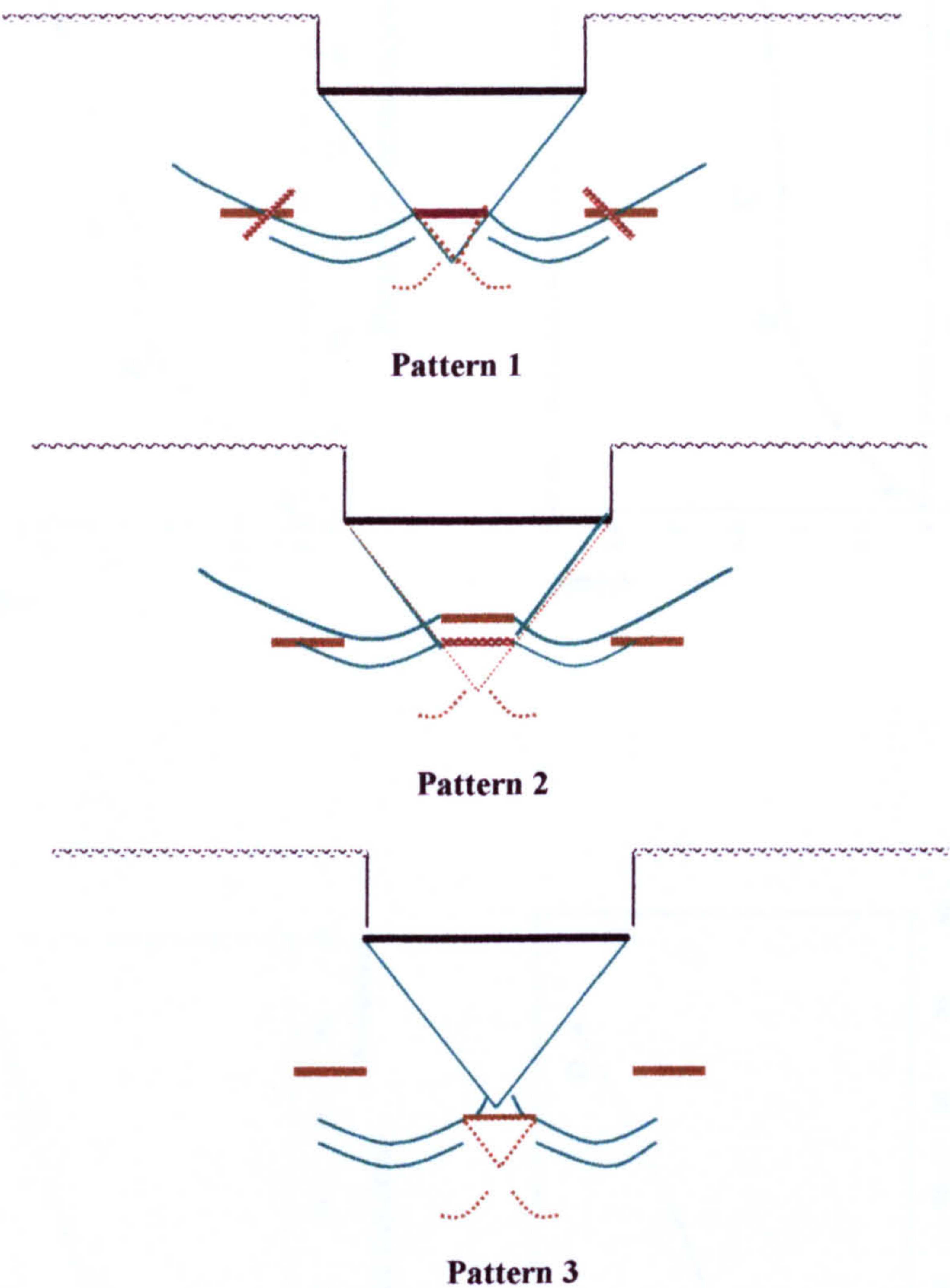


Figure 4.25. Soil failure pattern sketch under different stone patterns

4.8.4. Summary of discussions

It can be concluded that stones in the soil can have some benefit by increased soil strength and load support in the surface. The increase in soil strength will be dependent upon the shape, dimension, position and direction of the stones. The load-sinkage result indicated that there was potential in the stone content soil to support more loads for a given sinkage compared with stone free soil.

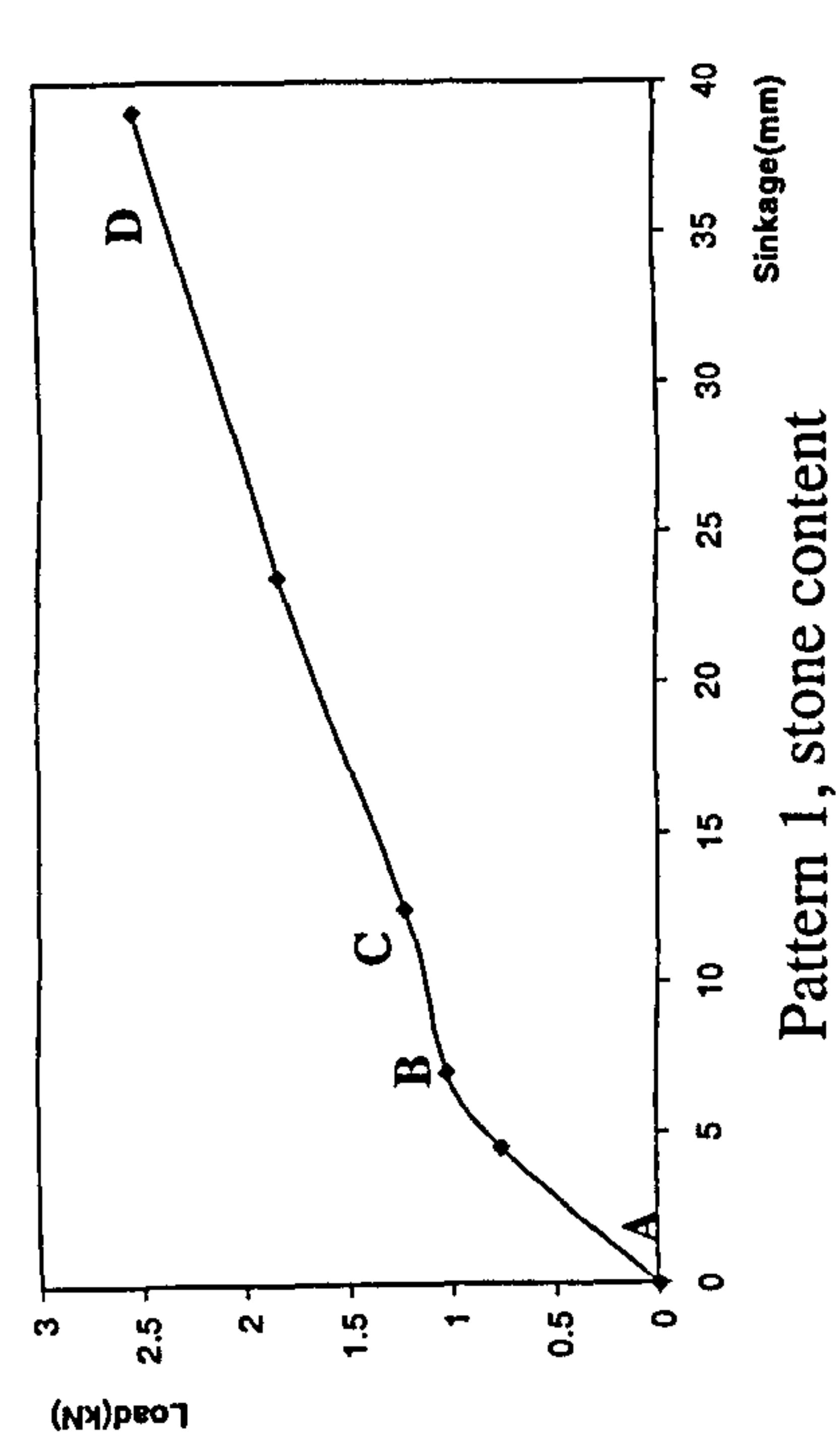
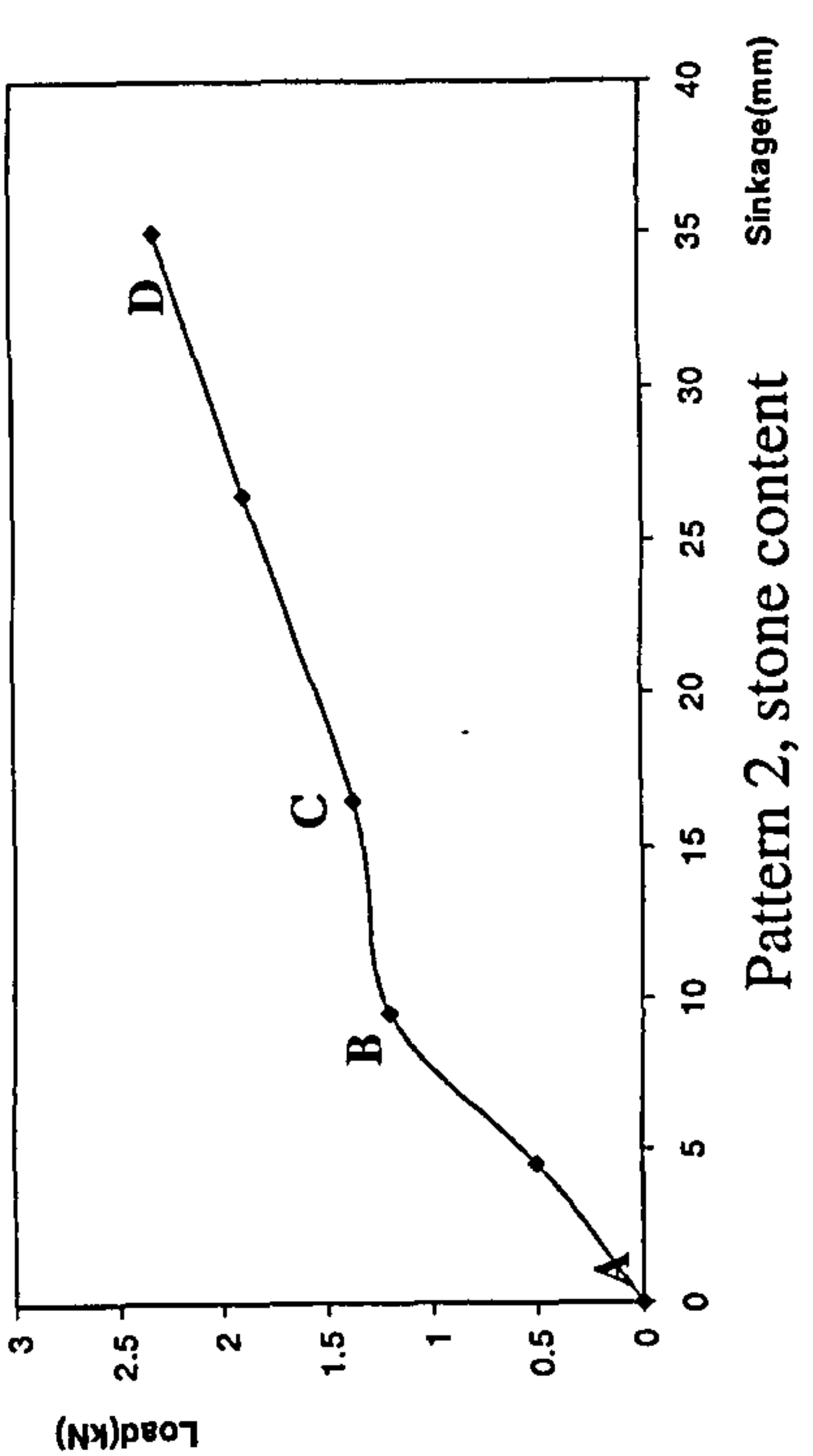
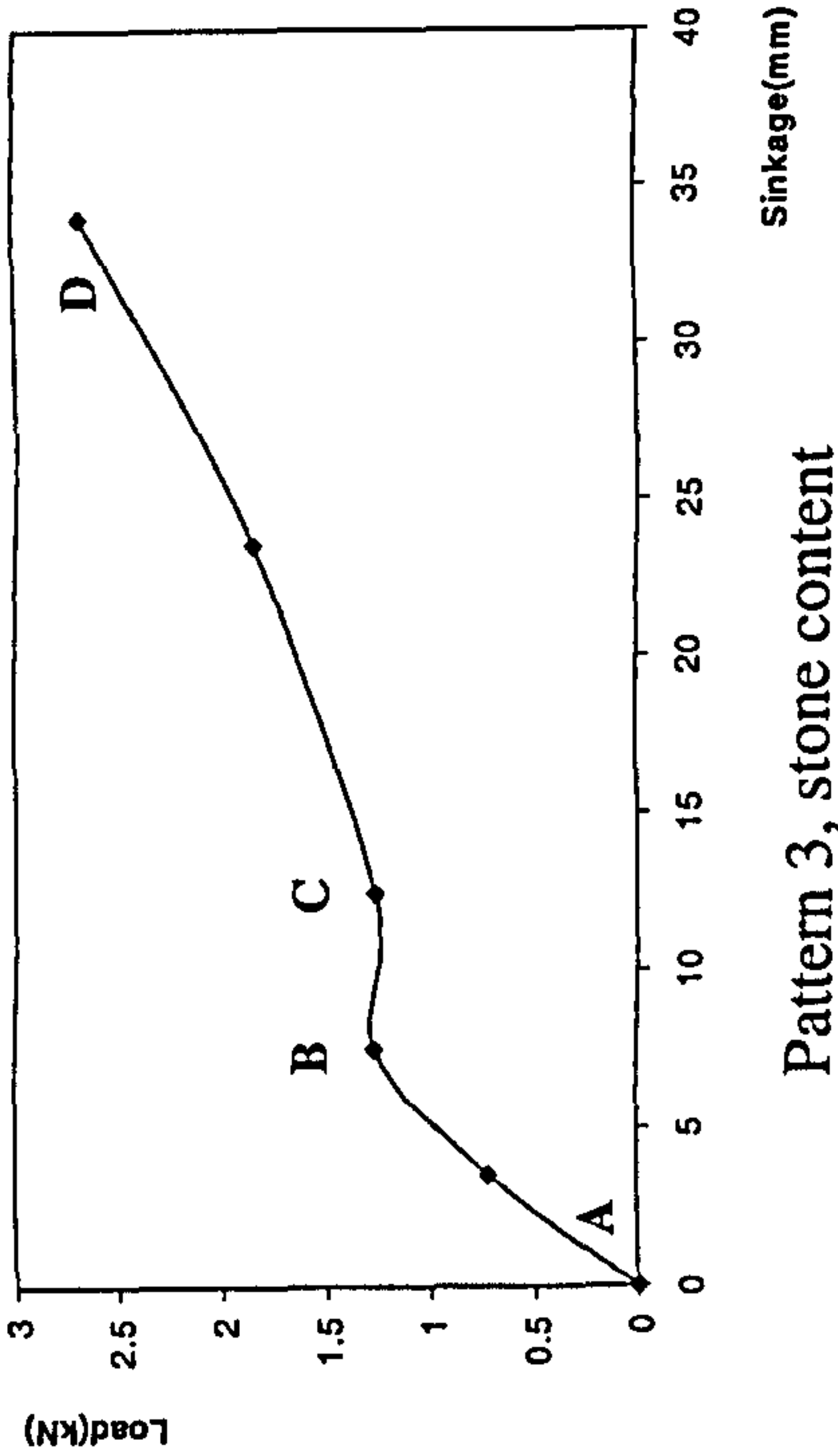
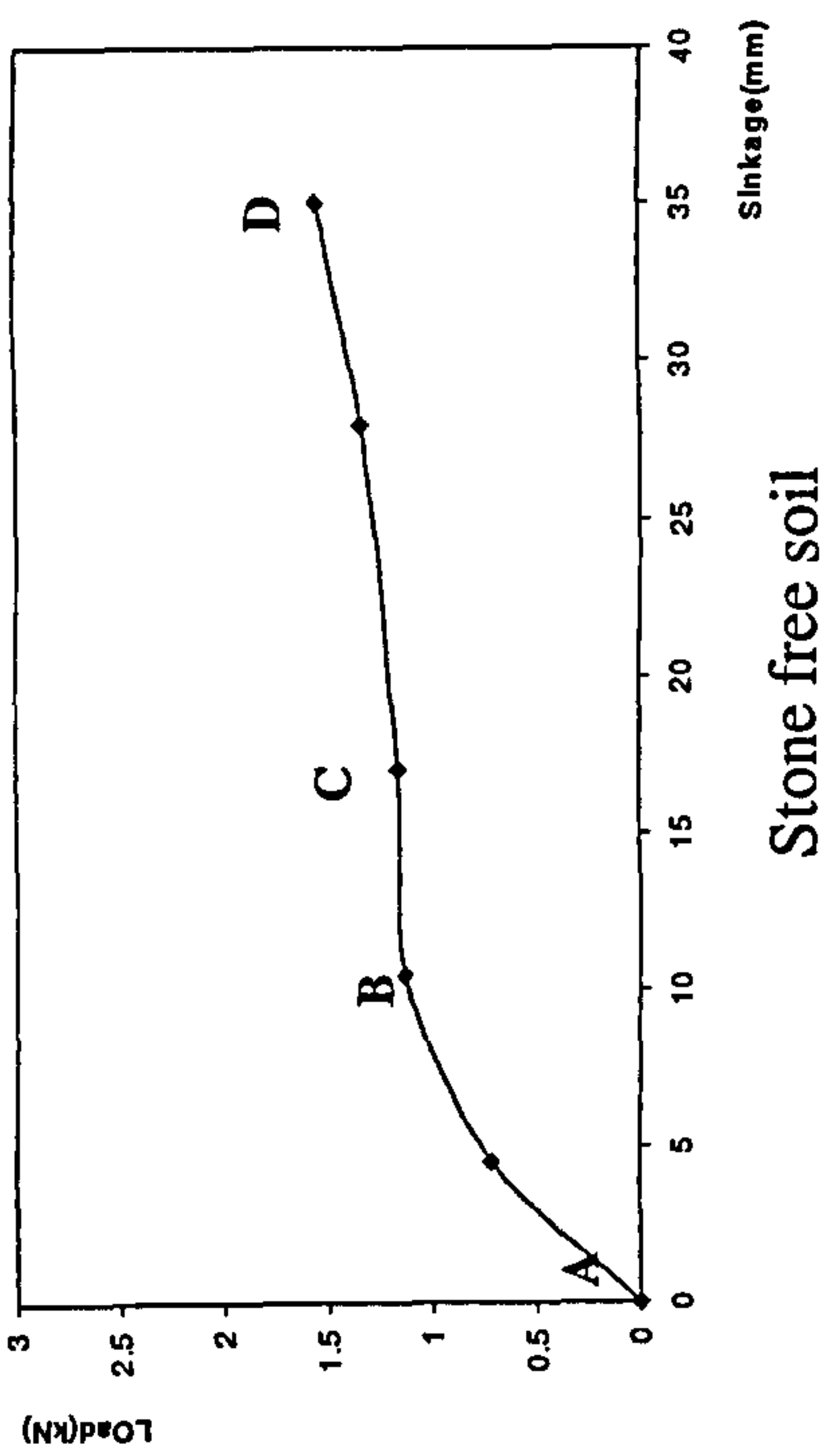


Figure 4.26. Different stone patterns in the stone content soil compared with stone free soil

4.9. Conclusions

- 1) There was a significant difference between the flat plate with a definite failure point and curved plates with almost linear load-sinkage relationships, hence the flat plates simulated more closely low pressure tyre behaviour.
- 2) The size of the active wedge and passive planes were found to be depended on the width of the plates.
- 3) In dual arrangements, there was the possibility to increase soil support with less displacement at depth by selecting appropriate spacings between them.
- 4) There were different modes of interaction identified in the dual tests starting from mode 0 (no interaction) to 3 (strong interaction) between the failure planes, which were depended on the spacing between the plates.
- 5) The spacings between the dual plates which provided maximum interaction (modes 2 and 3) can be recommended to be not greater than the width of wheel, nor smaller than the 1/4 width of wheel.
- 6) There was an advantage, causing less movement at depth, from dividing a very wide wheel into spaced triple arrangements with the same contact pressure.
- 7) The triple spaced arrangement with the 20 mm raised middle plate was shown to cause minimum displacement at depth.
- 8) It is necessary to measure and analyse the strain and soil displacement limit more accurately at depth for the selected promising arrangements to allow more substantive conclusions to be drawn.
- 9) Stone content in soil can have some benefit in terms of increasing surface support depending upon their shapes, dimensions, positions and directions. The stones can simulate the effect of firmer layer at tillage depth in the field.

Chapter 5. Soil displacement limits under simulated wheel arrangements

5.1. Introduction

The most promising arrangements selected from previous tests are investigated in this chapter to identify soil displacement limits accurately. A sandy loam soil was used in the glass-sided tank and prepared in two layers, a looser surface layer and a denser lower layer simulating common field conditions. Round beads in a grid pattern were used as markers in the soil to identify soil movements after the tests. A different photographic technique was used enabling the transfer of images into a computer for further analysis. A software package, Global Lab Image (GLI), was used to analyse the images and reveal the movement and displacement accurately. The software could read and convert the bead locations into an array of data.

The selected arrangements were investigated under both specific sinkage and loading situations. In each case the soil movement pattern and displacement limits were identified using the image analysis software. The load-sinkage relationship was also recorded during the experiments. The results of these experiments provided clear accurate evidence of displacement at depth to identify the most promising configurations.

The main objective of this chapter is to identify those arrangements showing the most promising types of deformation to minimise compaction at depth and also provide reasonable load support at the surface.

5.2. Experimental procedure

5.2.1. Soil preparation

The soil was prepared to simulate a common field condition with a dense lower section and looser upper section. A sandy loam soil was used in the glass tank to provide real soil conditions (see Table 5.1 for more detail).

Table 5.1: Soil characteristics under investigation

Soil	Sand(%)	Silt(%)	Clay(%)	Organic matter(%)	Moisture content(%)
Sandy loam	68.5	19.0	12.5	3.2	8.2

The densities of the two layers simulated field situations. The dense bottom layer was prepared by filling the tank in layers approximately 30 mm thick. Each layer was compacted separately, to about 1.5 Mg.m^{-3} density by hand. The density was measured and controlled by taking at least two samples during each soil preparation. The process was repeated until the tank was half filled (125 mm thick). Figure 5.1 shows the compacting process in the bottom layer. The tank was then filled with looser soil at a density of 1.25 Mg.m^{-3} and its surface levelled prior to positioning the markers.

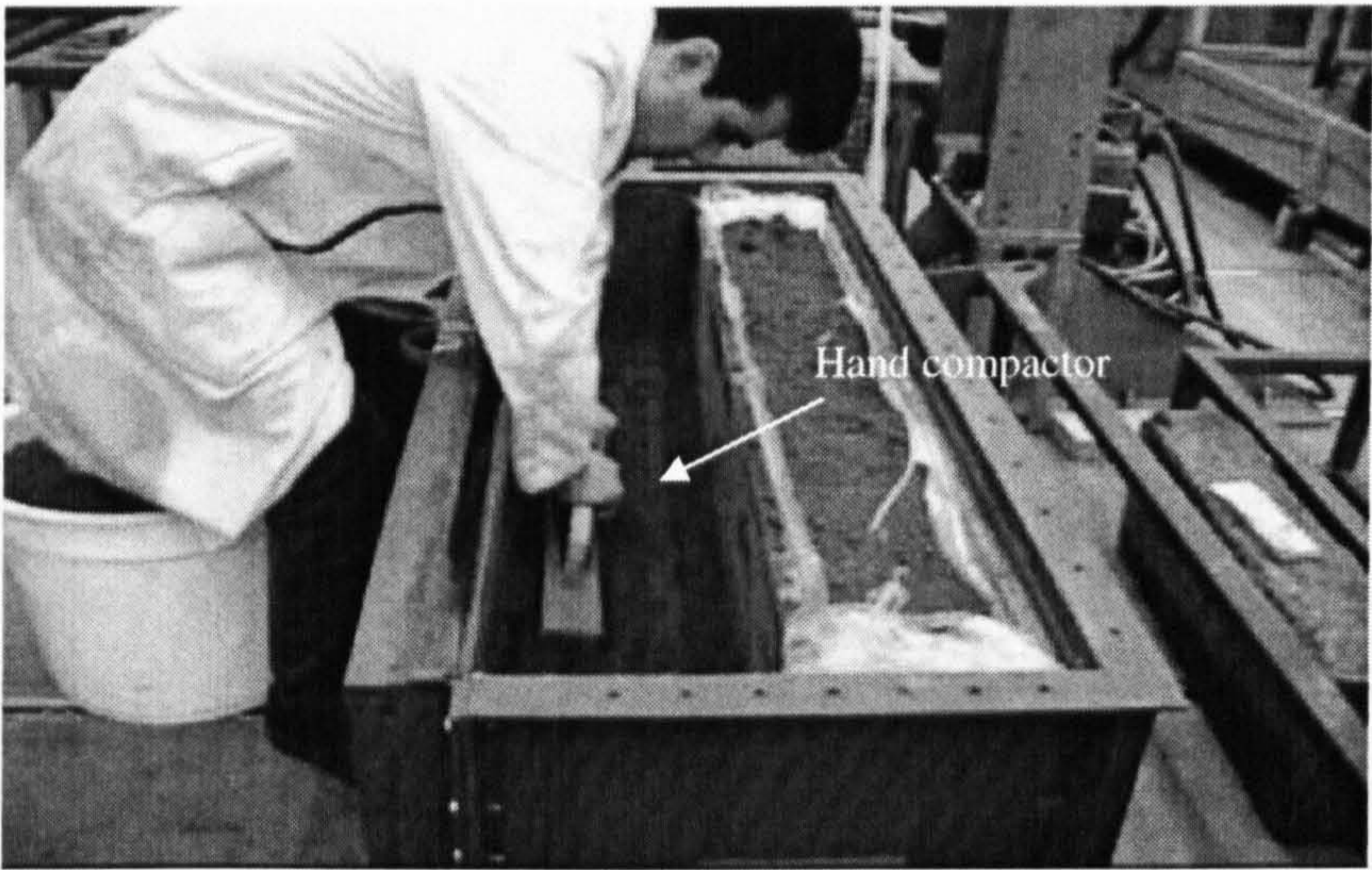


Figure 5.1. Soil compacting process by hand in the glass tank

5.2.2. Soil marking

After soil preparation, the top cover of the tank was bolted to the main frame to retain the soil. The tank was then rotated through 90° , to bring the glass frame to the top rather than the front. By removing the glass frame, the soil could be prepared for the marking process (see Figure 5.2).

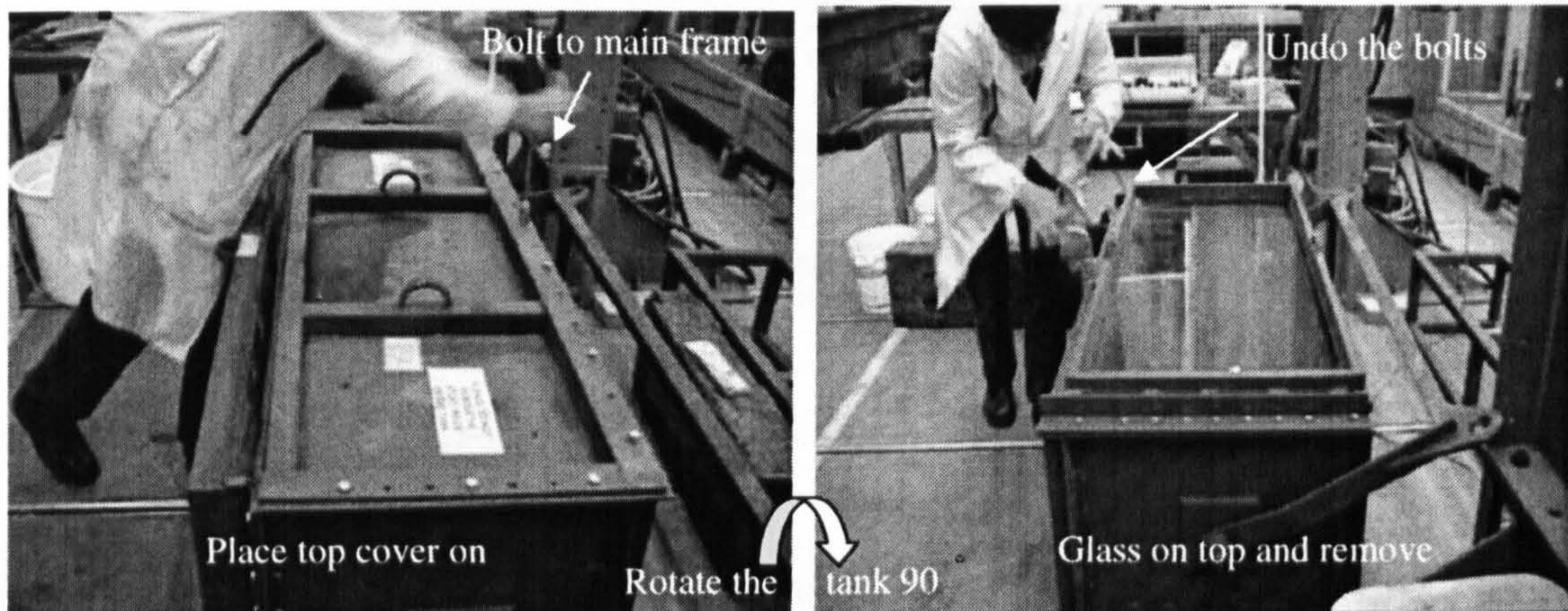


Figure 5.2. Soil marking process stages with rotating the glass tank

Round beads 5 mm diameter were used as markers inserted into the soil in a grid pattern to identify the soil movements and displacement limits. A perspex sheet was made with dimensions similar to the width and depth of the prepared soil in the tank and drilled to provide a grid of holes in 23 rows and 11 columns (253 total) 25*25 mm apart for the insertion of the marker beads. Hole diameter was 5.3 mm which was slightly larger than bead diameter. This provided an area 550 mm wide and 250 mm deep to investigate the soil movement under the plate arrangements. Before positioning the beads, the perspex sheet was bolted to the tank to ensure it was in the same place for all treatments and to avoid any displacement during bead insertion. A small plunger was made to insert the beads through the perspex sheet into the soil. The plunger tip diameter was slightly smaller than the perspex holes enabling it to push the beads into the soil. Figure 5.3 shows the perspex sheet and plunger developed for the marking process.

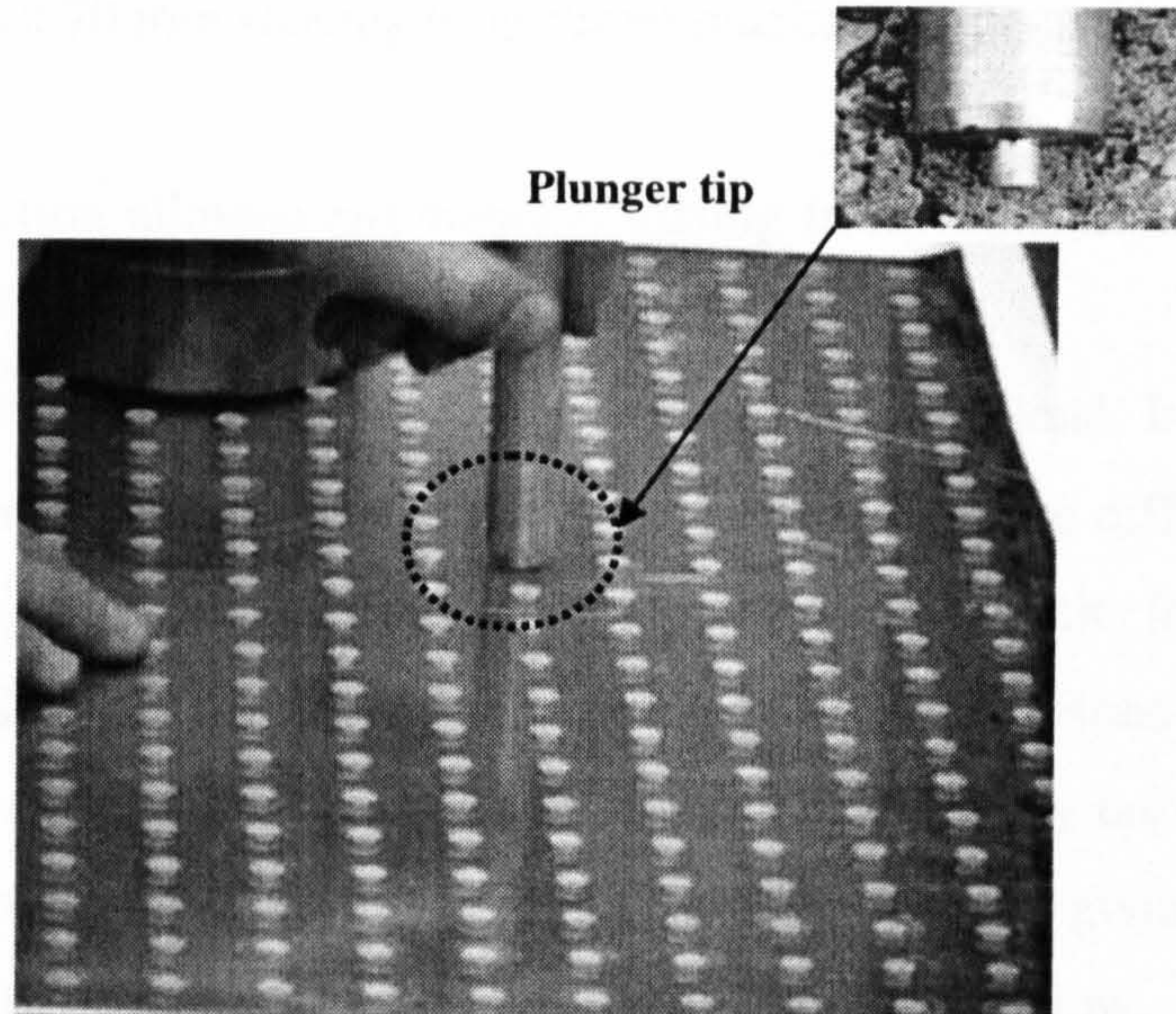


Figure 5.3. Developed Perspex sheet and plunger for beads insertion

After bead insertion, the perspex sheet was removed slowly, the glass frame replaced and the tank re-rotated to bring the glass frame to the front again. Finally, the top cover was removed to start the experiment.

5.2.3. Results monitoring procedure

The result monitoring and image analysis process as using the global lab image (GLI) software package is explained in Appendix 1. This package needs digital photographs and converts the bead locations into an array of data.

5.3. Arrangements tested

The following plate arrangements were investigated and compared in terms of their displacement limits:

- 1) Very wide plate simulating a terra tyre ($210 \times 150\text{mm}$ plate dimensions)
- 2) Triple spaced plates at the same level with the same overall width as the terra ($70 \times 150\text{mm}$ each)
- 3) Triple spaced plates but with the middle plate raised 20 mm, overall width as terra ($70 \times 150\text{mm}$ each)

- 4) Dual plates with a 70 mm spacing to generate maximum interaction in the centre

This treatment selection allowed any benefits arising from using triple spaced plates of the same overall width as the simulated terra to be identified.

The arrangements were compared for both given sinkages and load. In the first tests, the displacement limits and tolerated loads were identified for two different sinkages. These tests were followed by the investigation of displacement limits for a given load, the actual sinkage for this load being recorded. Finally comparisons were made in terms of both displacement limits and supporting load to identify the most effective configurations. Two replications of each arrangement were made giving a total of 24 treatments. The total number was obtained from the expression below.

$$4 \text{ arrangements (2 given sinkages + 1 given load)} = 12 * 2 \text{ replications} = 24 \text{ total}$$

5.4. Results and discussions

Only the final graphs made from the image analysis process are discussed in this section. Photographs recorded during the analysis are given in Appendix 1.

It has to be mentioned that the displacement limit given in the following results is the deepest marked layer which showed bead movements identified by Image analysis software. The actual displacement limit could occur somewhere between the identified layer and the next marked layer below. As however as the marked layers were 50 mm apart, there could be an error of up to 49 mm in the recorded displacement limit. Since however comparisons between treatments were made on a basis of differences of 50 mm, any error in the actual displacement limit would not affect the overall comparisons and conclusions.

5.4.1. Displacement limits for given sinkages

a) 50 mm sinkage:

Loading proceeded until 50 mm of sinkage occurred, loading was then stopped and the image photographed for analysis. Figures 5.4 – 5.7 show the bead displacements and the tolerated loads at 50 mm sinkage

for the different treatments (D.L. indicates the displacement limit at depth). The simulated terra supported the highest load but the greatest depth of soil was affected. Displacement occurred to a depth of 250 mm, showing the potential of this arrangement to cause deep movement. (see Figure 5.4). This deep movement was due to a very large active wedge and passive planes identified previously.

By dividing the very wide tyre in to three narrow ones, but keeping the same overall width as the terra, the image analysis results confirmed shallower movements. The soil displacement limit under the triple spaced plates at the same level was one layer shallower than the terra, 225 mm depth (see Figure 5.5). Moreover soil movement in the shallower layers were significantly less than with the terra plate. This was due to smaller individual active and passive zones under the plates and the interactions between them.

One noticeable point with the spaced patterns is that, not only there is an advantage in terms of strain, but also there is no significant difference in the tolerated loads (compare the tolerated loads 8.58 and 8.33 kN).

The third arrangement with a 20 mm raised middle plate proved the most promising configuration in terms of strain. Figure 5.6 shows that the soil was not displaced in the dense section under this arrangement and the displacement limit was significantly shallower (150 mm depth) than the others. Moreover the beads under the middle plate only moved slightly due to interaction between the plates and the formation of a static area in the middle. This confirmed the results obtained in the sand tests identified previously. The tolerated load for this arrangement was however less than for the others.

The results of the dual arrangement indicated that the displacement limit was just above the dense section 150 mm depth, which was the same as with the triple raised one. The tolerated load was however the lowest (see Figure 5.7).

Given 50 mm sinkage:

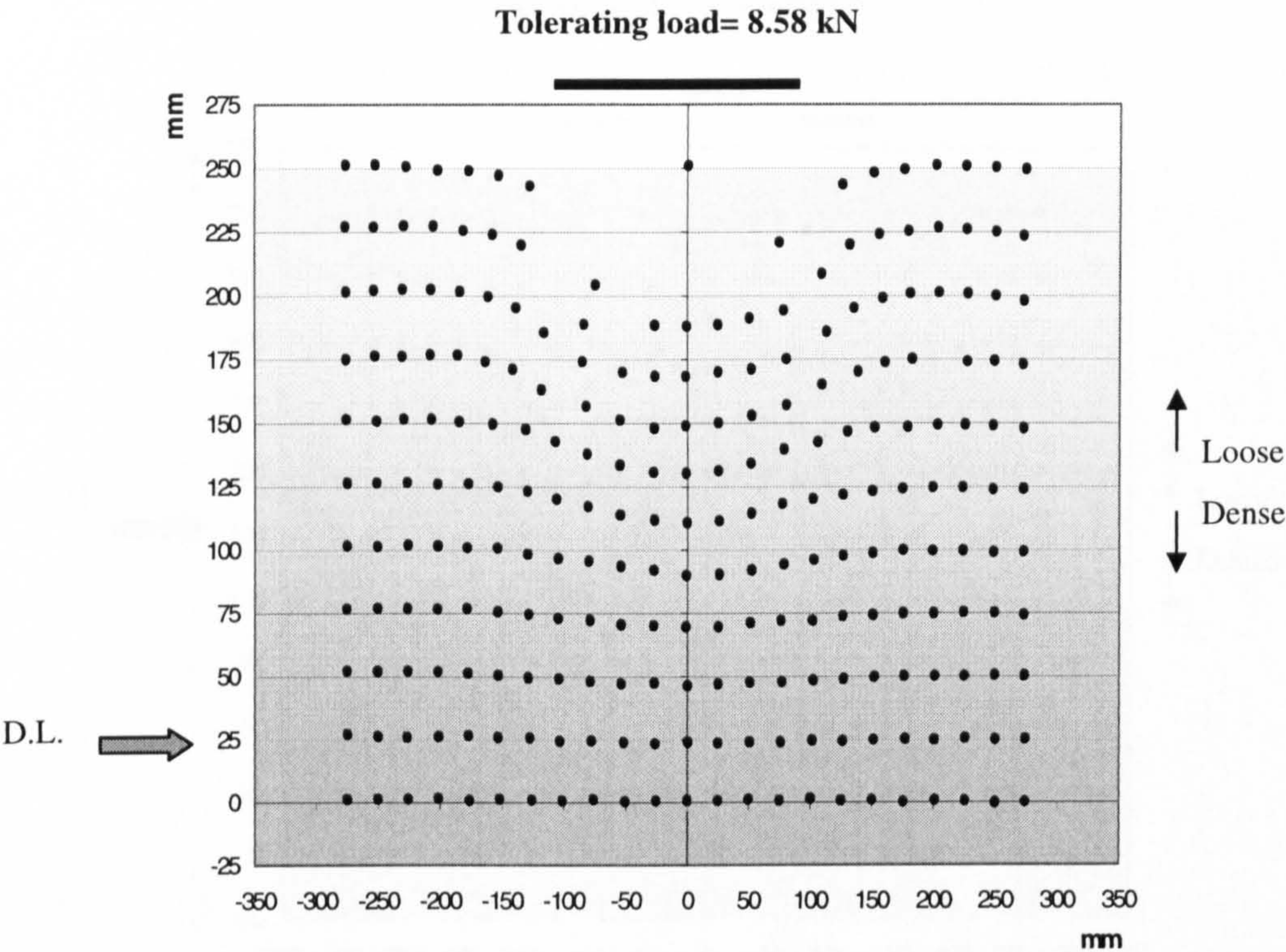


Figure 5.4. Soil displacement limit and movement under Simulated Terra

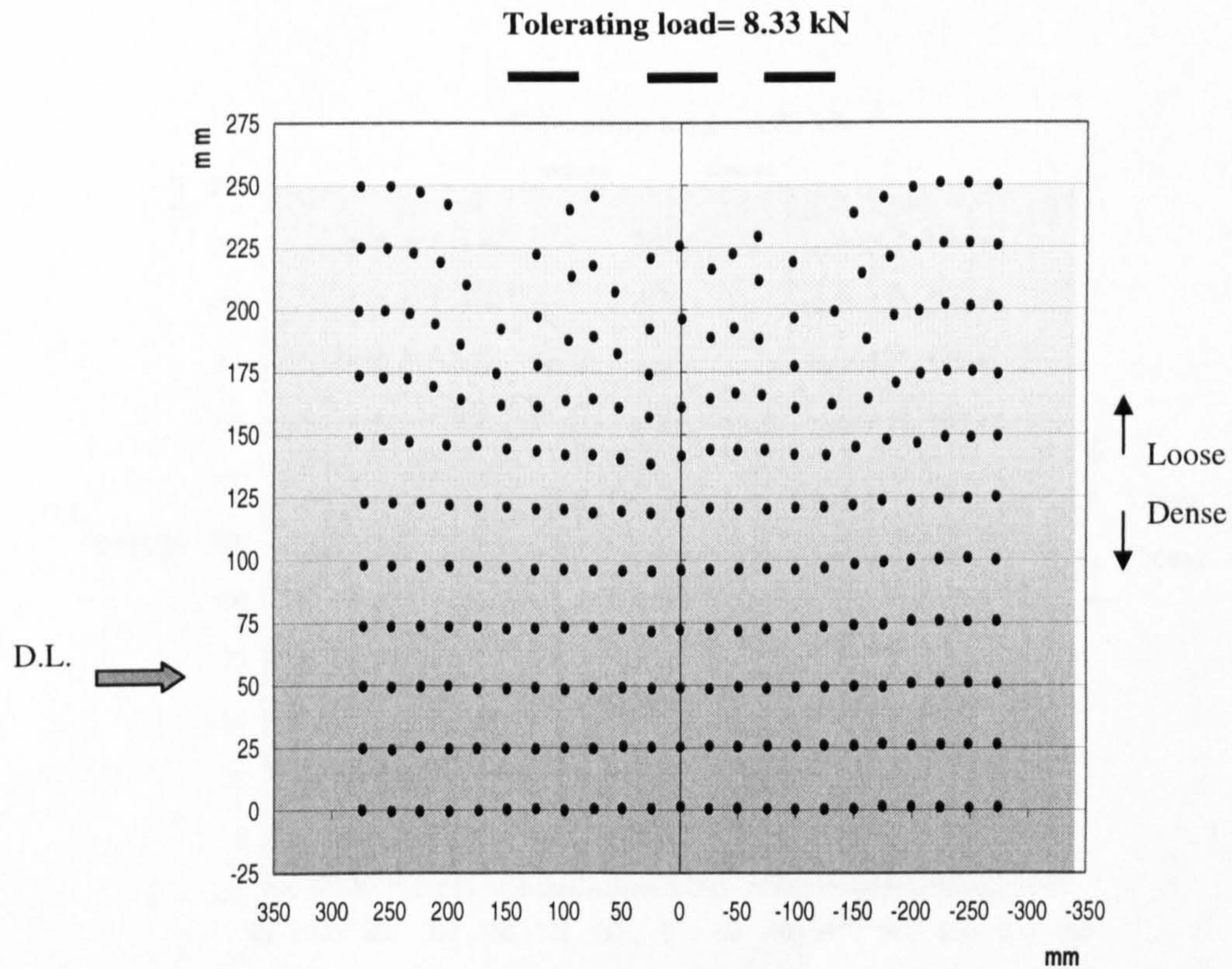


Figure 5.5. Soil displacement limit and movement under Triple spaced with same level plate

Given 50 mm sinkage:

Tolerating load= 6.62 kN

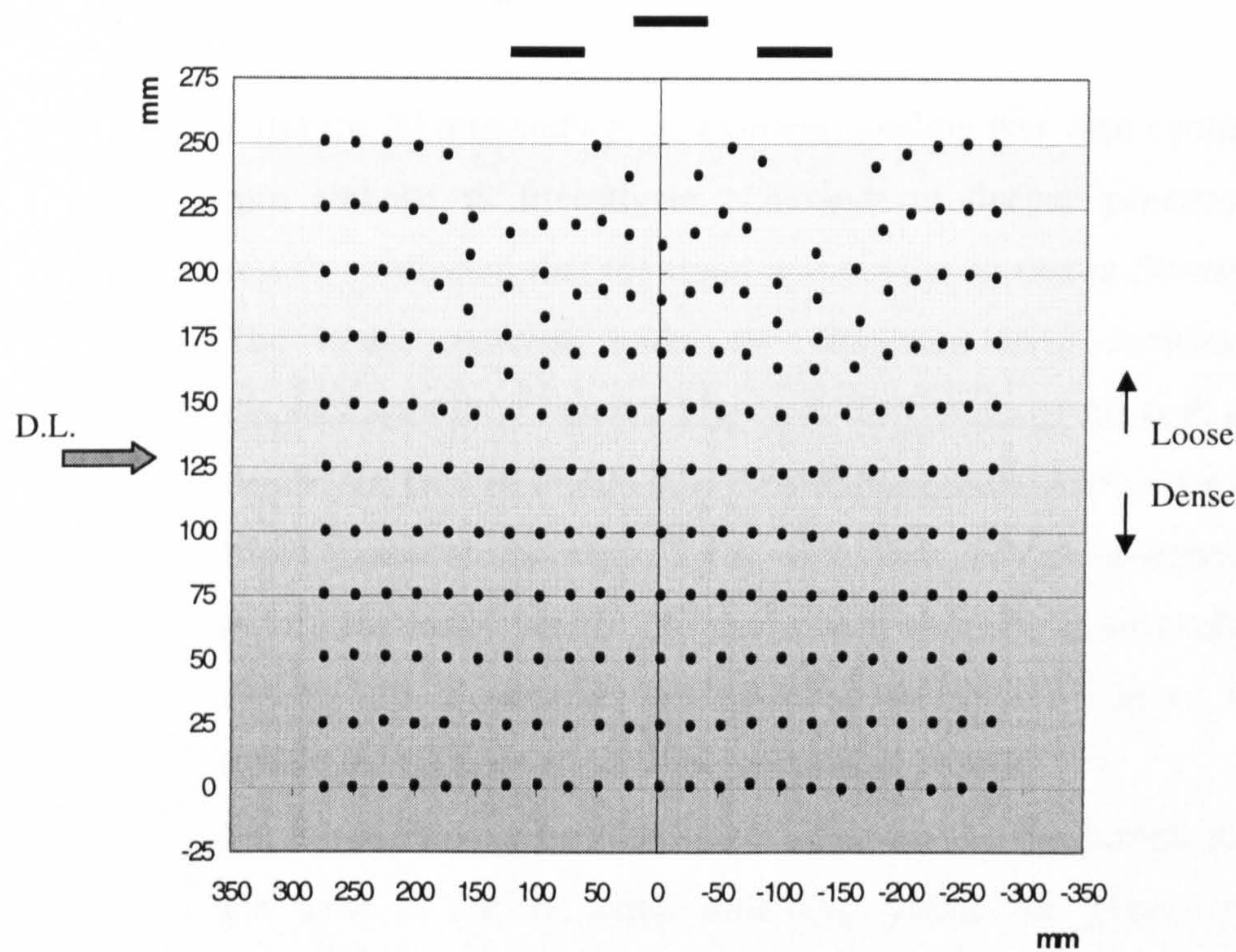


Figure 5.6. Soil displacement limit and movement under triple raised middle plate

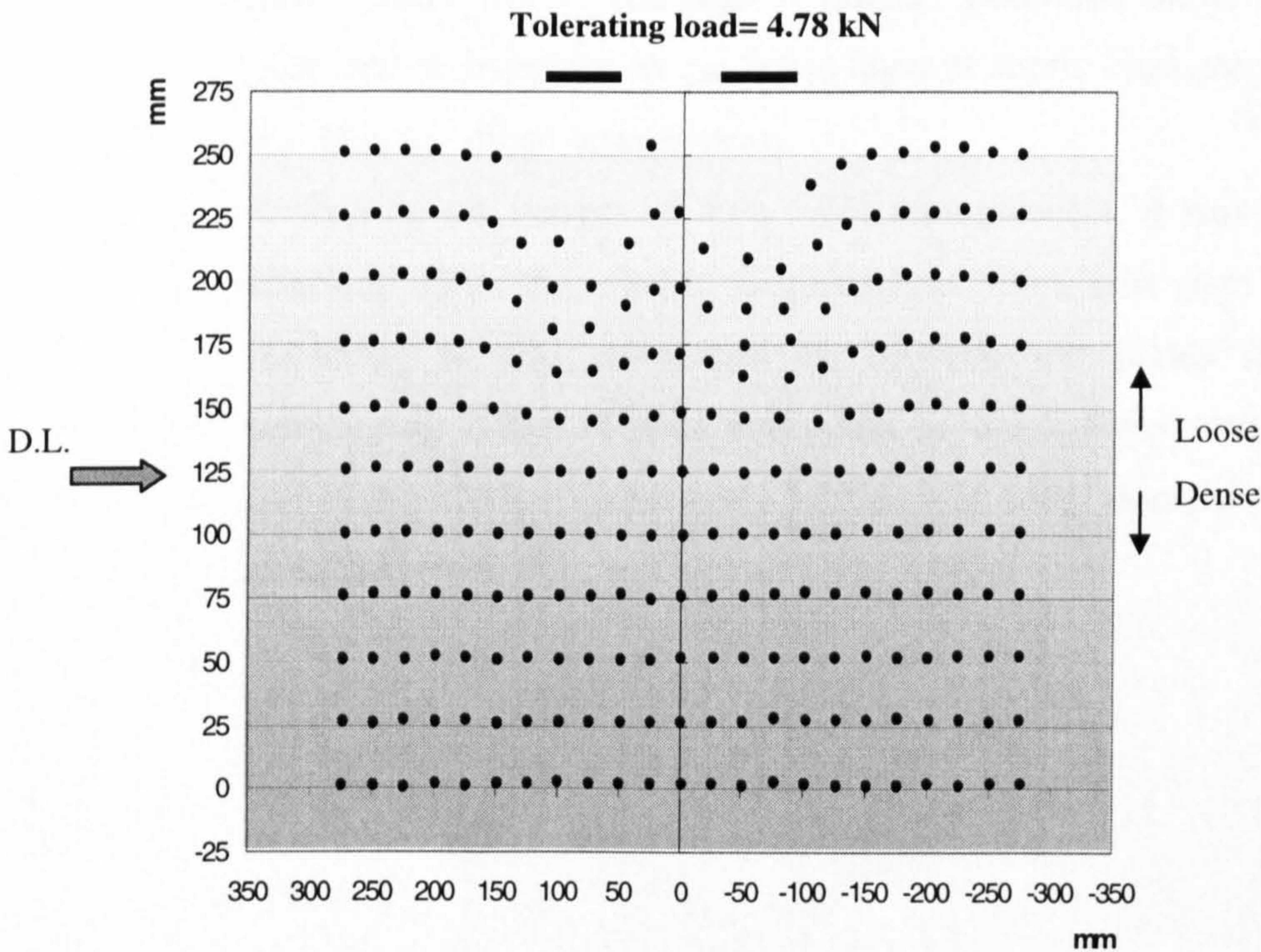


Figure 5.7. Soil displacement limit and movement under dual for a given 50 mm sinkage

b) 90 mm sinkage:

After the 50 mm sinkage assessment, loading was then continued to 90 mm sinkage to investigate behaviour at deeper penetrations. The results confirmed that the trend was similar to that at 50 mm sinkage. The image analysis under the simulated terra showed that the displacement limit extended down to the bottom of the tank at 275 mm depth (see D.L. in Figure 5.8). The displacement limit under the spaced triple plates at the same level were also moved downward to just before the last layer to 250 mm which was one layer shallower (see Figure 5.9). Comparing the tolerated loads there was no significant difference between these arrangements as before.

For the triple raised middle plate, although the displacement limit was the same as for the triple with level plates, the general movement above that limit was less (see Figure 5.10 and compare the movement). The tolerated load was significantly higher compared with that at 50 mm sinkage due to the high resistance generated under the middle plate and deformation in the dense layer at depth. However it was still less than the other arrangements.

Reviewing the images of both triple arrangements, it was possible to conclude that, the deeper displacement limit was due to a high resistance to soil movement in between the plates as well as surcharging effects. Hence soil could be blocked between the plates converting them in effectively into a rigid wide plate, similar to the simulated terra.

Given 90 mm sinkage:

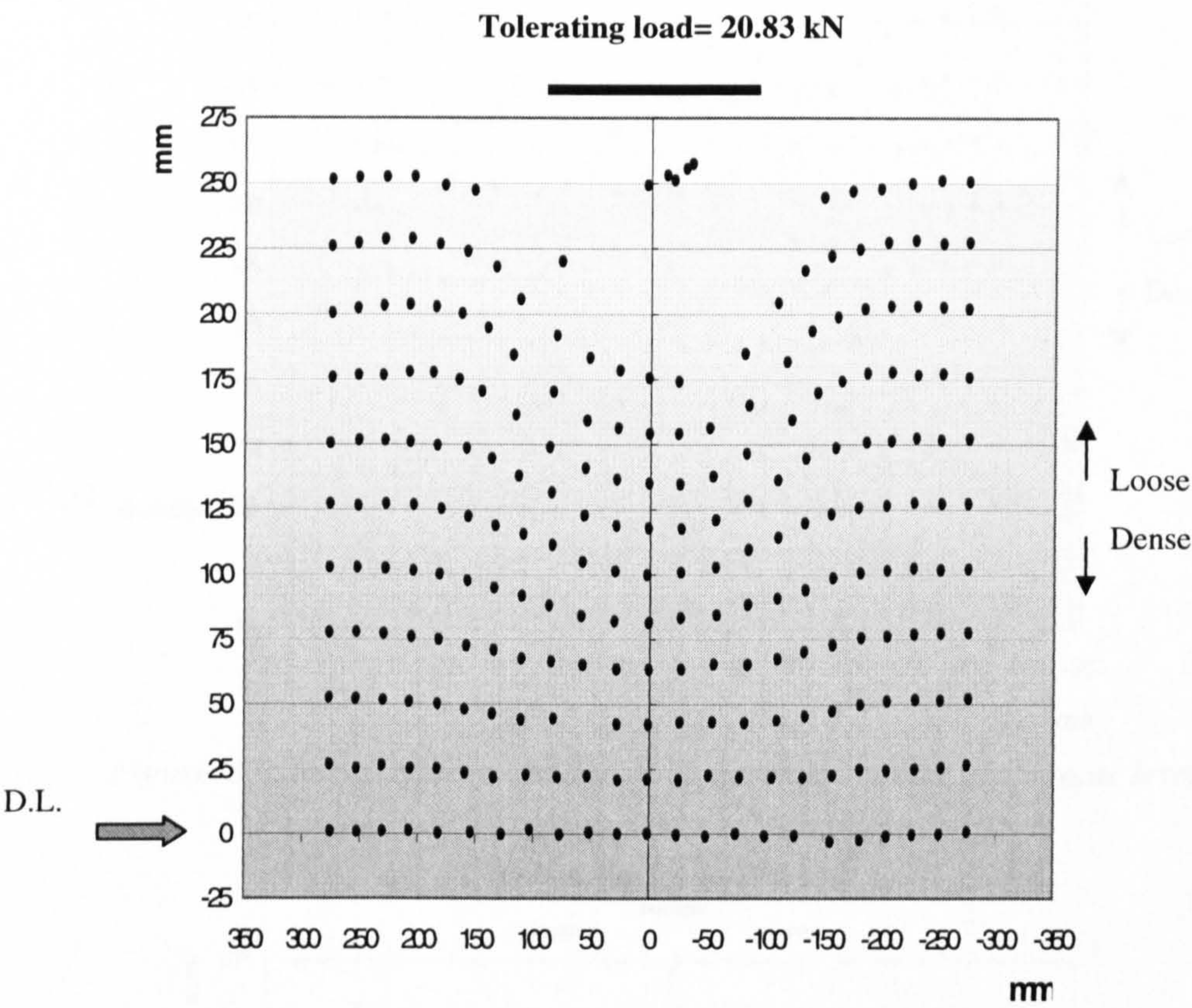


Figure 5.8. Soil displacement limit and movement under simulated Terra

Given 90 mm sinkage:

Tolerating load= 21.03 kN

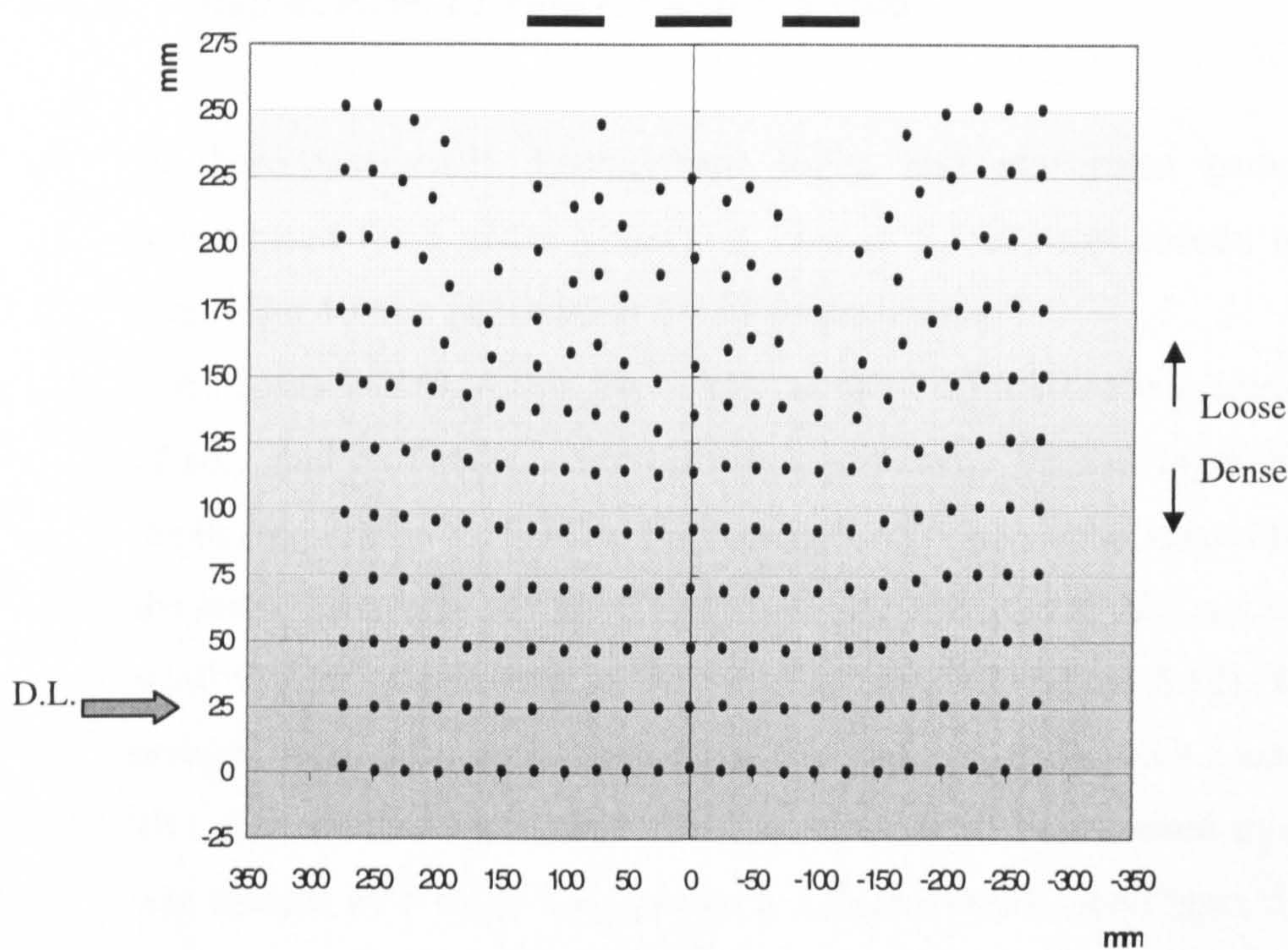


Figure 5.9. Soil displacement limit and movement under triple same level plate

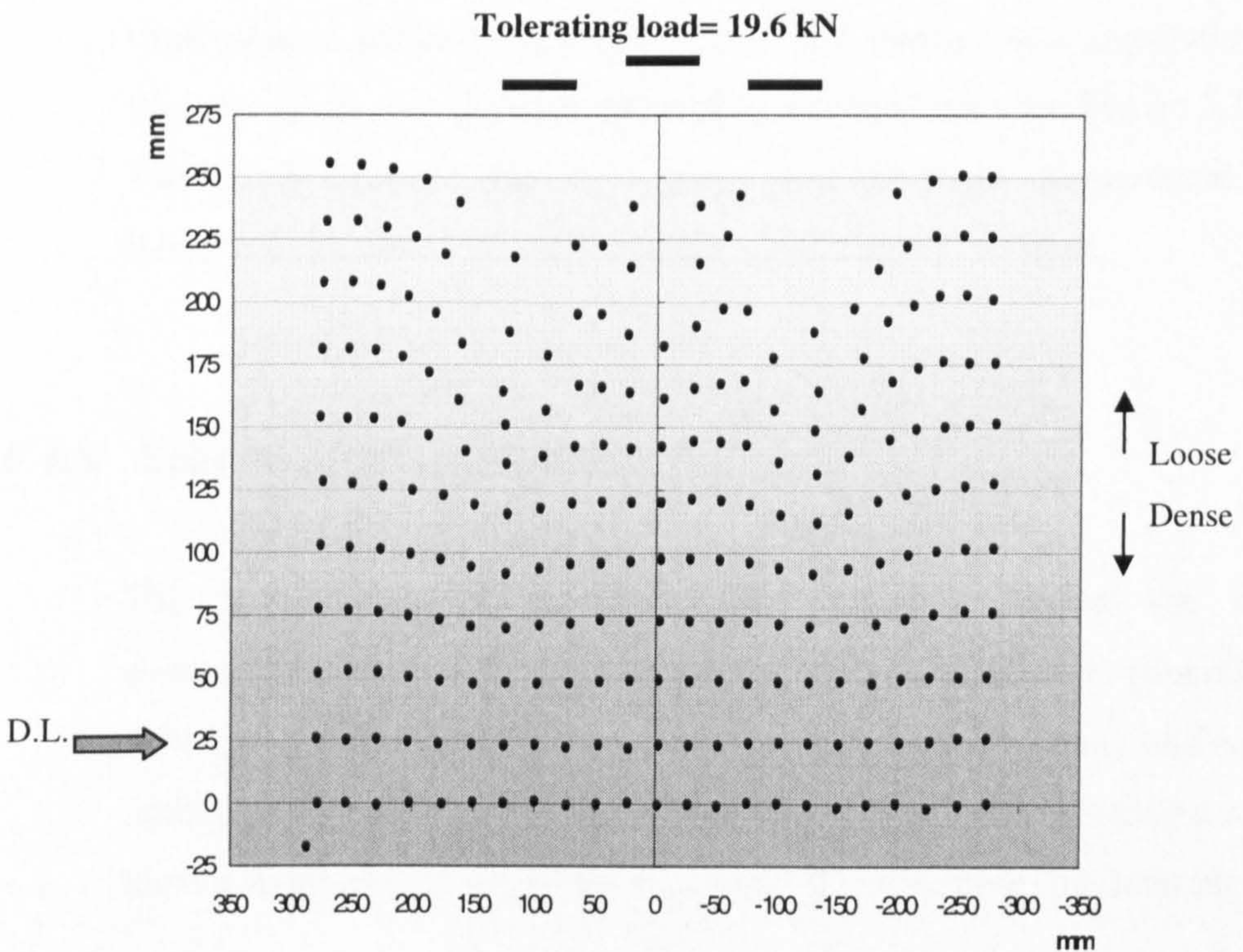


Figure 5.10. Soil displacement limit and movement under triple raised middle plate

5.4.1. Displacement limits for a given load

In these tests, soil displacement limits and movement patterns were investigated for a given loading. A load of 8.5 kN was chosen to provide more than 40 mm penetration for all arrangements. .

The results indicated that the simulated terra disturbed the greatest amount of soil and its displacement limit was just above the last layer at 250 mm depth (see Figure 5.11). The displacement limit under the spaced triple with the level plates was one layer shallower than the terra at 225 mm depth with relatively less movement in the dense section (see Figure 5.12). There was no significant difference between the two sinkages under such a load.

The displacement limit under the spaced triple with the raised middle plate was similar with triple level plates at 225 mm depth (see Figure 5.13). The sinkage was, however slightly more than with the other arrangements.

The displacement limit under the dual arrangement was similar to both triple spaced plates at 225 mm depth. The sinkage was significantly more than the others, not the most promising arrangement (see Figure 5.14).

The results indicate that for a given load the triple arrangement with the raised middle plate caused minimum displacement at depth.

5.4.3. Load-sinkage relationship

The load-sinkage relationships were recorded during the tests for comparison purposes between the arrangements. The results generally reveal different failure graphs between the non-uniform and uniform soils. Although the first parts of the curves (Figure 5.15) where sinkage was in the loose condition were fairly similar, in the dense section, the load increased

Given 8.5 kN load:

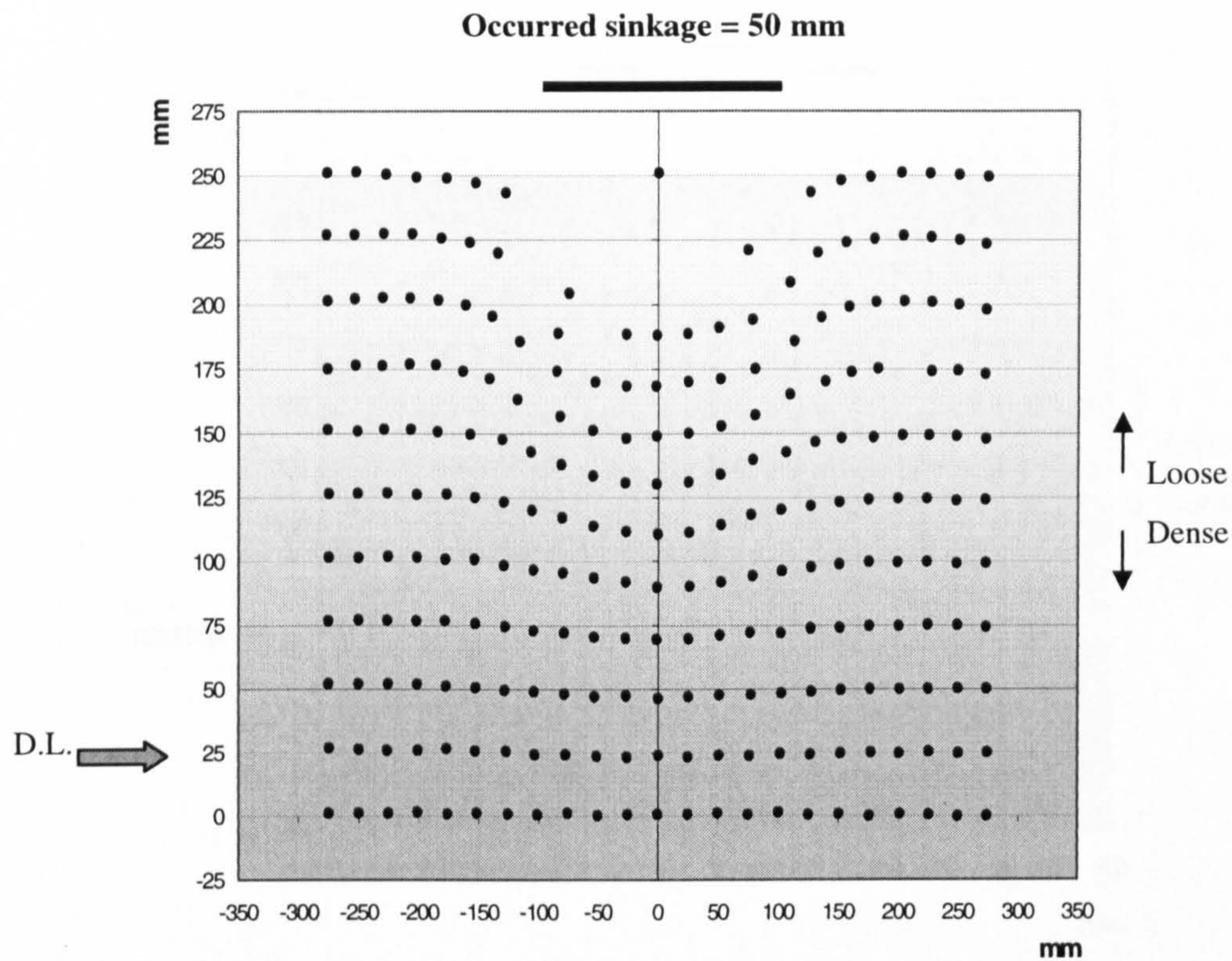


Figure 5.11. Soil displacement limit and movement under simulated terra

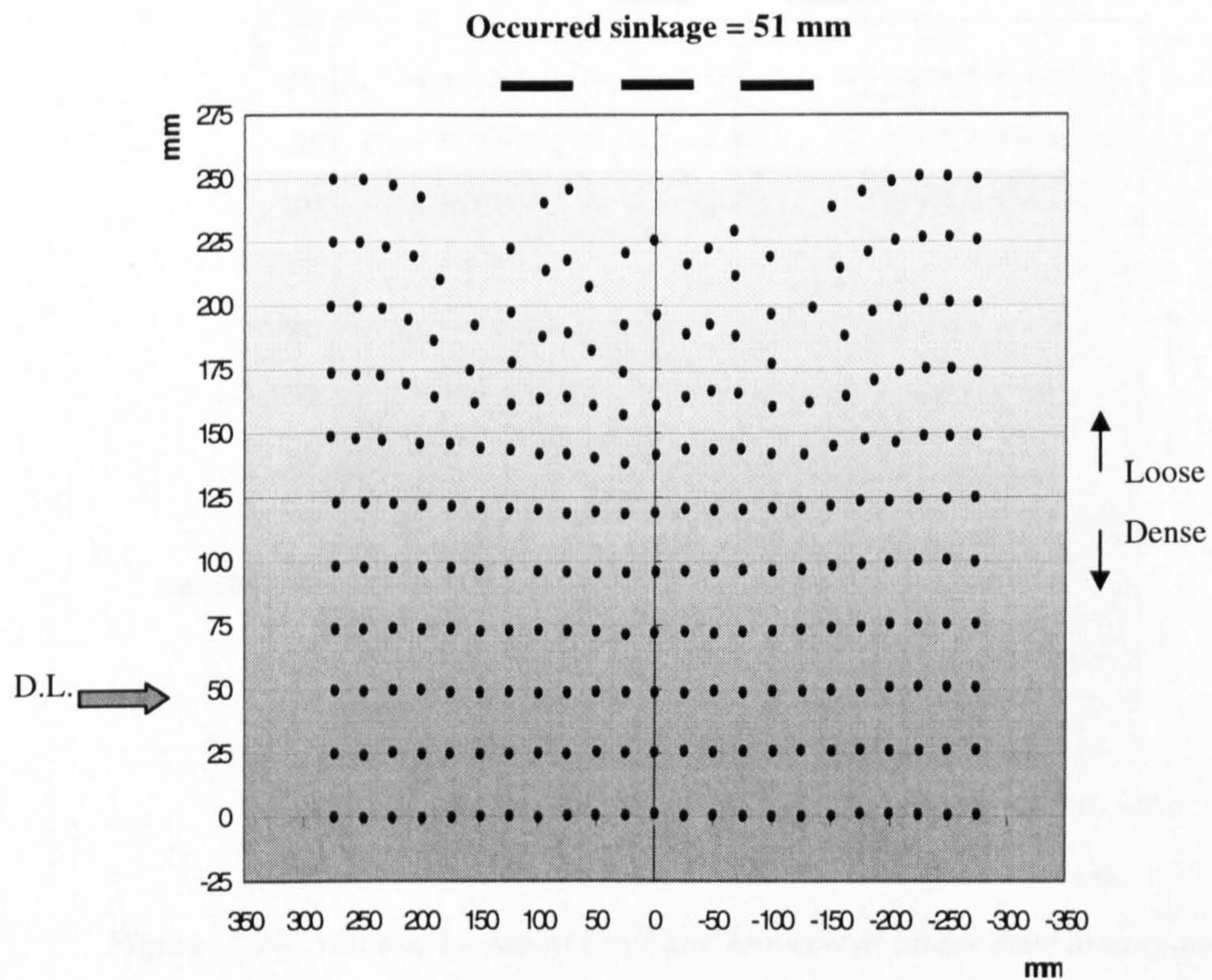


Figure 5.12. Soil displacement limit and movement under Triple same level plates

Given 8.5 kN load:

Occurred sinkage = 57 mm

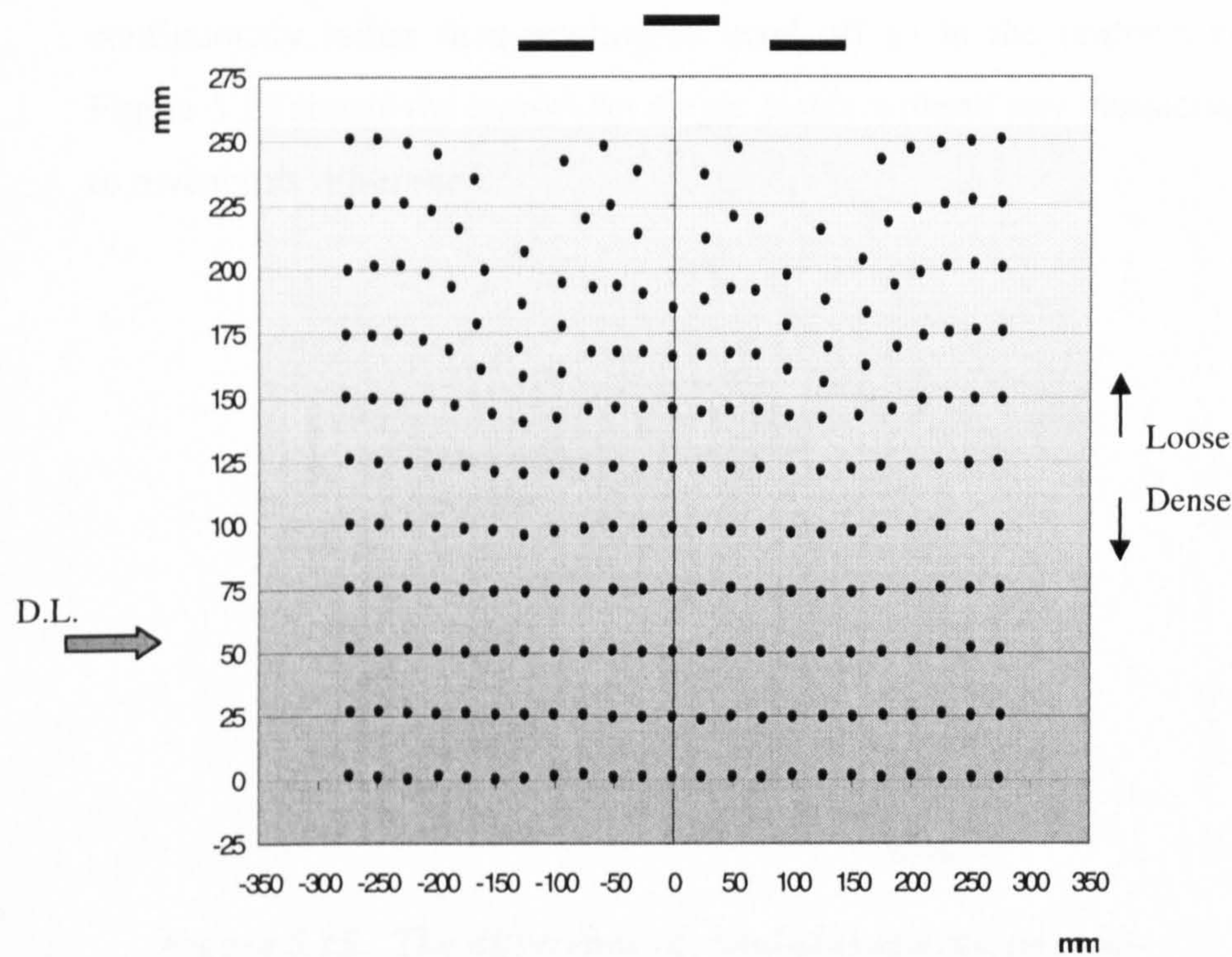


Figure 5.13. Soil displacement limit and movement under triple raised middle plate

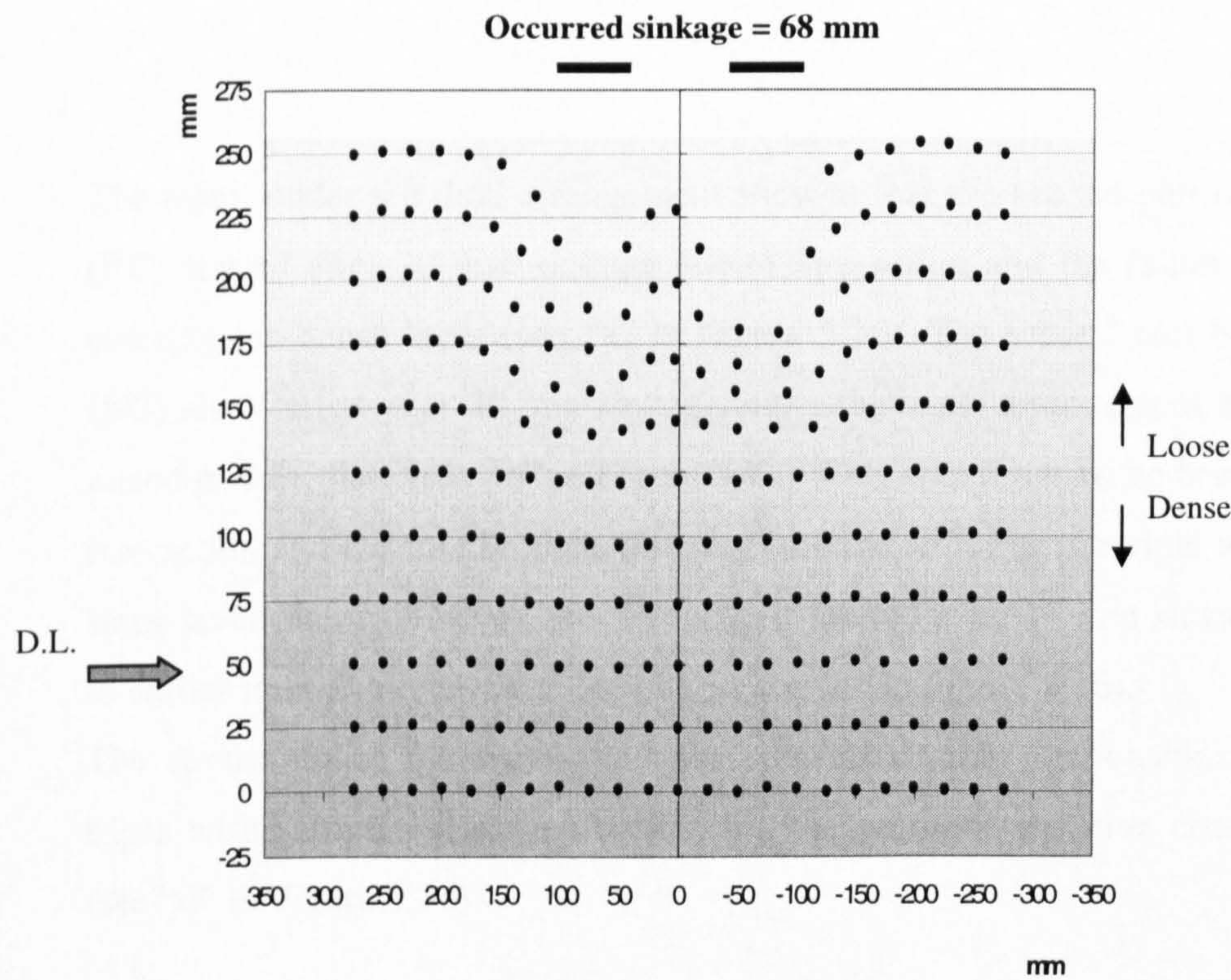


Figure 5.14. Soil displacement limit and movement under dual arrangement

continuously rather than tending to level off as in the uniform condition. Figure 5.15 shows the results for single plates without any interaction effects to reveal this difference.

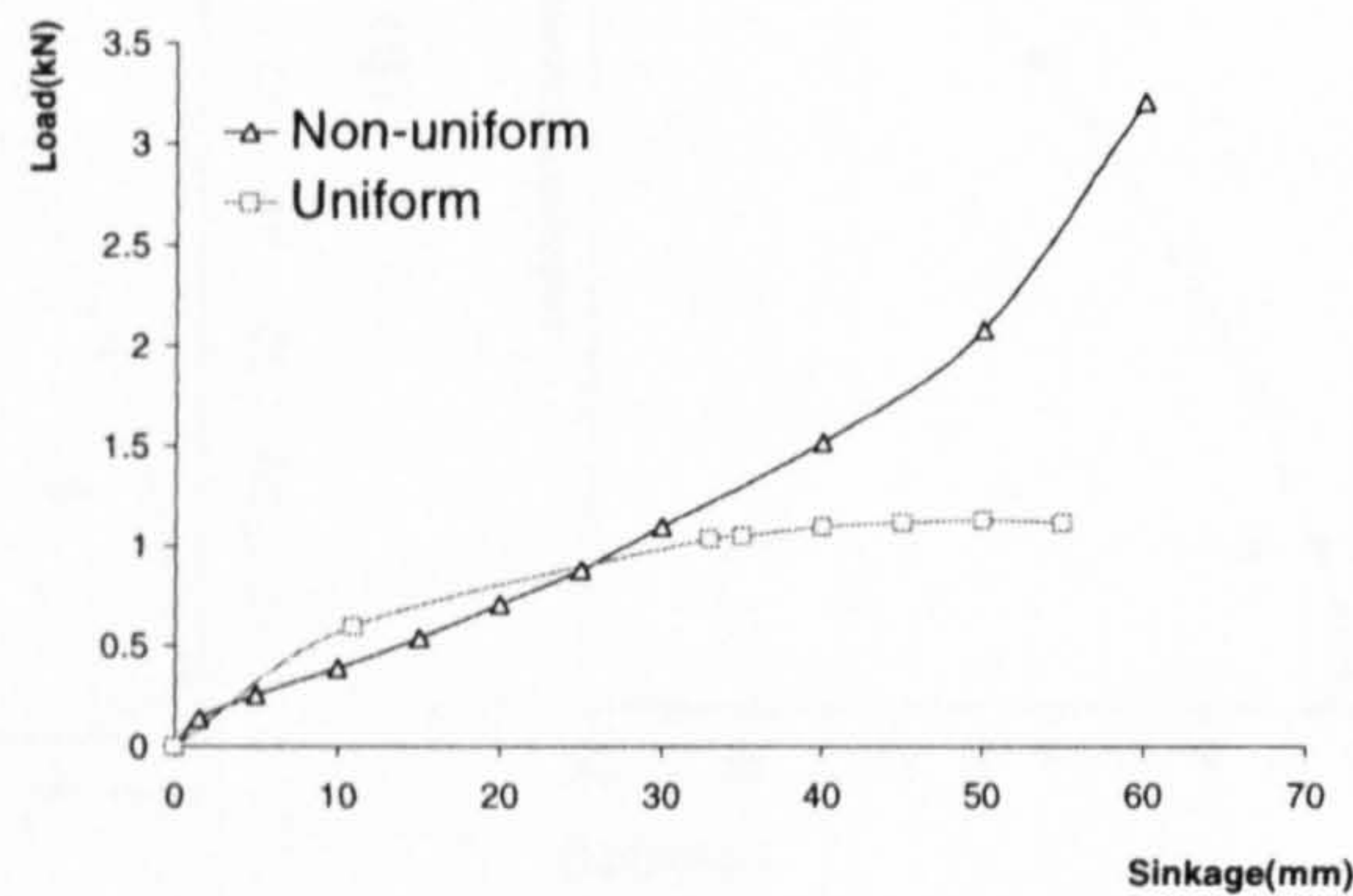


Figure 5.15. The difference of load-sinkage relationship in uniform and non-uniform soil conditions

The result under the dual arrangement showed that the second part of curve (BC) started after 20 mm sinkage due to interaction and the failure planes entering the dense layer (see “a” in Figure 5.16). The second part of curve (BC) also started after 20 mm sinkage under the triple arrangement with the raised middle plate (see “b” in Figure 5.16). This was found to be because of interaction and the middle plate entering into the soil. For the triple with the same level plates however, the second part started after 15 mm sinkage due to earlier interaction between the plates (see “c” in Figure 5.16).

The results under the simulated terra showed similar relationships to the triple with same level plates, confirming the previous tentative conclusion (see “d” in Figure 5.16).

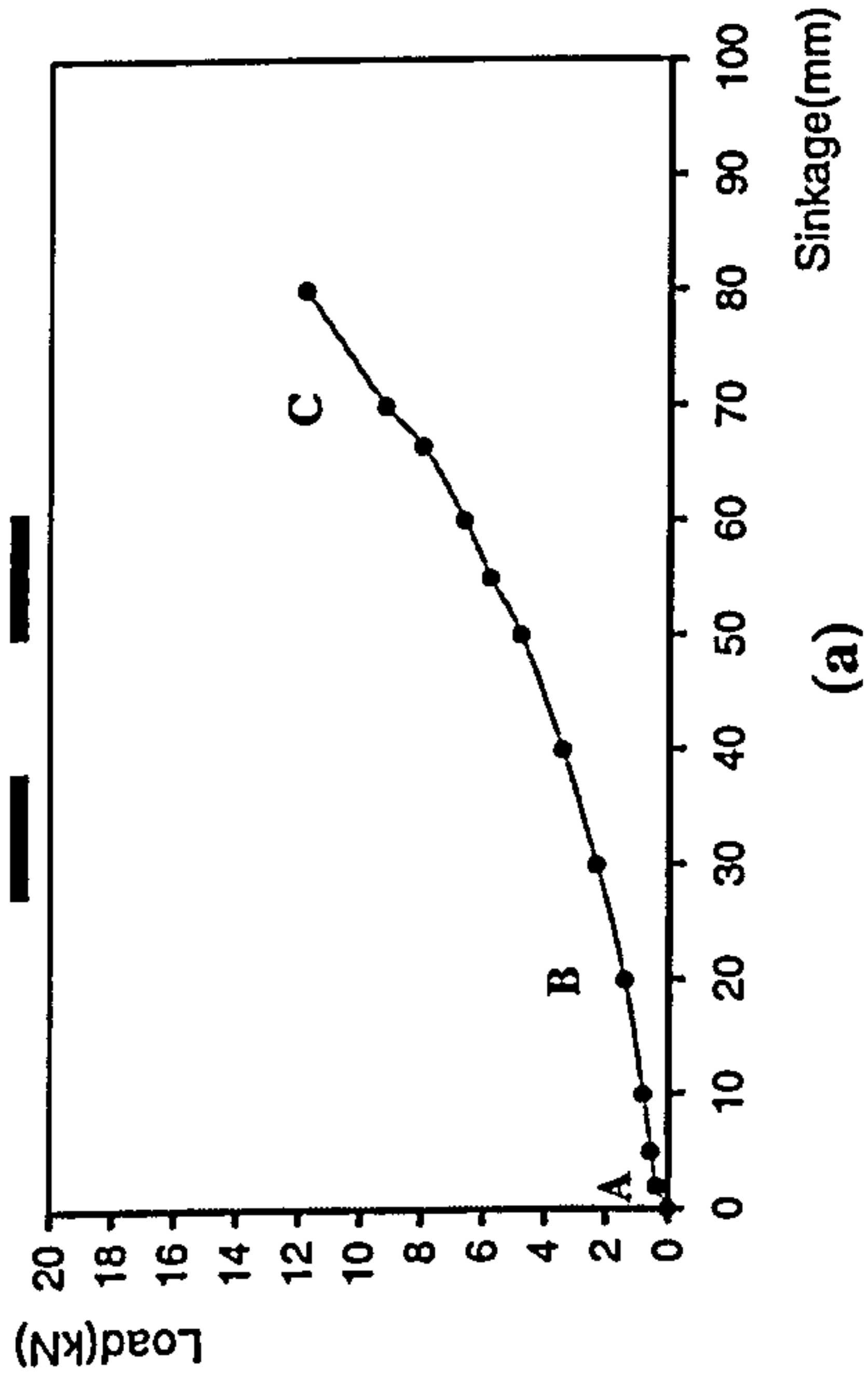
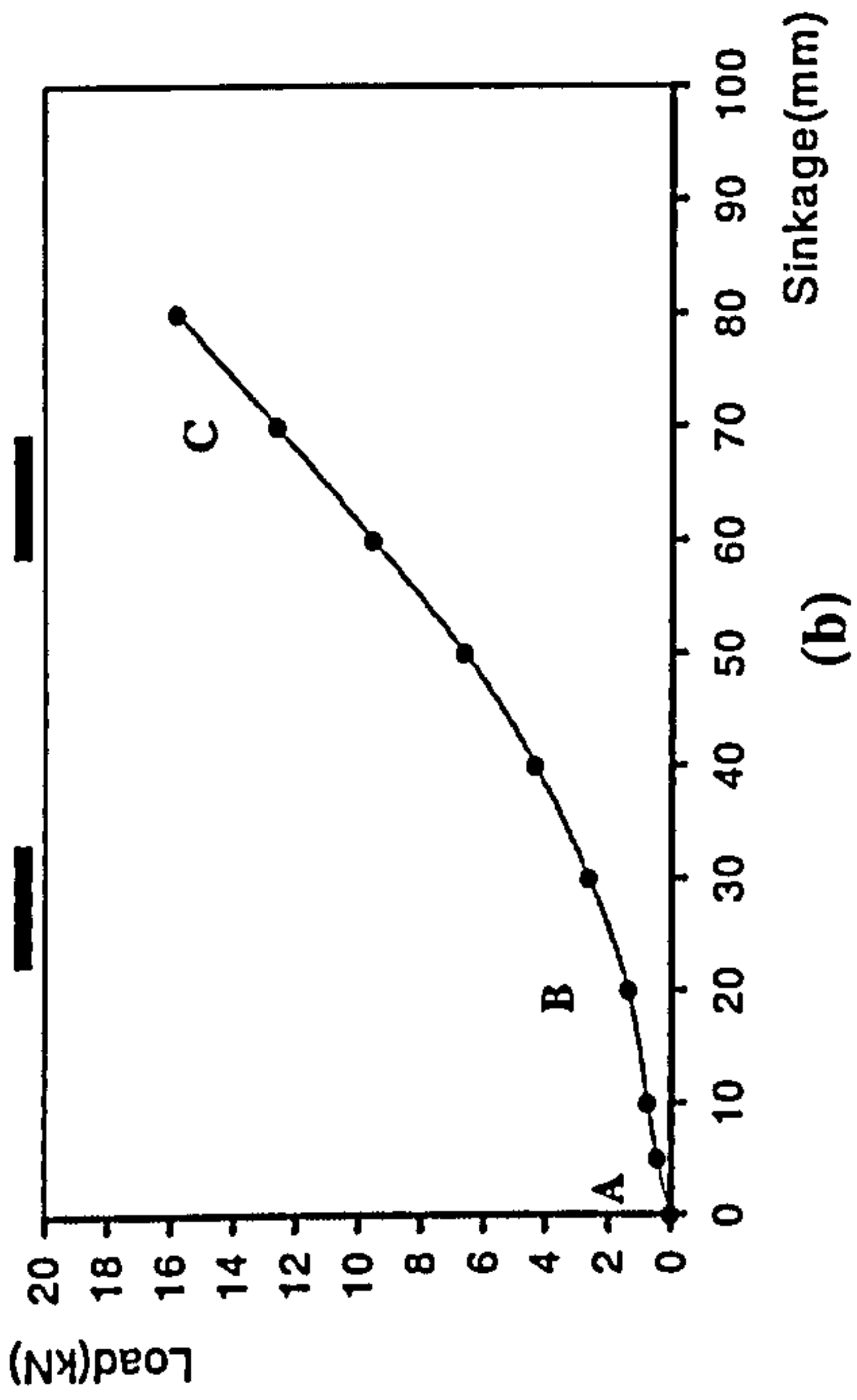
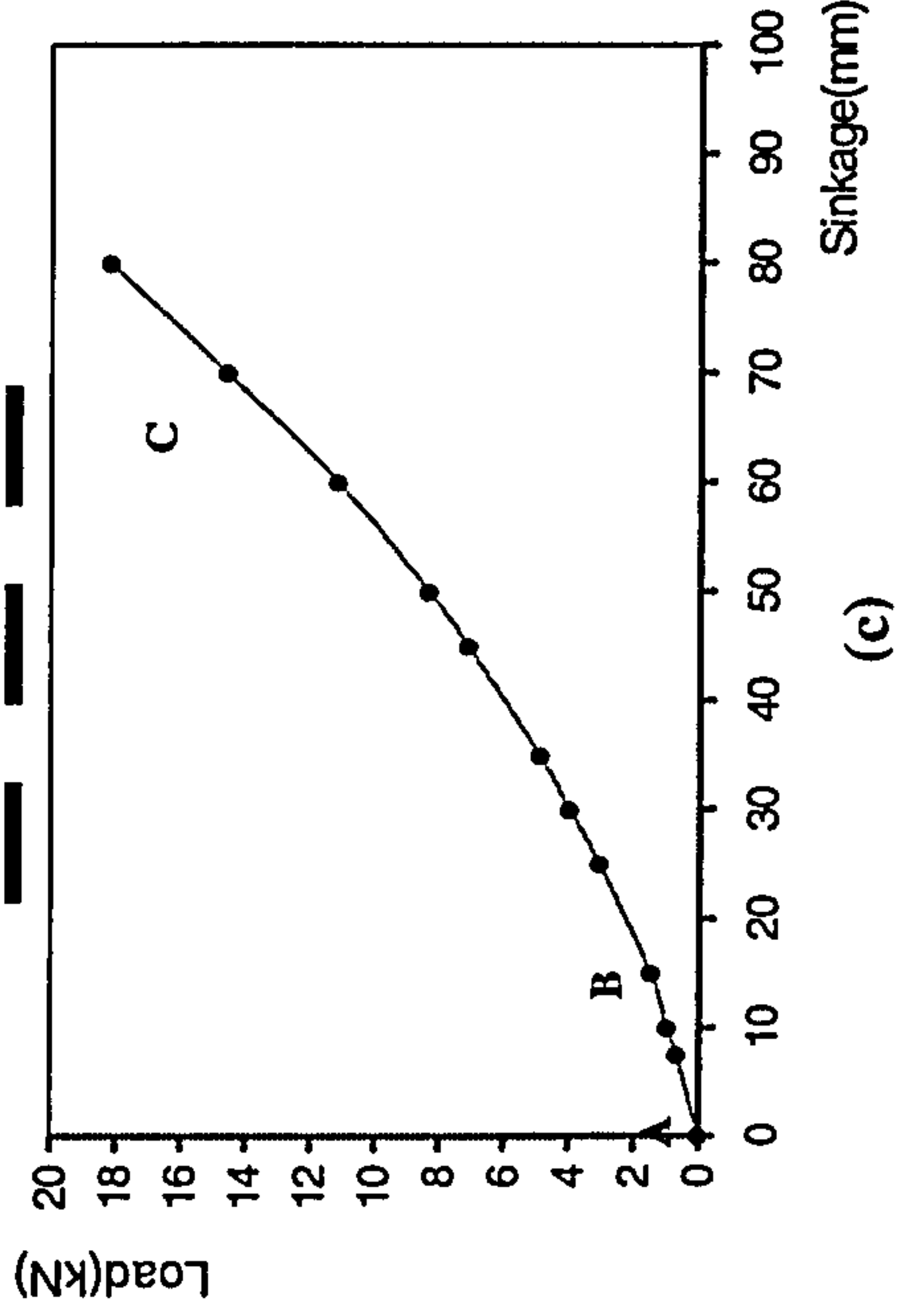
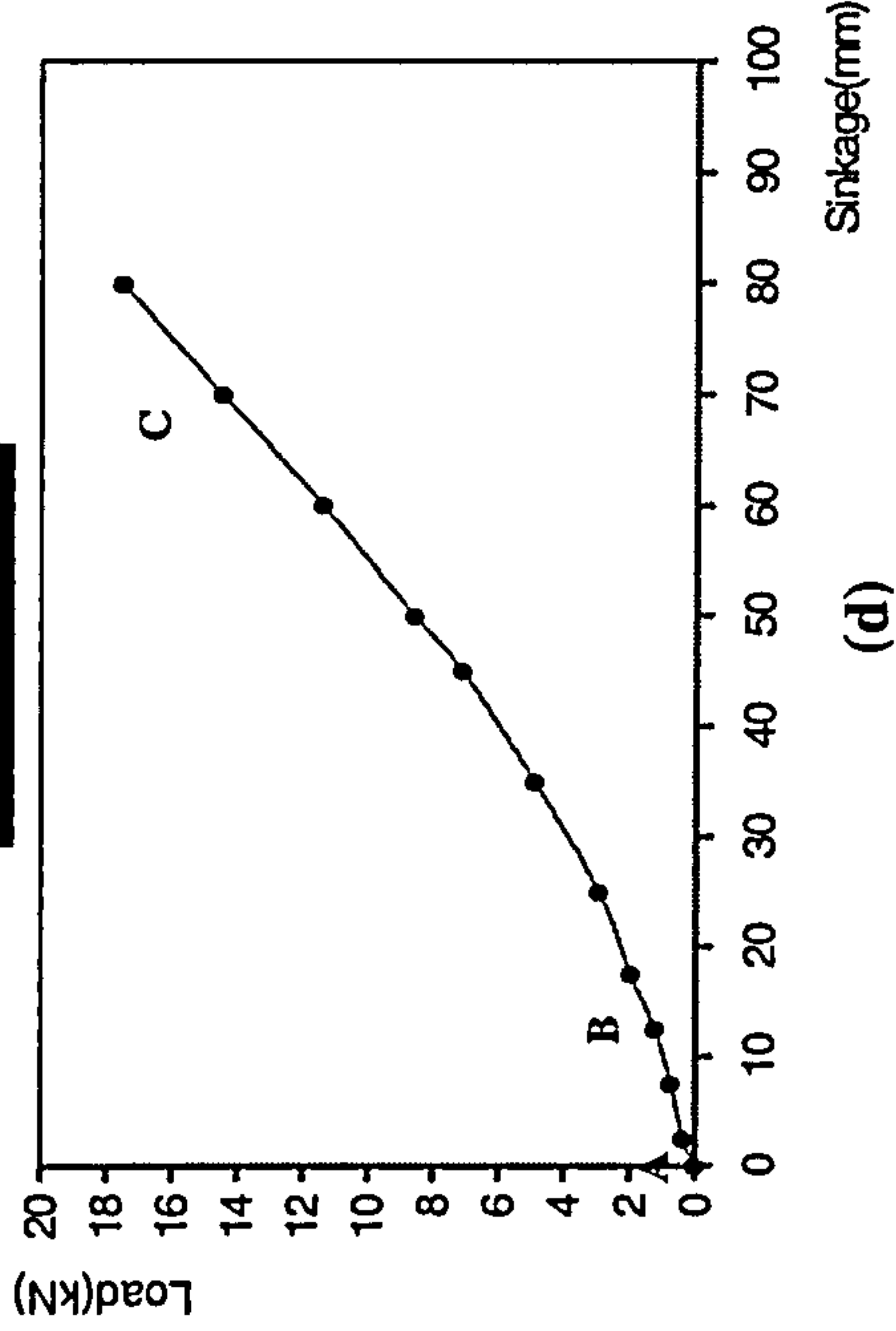


Figure 5.16. Load-sinkage relationship under different arrangements in a non-uniform soil
(a) Dual arrangement
(b) Triple with raised middle plate
(c) Triple with the same level plates
(d) Simulating terra

5.5. Summary of discussions

By comparing the image analysis results, it is clear that the simulated terra has the greatest effects on the soil at depth. By dividing it into three spaced narrow plates at the same level, the strain at depth is decreased whilst the tolerated load remains the same. This means that there can be a benefit in terms of reduced movement at depth by using spaced wheels with the same overall contact pressure as compared with the very wide wheel such as a terra tyre. By placing the middle plate 20 mm higher, the strain at depth is decreased very significantly. This arrangement also showed the minimum displacement at depth for a given load.

The depths of soil displacement for the different arrangements for a given load are given in Table 5.2. and for given sinkages in Table 5.3. Also the displacement limits and tolerated loads for both the given sinkages and given load cases are compared in graphs 5.17 and 5.18 respectively. It is clear that the simulated terra has the greatest displacement at depth under both the given sinkage and load cases.

A comparison of the data in the table 5.3 particularly reveals that for the same displacement limit of 225 mm (occurred under terra at 50 mm sinkage and under triple same level at 90 mm sinkage), the tolerated load is significantly higher for the triple same level. This means that for the same affected depth of 225 mm, the simulated terra would support an 8.5 kN load, yet the triple one would support a load 2.5 times this.

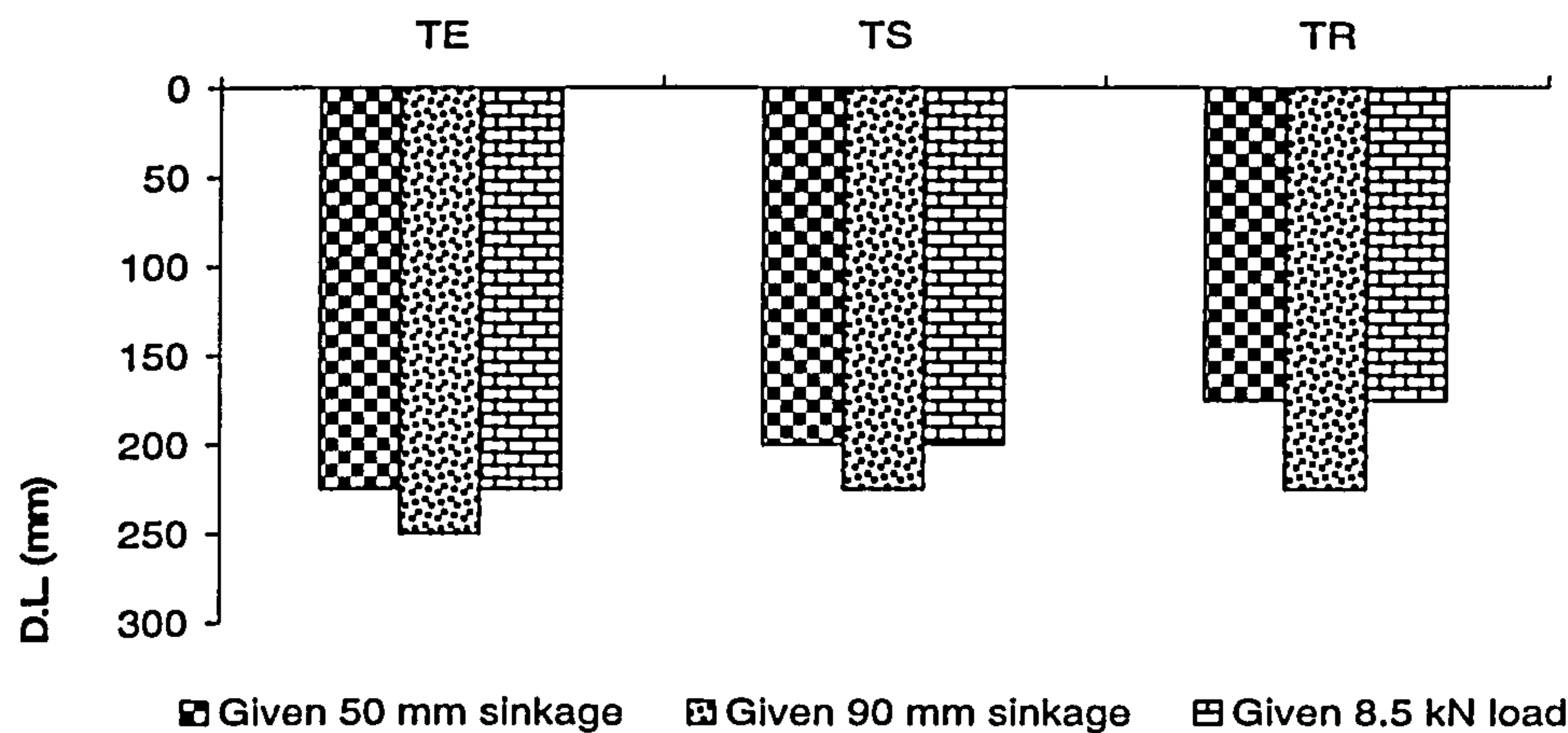


Figure 5.17. Soil displacement limits (D.L.) comparison under arrangements
TE = Simulating terra TS = Triple with same level plates TR = Triple with raised middle plate

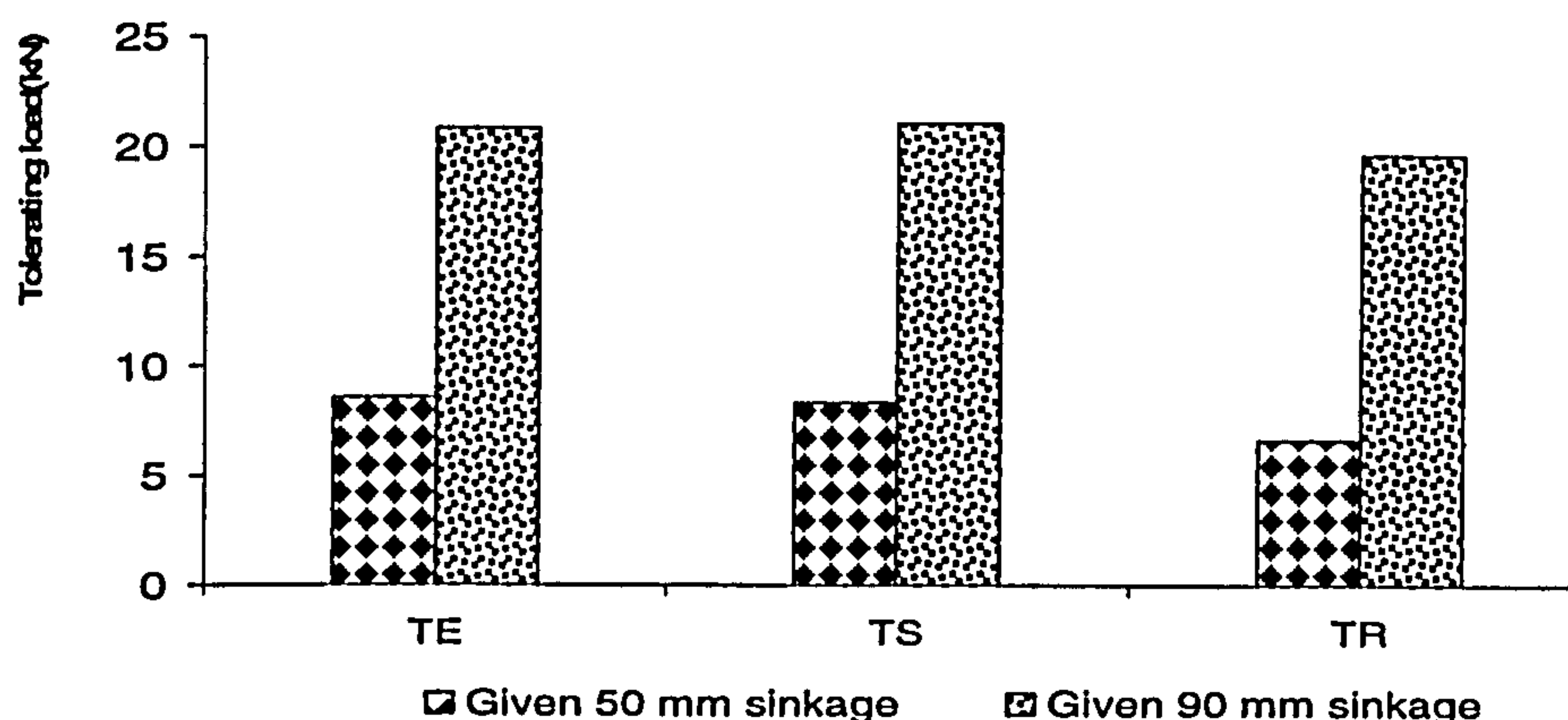


Figure 5.18. Tolerating load comparison under arrangements
TE = Simulating terra TS = Triple with same level plates TR = Triple with raised middle plate

On the other hand it is possible to conclude that the simulated terra would cause deep movement even with the smaller sinkage.

The comparison between the simulated terra and triple with raised middle plate at 90 mm sinkage also revealed that there was no significant difference between the tolerated loads, whilst shallower displacement occurred with the spaced triple. The triple arrangement with the raised middle plate is therefore an effective configuration for a situation where high penetration sinkage can be tolerated. Moreover the comparison of both triple arrangements indicates that the soil movement under the triple with same level plates is generally more than the raised one. It should be mentioned that based on the literature, undesired compaction can increase gradually with a little movement every year. Hence even with the same displacement limits under both triple arrangements, the raised one could reduce the risk of compaction forming over the years.

Table 5.2: Sinkage (mm) and soil displacement limit (mm) for a given load

Given 8.5 kN load		
Treatments	actual sinkage (mm)	D.L. * (mm depth)
Terra	50	250
Triple same level	51	225
Triple raised one	57	225
Dual	68	225

*Displacement limit

Table 5.3: Tolerated load (kN) and soil displacement limit for given sinkages

Treatments	Given 50 mm sinkage		Given 90 mm sinkage	
	Tolerated load	D.L.*	Tolerated load	D.L.*
Terra	8.58	225	20.83	250
Triple same level	8.33	200	21.03	225
Triple raised one	6.62	125	19.6	225
Dual	4.78	125	-----	-----

It can be concluded that although the terra can support high loads, this is accompanied by the greatest displacement at depth. Major benefits can be achieved by using triple spaced arrangements which can minimize the effect of large active and passive failure zones as well as creating interaction between the wheels. This can decrease the soil displacement at depth without changing the tolerated load significantly.

It is necessary to confirm in large scale tests with actual wheels whether the benefits identified in these simulated tests of using spaced arrangements rather than singles can be achieved for both displacement limit and tolerated load or not. Therefore further investigations were arranged using rigid wheels in the soil bin for the following treatments.

- 1) Simulated terra tyre (wide wheel)
- 2) Triple spaced with wheels at same level
- 3) Triple spaced with raised middle wheel

5.6. Conclusions

- 1) The very wide plate simulating a terra tyre has the maximum potential to cause deep compaction at both given sinkages and load
- 2) By dividing the terra into three narrow spaced plates, there is the opportunity to reduce the displacement at depth whilst carrying the same load
- 3) Although the displacement limit for the simulated terra at 50 mm sinkage is the same as for the triple arrangements at 90 mm sinkage, the tolerated loads are significantly greater under the triple treatments
- 4) By raising the middle plate in the triple arrangement, it is possible to minimise the displacement at depth
- 5) The advantages of the triple with raised middle plate is also very considerable under high penetration (sinkage) conditions
- 6) The load-sinkage curves of uniform soil are not applicable to the non-uniform conditions commonly found in the field
- 7) The load increased continuously with increasing sinkage in the non-uniform condition due to the soil state and interaction between the plates

Chapter6. Soil displacement limits under rolling rigid wheels in large scale tests

6.1. Introduction

The most effective arrangements identified in previous tests were investigated in the soil bin as large scale tests. Rolling rigid wheels were used and arranged in the most promising configuration patterns. A wheel holding frame was developed for attachment to the soil processor. The frame allowed a range of wheel spacings and configurations to be investigated. A sandy loam soil was used in the bin and prepared in two layers, a looser surface layer and a denser lower layer, simulating common field conditions and similar to previous tests.

A soil marking technique enabled soil movement and displacement limits to be monitored under the different treatments. Marker positions were revealed in a vertical profile after a run, their positions being recorded as a digital image and transferred to a computer for further analysis.

A constant load was used for all treatments, the load being applied on the top of the wheel frame.

The results of these experiments provided accurate evidence of soil displacement limits in two directions (x and y) below an external load in large scale tests. It was then possible to identify the most promising arrangements for reducing soil displacement at depth.

The main objective of the tests described in this chapter was to confirm the results obtained in small scale tests using the plate sinkage relationships.

6.2. Experimental procedure

6.2.1. Soil preparation

A sandy loam soil was used (see Table 6.1 for more details) in a soil bin of dimensions 1.5 m wide 1.0 m deep and 20 m long. The soil preparation procedure was conducted relative to a fixed datum at the ground surface. The soil was completely removed to one end of the bin and then returned in loose uniform layers approximately 75 mm thick which were each compacted to the required density.

Table 6.1. Soil characteristics under investigation in soil bin

Soil	Sand(%)	Silt(%)	Clay(%)	Organic matter(%)	Moisture content(%)
Sandy Loam	68.5	19.0	12.5	3.2	11.06

To simulate common field conditions, the bottom layer was prepared to a higher density than the top layer. Some initial tests were carried to identify the number of required rolling passes from 1 to 5, to provide the appropriate densities. The results showed that three rollings could provide a density of 1.45-1.5 $Mg.m^{-3}$ which was appropriate for the bottom soil layer. One rolling was found to be appropriate for the loose section giving a 1.25-1.3 $Mg.m^{-3}$ density. Three rolling passes were therefore applied to each soil addition, until the bottom dense boundary layer was 300 mm in thickness (half of depth) with an average density of 1.46 $Mg.m^{-3}$. The same procedure but applying only one rolling was followed to produce a 300 mm thick top layer with an average density of 1.27 $Mg.m^{-3}$.

6.2.2. Soil marking

After rolling each layer during soil preparation, a ridge roller with parallel V-shaped projections at 50 mm spacing was run along the bin. The ridge roller left small V-shaped slots 3 mm deep and 50 mm apart on the surface of each layer. A spraying bar with hypodermic syringe needles was mounted immediately behind the ridge roller to introduce paint into the slots. The needle tips were adjusted to be exactly in line with the V-shaped slots. A thread of diluted white emulsion paint was trickle through the nozzle and needles into the slots (see Figure 6.1). A constant supply of paint was maintained along the length of the bin by ensuring a constant forward speed of the processor and paint head between the paint container and the needle tips. A solenoid switch was used to start and stop the paint flow. The process was repeated for all soil layers.

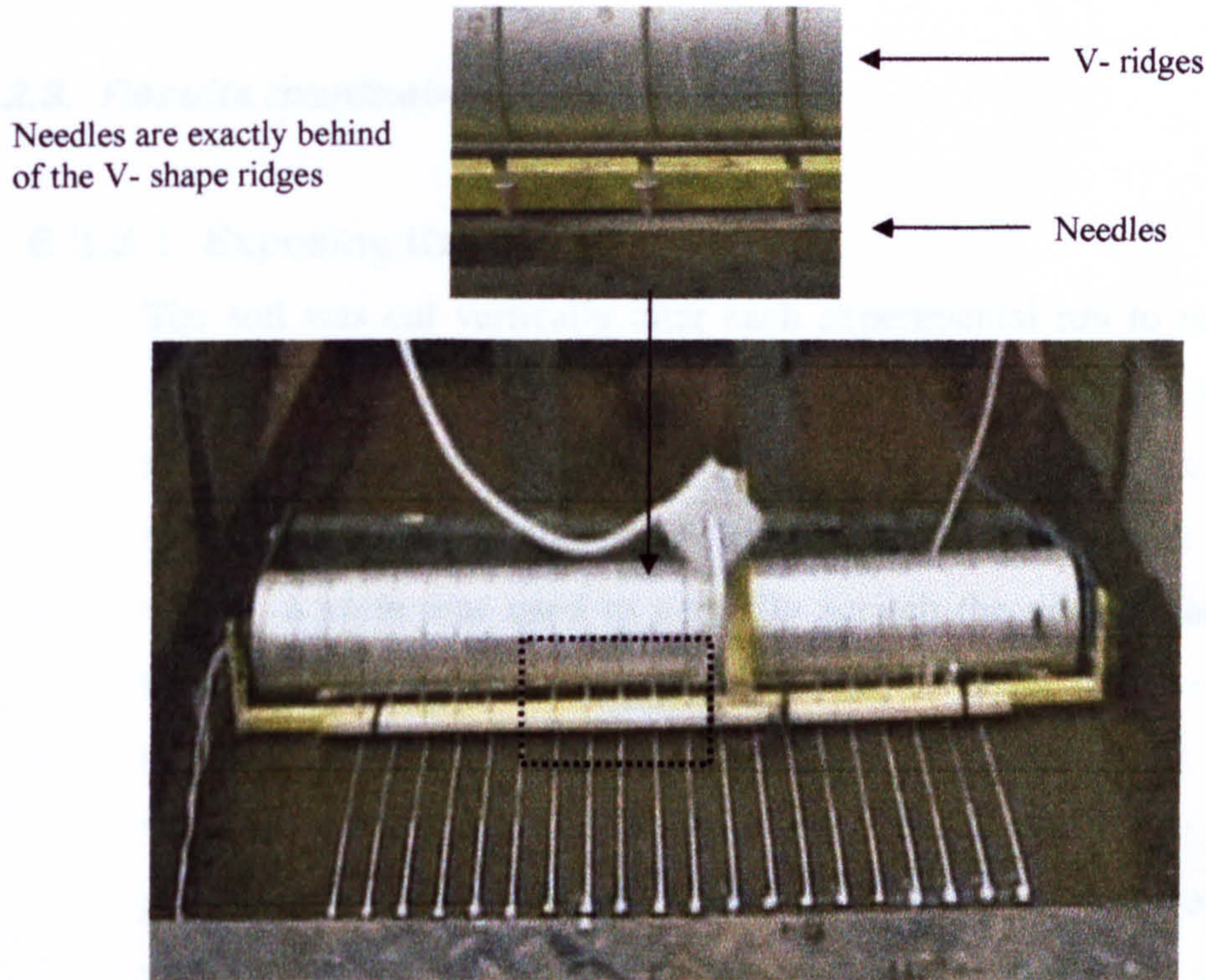


Figure 6.1. Ridge roller and painting needles in operation

The paint was absorbed by the soil and formed a very small V-shaped white mark which was just discernible from the surrounding soil. To assist in identifying the mark locations after the tests, the thin surface layer of soil was moistened after painting (see Figure 6.2). This moistening changed the cohesion of the soil slightly, and this local change was immediately visible to the eye in any vertical profile.

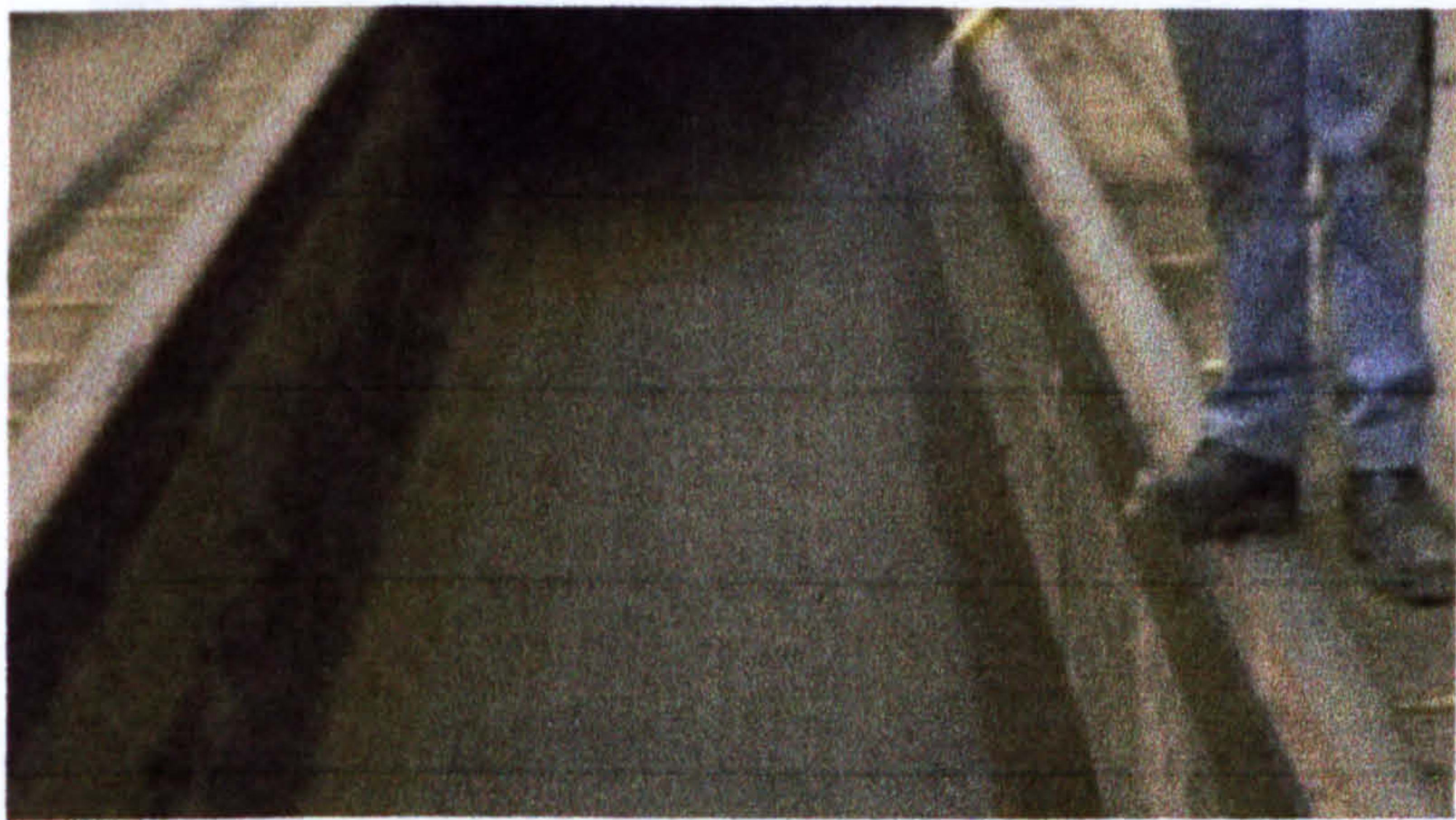


Figure 6.2. Water spraying on the painted soil providing more contrast

6.2.3. Results monitoring

6.2.3.1. Exposing the markers:

The soil was cut vertically after each experimental run to reveal a cross-section profile. The exposed vertical face was smoothed manually with a spade. After careful brushing to expose the moistened zones, the white v-shaped marks were identified. Where markers were not immediately visible, a knife was used to carefully scratch the vertical face to reveal them. Once each mark was exposed, a white headed map pin, 3 mm in diameter and 15 mm long, was positioned in the centre of the V mark. This was to improve the soil/marker contrast to enable the identification of the pins during image processing. Figure 6.3 shows the exposed markers in the vertical profile. When all the pins were located, a wooden structure was suspended in front of the profile to frame the pins.

Each profile was recorded with a SONY digital video camera positioned centrally at approximately 1.5 meters in front of the profile. A still NICON camera was also used to create still photographs. After recording, the frame and pins were removed from the bin and another slice of soil was cut to expose a second profile. The images recorded with the digital camera were then transferred to a computer for analysis.



Figures 6.3. Exposing the markers in the vertical soil profile

6.2.3.2. Image analysis:

All the image analysis processes were performed using the Global Lab Image (GLI) package as indicated in the previous chapter and explained in appendix 1.

6.3. Arrangement settings

6.3.1. Treatment configurations

Three configurations selected from previous experiments were investigated using rigid rolling wheels, these were:

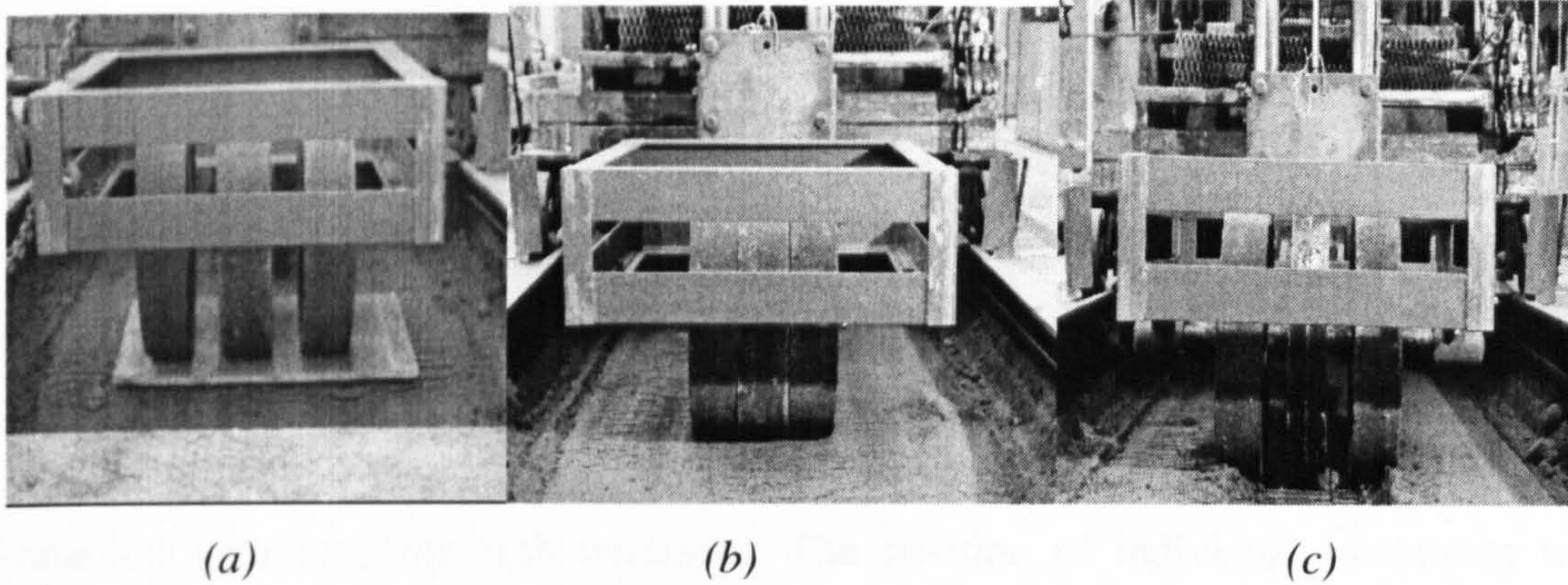
- 1) Triple spaced, with wheels at the same level
- 2) Triple spaced, with raised middle wheel
- 3) Very wide wheel as terra, with same contact pressure as triple

Three spaced rigid wheels of similar dimensions, 150 mm wide and 600 mm diameter were used to provide the first configuration (see “a” in Figure 6.4). These wheels were also used at zero spacing between them to provide the Terra wheel configuration (see “b” in Figure 6.4). A wheel of smaller diameter 525 mm, was used in the middle to provide the third configuration with an effective raised middle wheel. The difference in diameters allowed the middle wheel to work 37.5 mm shallower than the side wheels (see “c” in Figure 6.4).

The spacing between the wheels under both triple spaced arrangements was 100 mm, to allow soil movement and interaction in between without causing excessively deep movement.

6.3.2. Wheel frame

A frame was constructed to support the different wheel arrangements at the required spacings, the wheel shaft running in bearings (see also Figure 6.4). The frame was designed to be attached to the front of the soil processor and appropriate weights were placed on top. The attachment to the processor can be seen in Figure 6.5.



6.4. Treatment configurations using rolling rigid wheels

- (a) Triple with same level wheels (b) Very wide wheel as Terra
(c) Triple with raised middle wheel

6.3.3. Load application

The main objective in this test was to keep the load constant for all arrangements. A load of 19.6 kN was selected, based on previous experience working with full scale tyres and the relative size of the rigid wheels. This load allowed an appropriate wheel sinkage to occur. Hence by considering the weight of the wheels and other components, the total extra weight needed was calculated as below.

Mass of: each wheel = 56.5 kg frame = 97 kg Axle and components = 34 kg

Total weight = $3 * (56.5 + 97 + 34) * 9.81 = 2.95 \text{ kN}$

Therefore the **extra weight needed** was = $19.6 - 2.95 = 16.65 \text{ kN}$

The available weights allowed the application of 16.17 kN to give total of 19.11 kN load on each arrangement (see Figure 6.5).

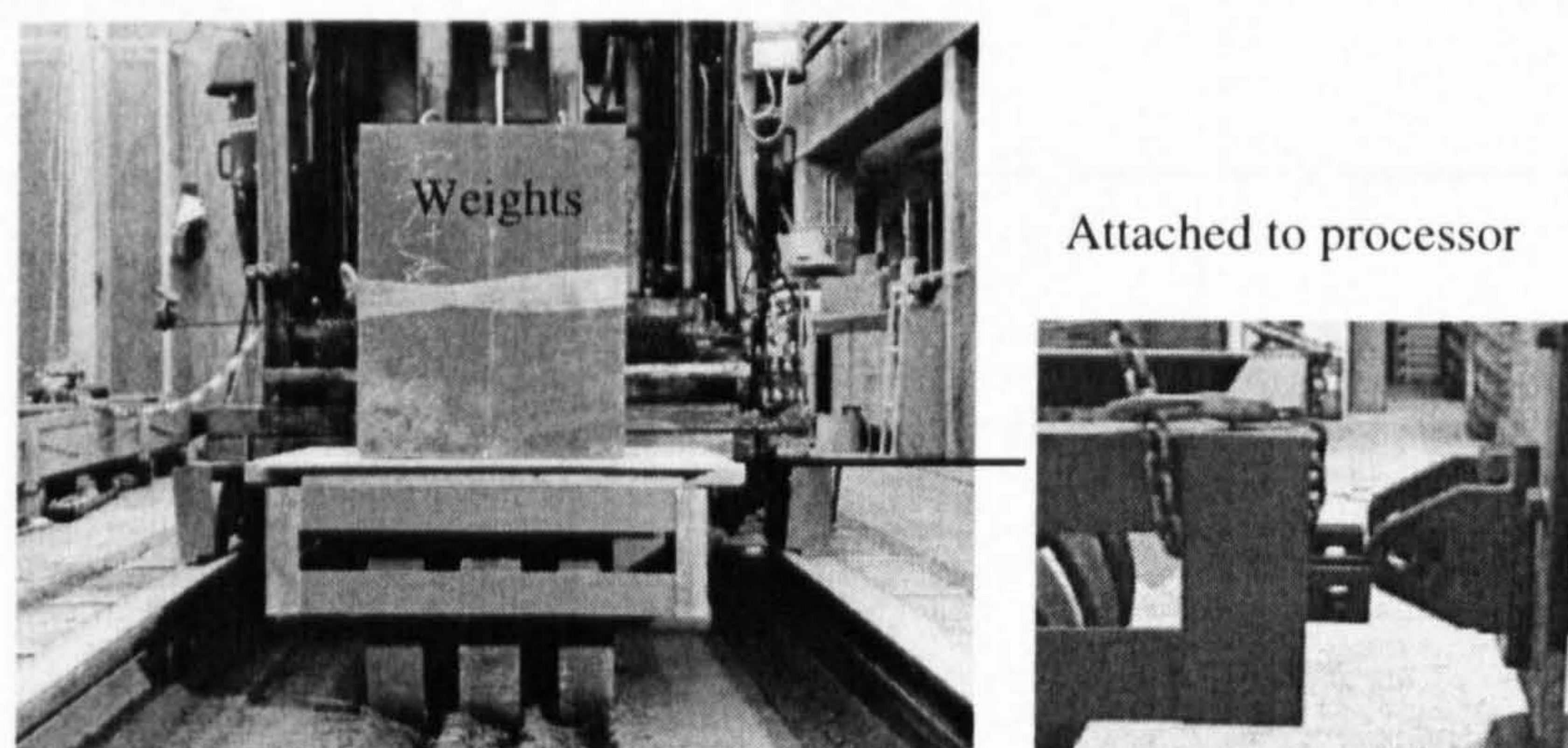


Figure 6.5. Extra weight application on the wheel frame

6.3.4. Experimental plan

Due to the soil preparation process, where it was necessary to remove all soil to one end of the bin, the maximum run length for the experiments was 15 m. This length was divided into three sections, the first used as a control and the other two for the investigations. Despite the very time consuming procedure, three bins were prepared enabling two runs for each treatment. The position of individual treatments was changed between the different bins and two vertical profiles (cross-section face) were cut in each section, giving four replications for each arrangement. Figure 6.6 shows the experimental plan for the three prepared bins.

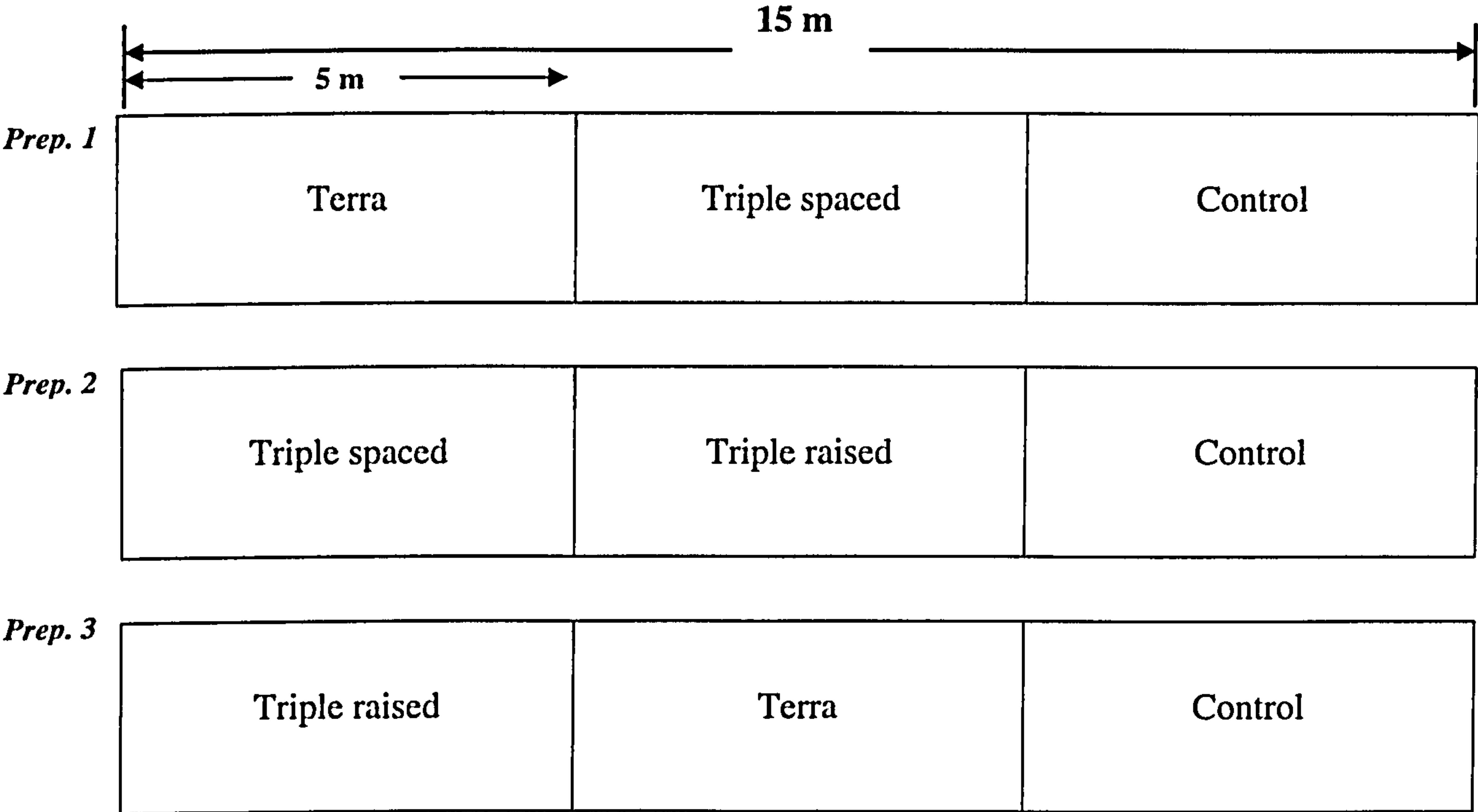


Figure 6.6. Experimental plan for three prepared bins

6.4. Soil displacement limits under constant load

In this section, the results indicating soil movement and displacement limits for the different treatments are presented together with the control profiles for each bin preparation. Any missing marks in the layers were due to possible blockage of the nozzle spray during the paint marking process.

The still photographs of all arrangements and replications are shown in appendix 2.

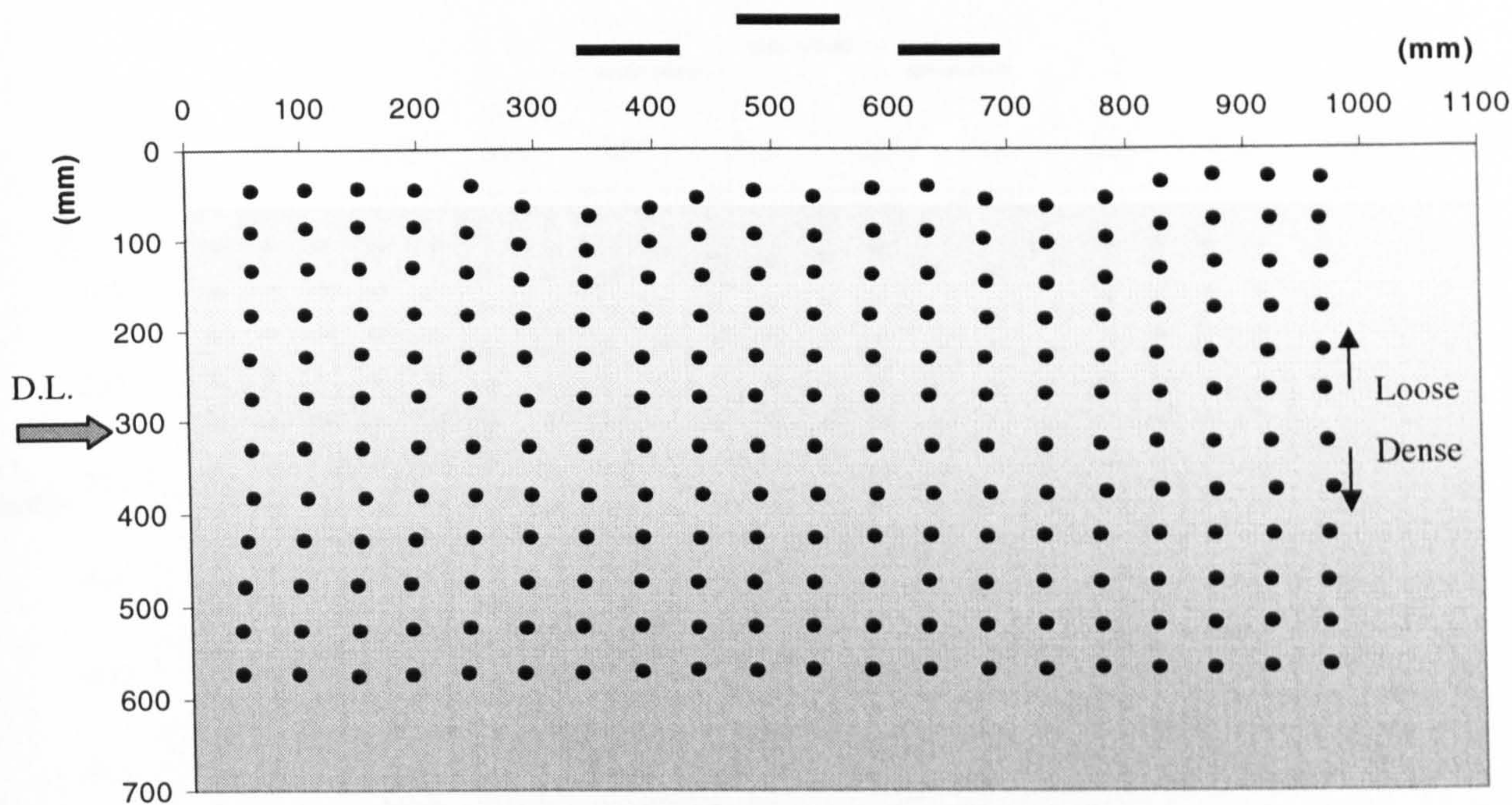
6.4.1. Bin preparation 1

In this preparation, two different configurations, triple wheels at the same level and terra with the same contact pressures were investigated as shown in Figure 6.6. The results in this prep were not analysed due to high numbers of missing marks. However the still photographs showed that deeper movement occurred under the terra arrangement (see photographs in the appendix 2).

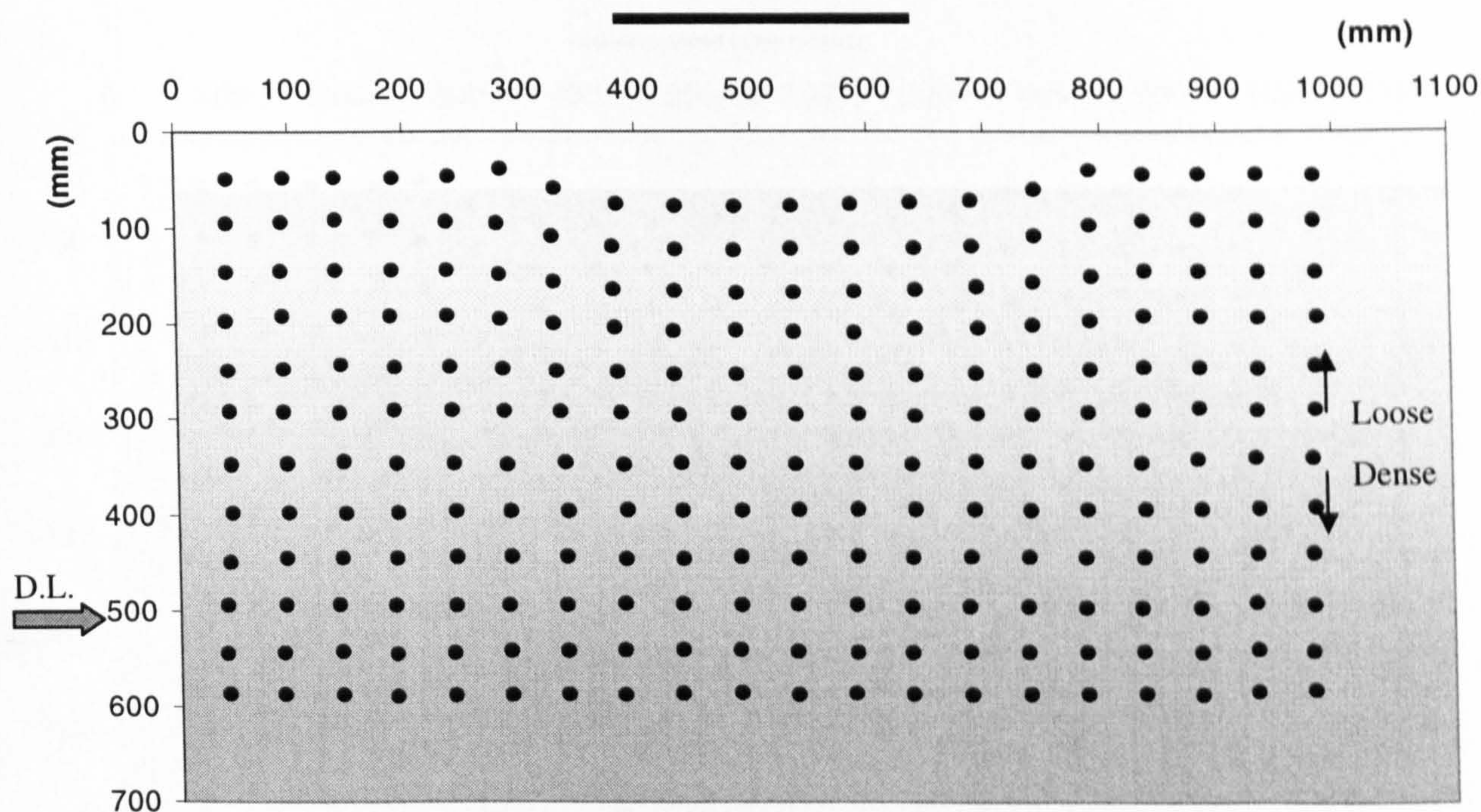
6.4.2. Bin preparation 2

In this preparation, two different configurations, terra and triple with raised middle wheel were investigated as shown in Figure 6.6. The results indicated that displacement limits were deeper under the terra (500 mm) than with the spaced triple (300 mm). Figure 6.7 shows the results under both arrangements. The triple with raised middle wheel caused no movement in the lower dense layer. This could be due to the interaction and the formation of a static zone in the central area allowing the load to be supported without causing movement at depth. The markers in the centre remained almost unchanged after the third layer. This area was also identified in the previous small scale tests using the plate-sinkage relationship. The movements in the top loose layer were also less than with terra configuration.

The second cross-section profile confirmed similar displacement limits (see Figure 6.8). Figure 6.9 shows the results of the control profile.

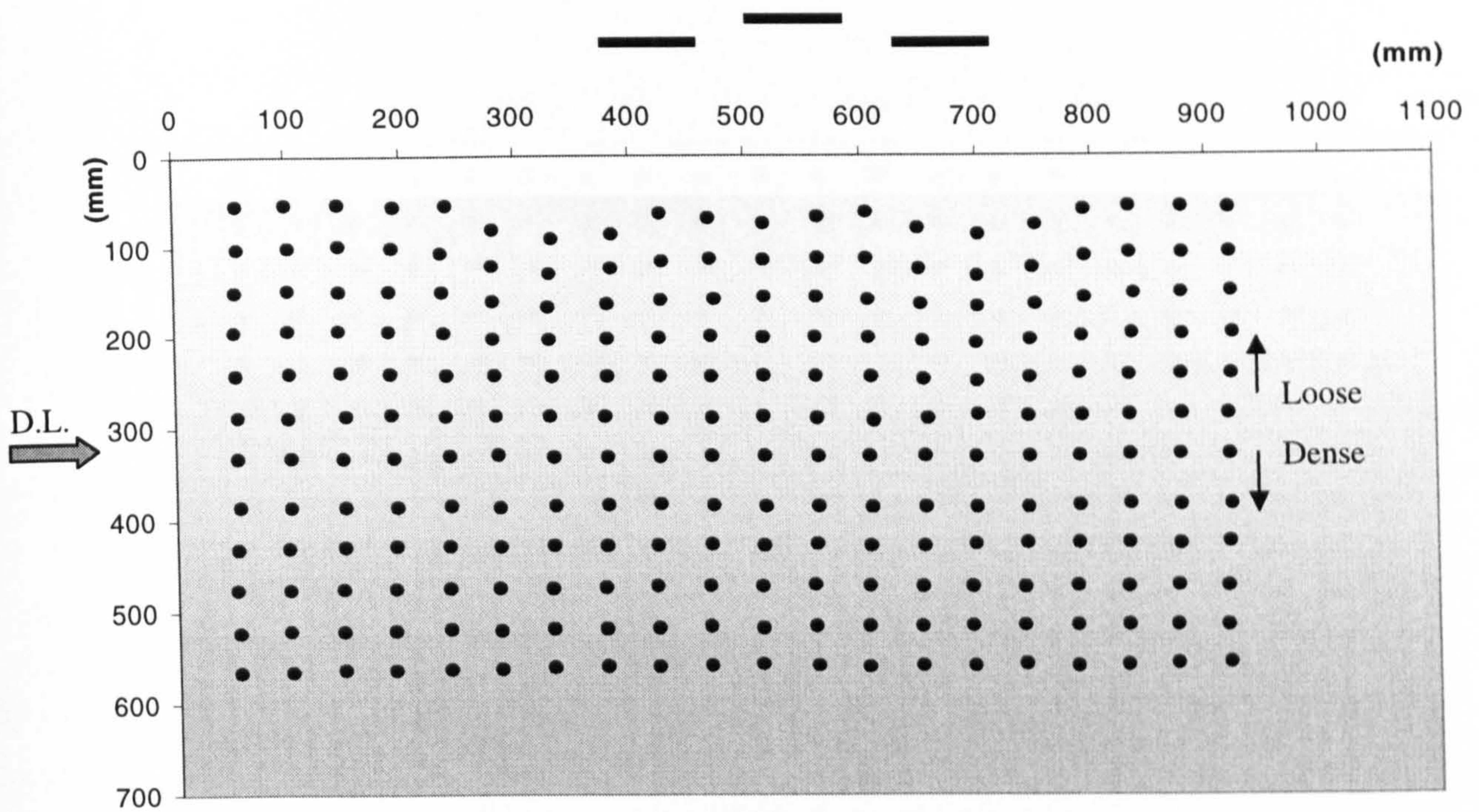


(a)

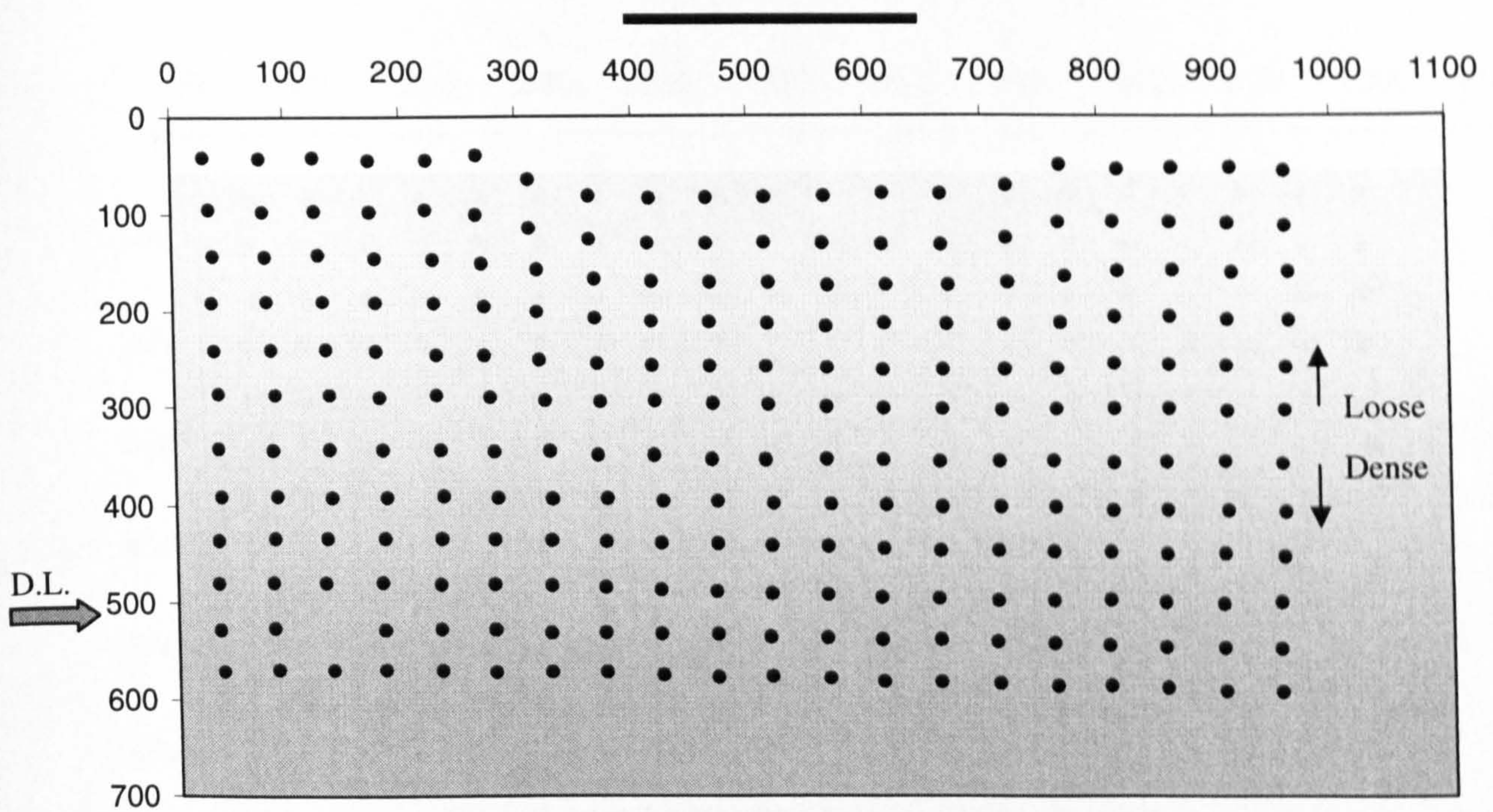


(b)

Figure 6.7. Triple with raised middle wheel(a) and simulated Terra(b)
in Prep 2, Replication 1



(a)



(b)

Figure 6.8. Triple with raised middle wheel(a) and simulated Terra(b) in Prep 2, Replication 2

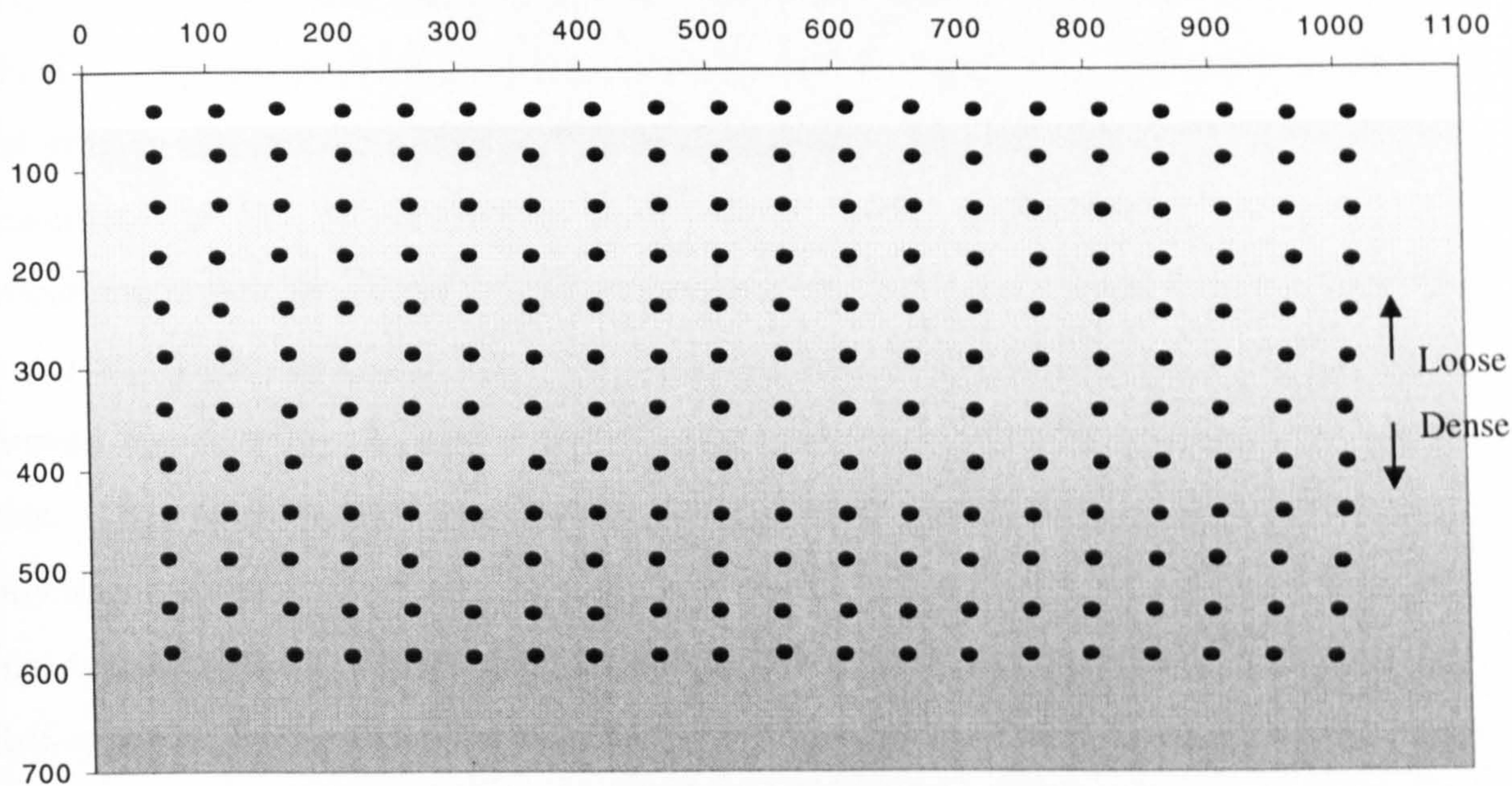


Figure 6.9. Evidence profile in prep 2

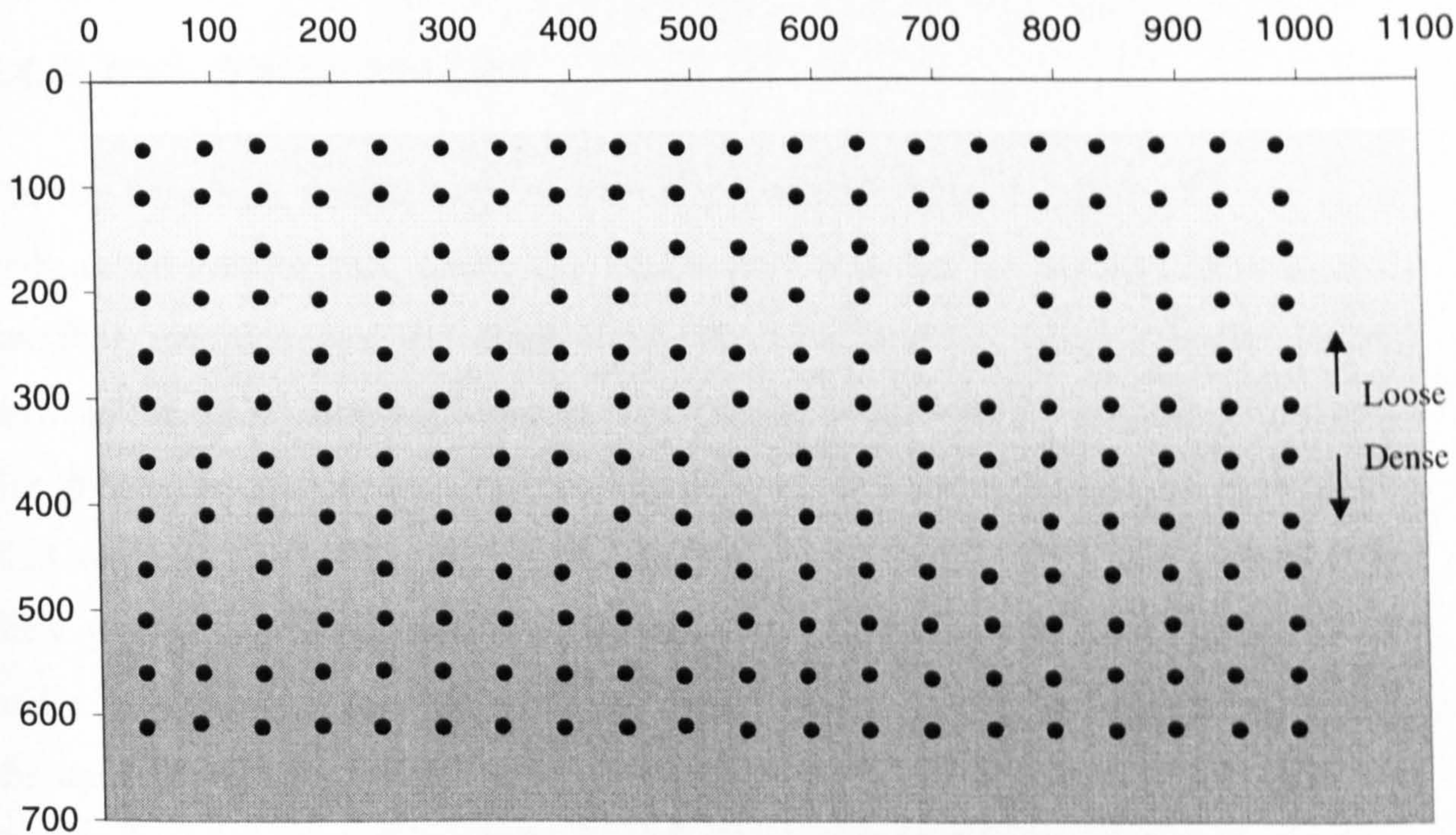


Figure 6.10. Evidence profile in prep 3

6.4.3. Bin preparation 3

In this preparation, both triple spaced wheels at the same level and with raised middle wheel configurations were investigated as shown in Figure 6.6. The results indicated that similar displacement limits (300 mm) occurred (see Figure 6.11). There was no movement in the lower dense layer under both configurations, although the arrangement with the raised middle wheel produced less movement in the middle due to a static zone forming. The triple arrangement with wheels at the same level, showed significantly shallower displacement limits than in the previous small scale tests. The small scale tests using plate-sinkage relationships indicated deeper movement under the triple with wheels at the same level than under the triple with raised middle wheel. These large scale tests using rigid rolling wheels showed similar displacement limits under both triple spaced arrangements whilst carrying the same load. The second cross-section profiles also confirmed similar displacement limits. (see Figure 6.12). Figure 6.10 shows the results of the control profile.

6.4.5. Bulk density changes

The dry base bulk density was measured in different locations after each run in the undisturbed control soil, under the wheels and between the wheels. The depth of sampling recorded was the depth from the actual surface. Surface levels differed between the three sampling locations due to sinkage under the wheels and sometimes rise in between the wheels. Three replications were measured at each location. Figure 6.13 summarises the results for all three bin preparations. The results showed that there was a significant difference between the density of the undisturbed soil and under the wheels. It was identified that there was no significant difference between the undisturbed soil and the soil between the wheels. No significant difference was found between the inside densities the different wheels arrangements.

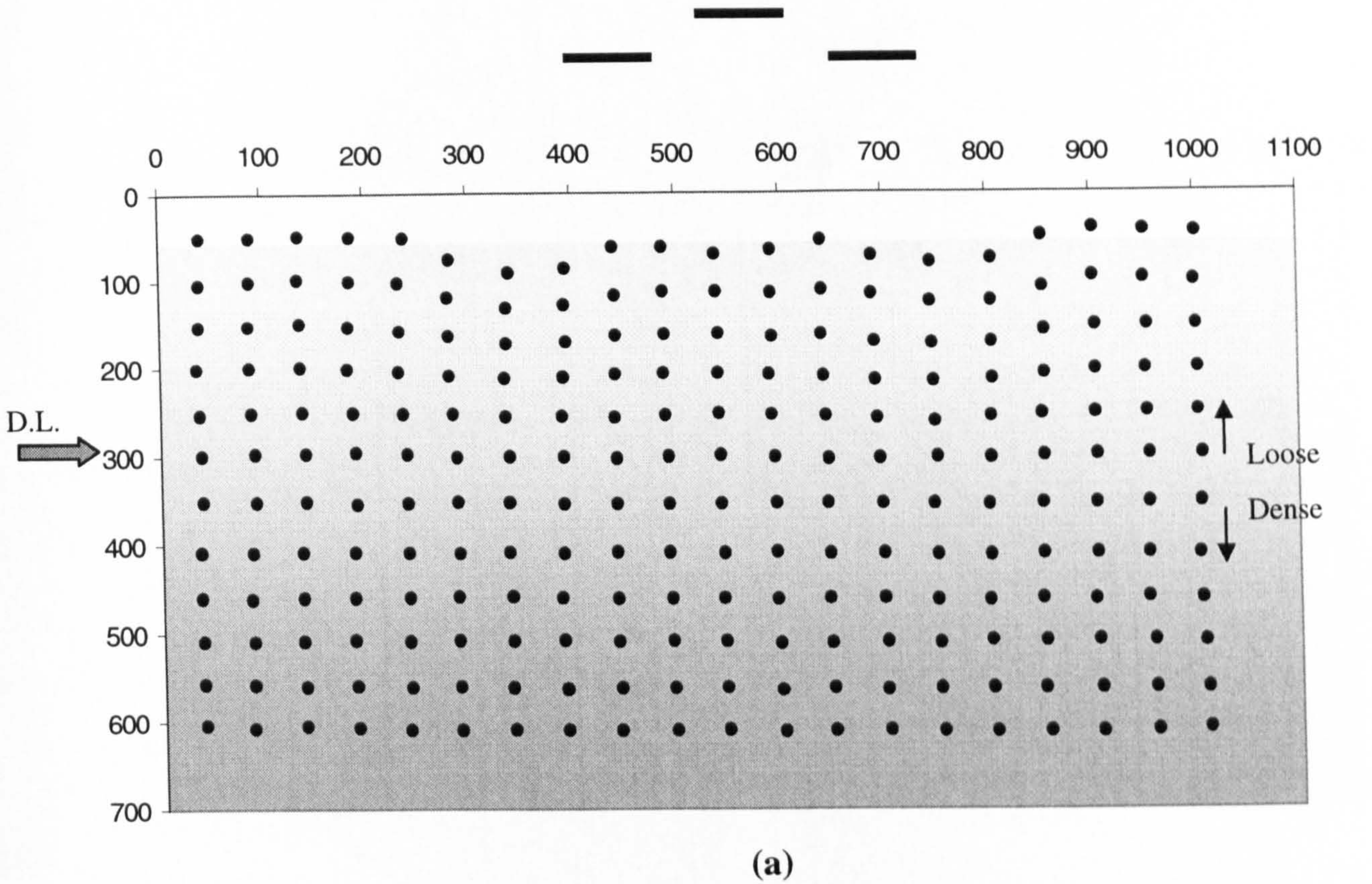
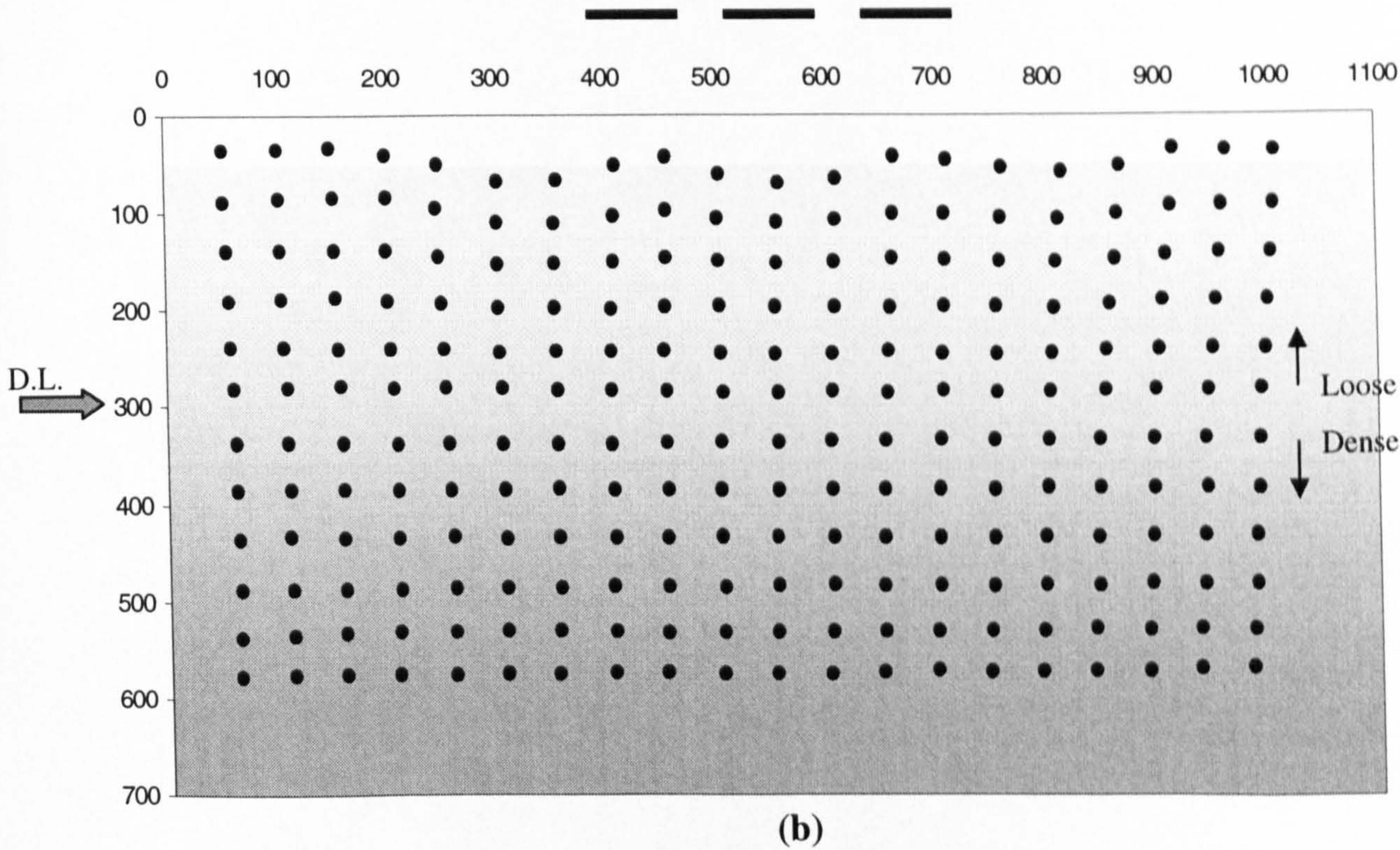


Figure 6.11. Triple with raised middle wheel (a) and same level wheels (b), in Prep 3, Replication 1

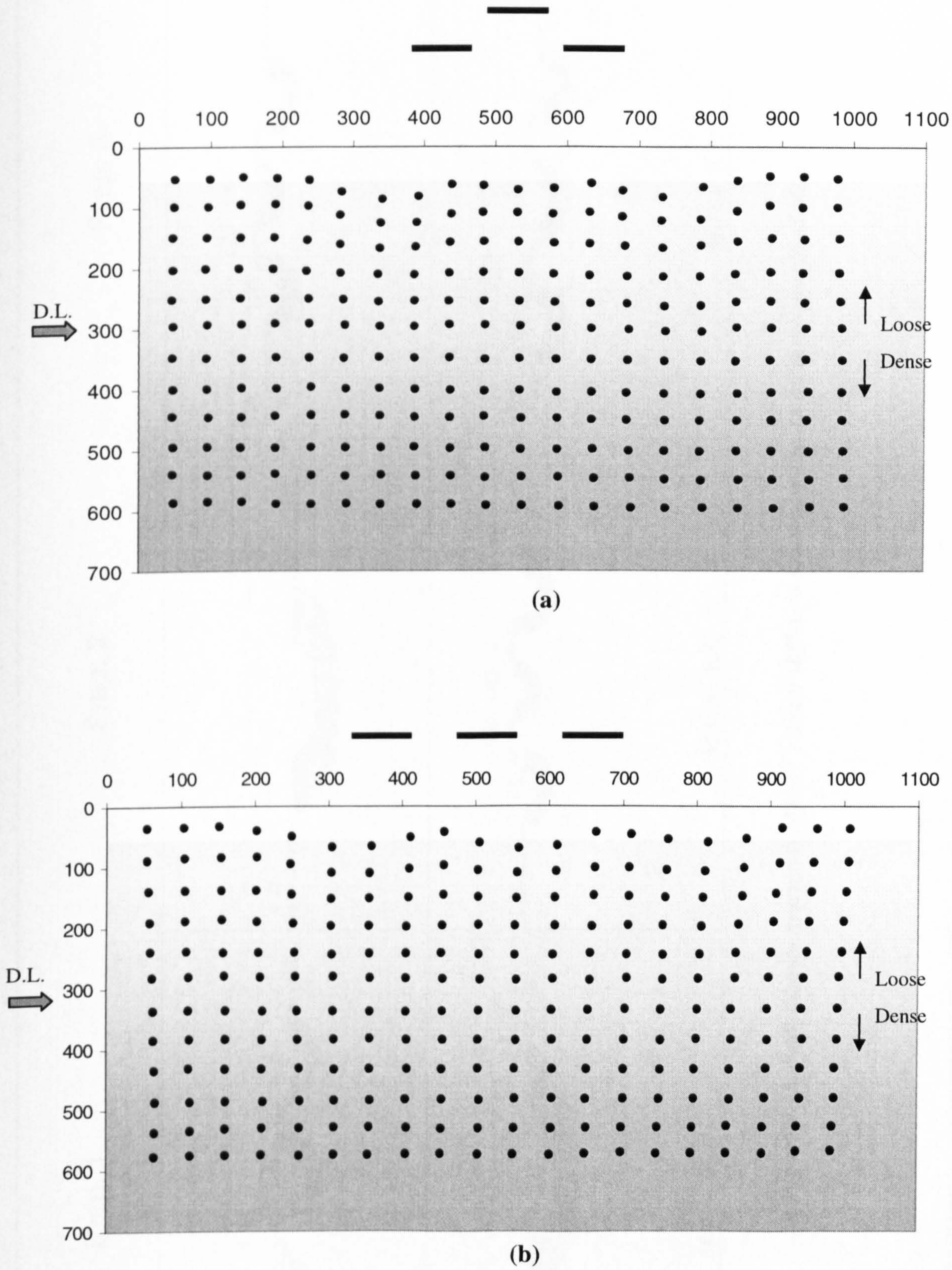


Figure 6.12. Triple with raised middle wheel (a) and same level wheels (b),
in Prep 3, Replication 2

Prep. 1

Prep. 2

Prep. 3

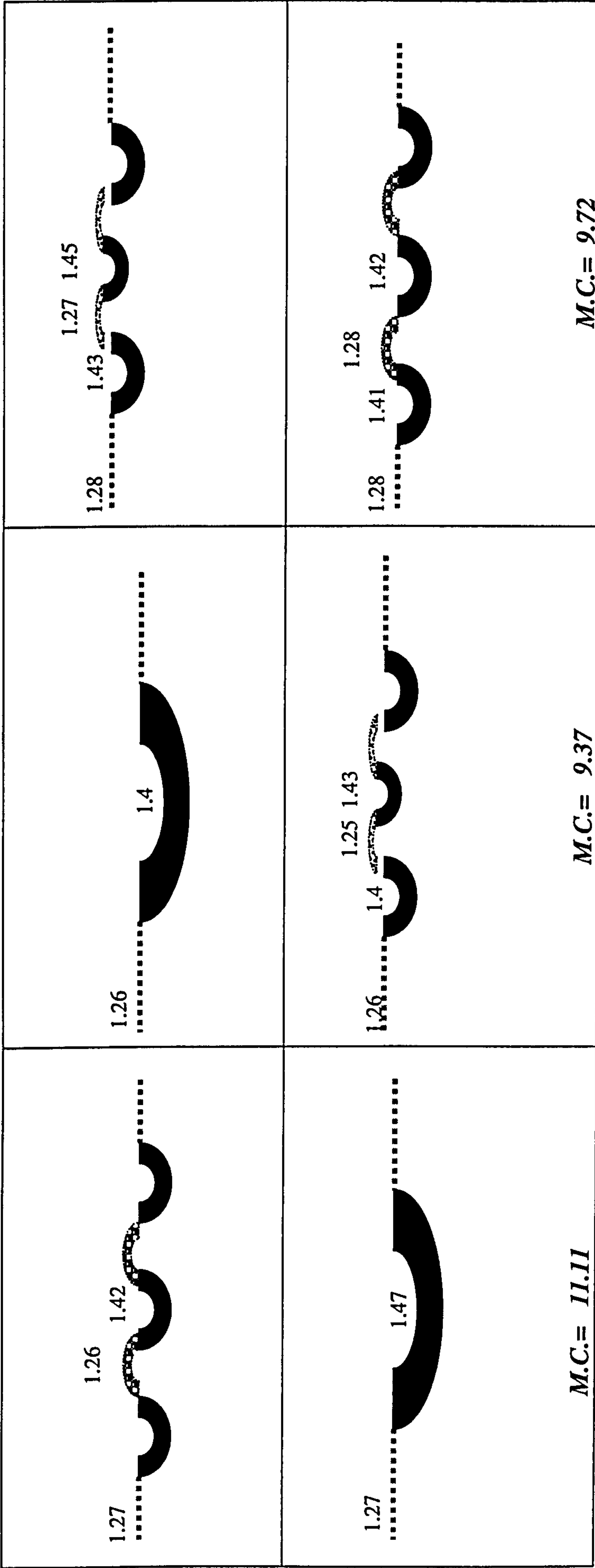


Figure 6.13. Bulk density averages($Mg.m^{-3}$) under different arrangements in all three prepared bins

6.5. Summary of discussions

The investigation of the displacement limits under the different arrangements in the large scale tests using rigid rolling wheels confirmed the results obtained in the small scale tests. It was shown that there was a benefit from using spaced arrangements rather than very wide wheels such as a terra tyre the contact pressures being the same. The strain at depth under spaced configurations was less whilst carrying the same load. Figure 6.14 shows a comparison of the displacement limits under the different arrangements carrying the same load.

The results in these tests also indicated more promising displacements under the spaced triple with wheels at the same level than was shown in the small scale experiments. The displacement limit was similar to that of the raised middle wheel arrangement which was shown to be deeper previously (see Figure 6.14).

Moreover the soil movements in the top looser layer were also least under the triple with raised middle wheel and most under the very wide (terra) arrangements.

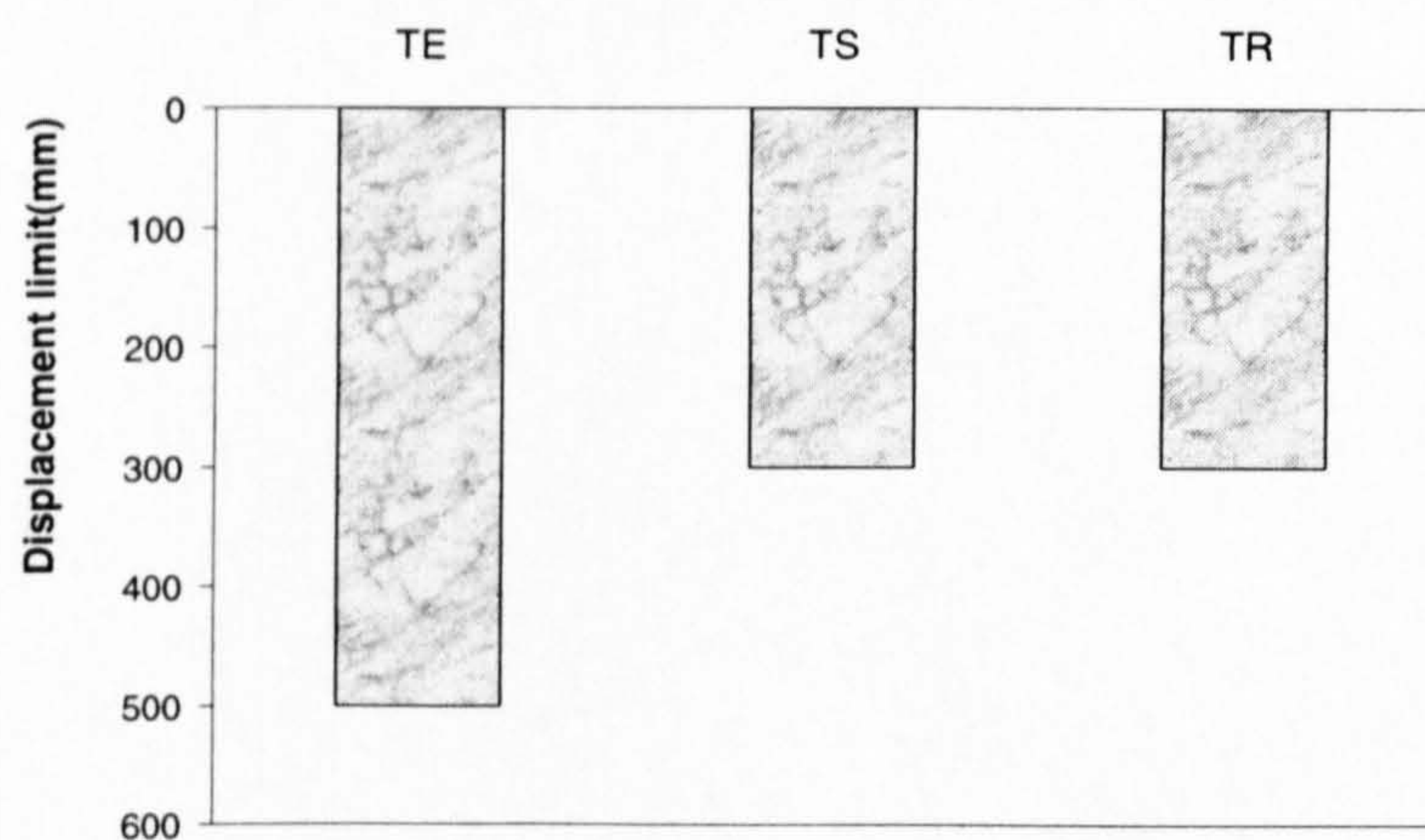


Figure 6.14. Soil displacement limit comparison under constant load

TE = Simulating terra TS = Triple wheels at the same level TR = Triple with raised middle wheel

6.6. Conclusions

- 1) A very wide wheel such as a Terra has the maximum potential to cause deep compaction.
- 2) By separating the Terra into three spaced narrow wheels, there is a opportunity to reduce the strain at depth whilst carrying the same load.
- 3) By raising the middle wheel in the triple spaced arrangement, it is possible to minimise the movement in the middle area as well as at depth.
- 4) The general soil movements in the top layer seemed to increase significantly under the Terra configuration compared with the spaced arrangements.
- 5) The full-scale experiments using rolling rigid wheels confirmed the results of small scale tests using plates in the glass sided tank.

Chapter 7. Field experiments of interacting wheels at different spacings

7.1. Introduction

Field experiments were arranged to investigate the influence of the spacing between dual wheels on soil compaction under different field conditions and to confirm that the findings from the glass sided tank studies had application in practical situations. The small scale tests in the glass sided tank described in chapter 4 showed that different failure patterns and interaction modes occurred under a wide range of arrangements. The spacing between the plates was found to be major factor affecting the interaction modes and therefore the forces and soil displacements. Hence the field experiments were performed over a range of spacings between the dual wheels.

The experiments were conducted in the south west region of Iran. Two fields were prepared providing loose and firm surface layers. Two single tractors were used to simulate the dual wheel arrangement and this enabled a wider range of spacings between the rear wheels to be investigated. The rear and front wheels on each tractor were adjusted to avoid any interaction between them. A single wheel carrying the same load as the dual wheels was also investigated for comparison. Dry bulk density and penetration resistance were measured at different depths as well as wheel sinkage and the contact area under each treatment.

The results suggested that there were some changes in terms of bulk density, penetration resistance and wheel sinkage depending upon the spacing between the wheels. The trends in the results followed the findings in the glass sided tank tests. It was also shown that there was a benefit from using dual wheels at an optimum spacing assumed to be due to the strong interaction between them. There were significant differences particularly between the smallest and largest wheel spacing treatments.

The link between the failure patterns, interactions and soil displacements identified in the glass sided tank and the practical situation provided confidence to continue with the glass sided tank studies.

7.2. Experimental procedure

7.2.1. Location

The investigations were performed in Khoozestan province, Dezful area in Iran. Dezful is located in the north of Khoozestan in the south west of Iran. Its longitude is 40.25° East and altitude of 82-m above sea level. The average annual rainfall is 350-mm and the common soil textures are clay-loam and silty-clay-loam. The area was selected because of being mostly affected by deep compaction due to heavy machinery operating in Agri-Industrial companies.

7.2.2. Field preparations

Two different surface conditions loose and firm were prepared for this investigation. The loose field was prepared using a mouldboard plough at 200 mm working depth followed by two passes with an offset disc harrow 1.4 m width. The firm field was prepared using a mouldboard plough with similar 200 mm working depth, followed by one pass with a disc harrow. A land plane was finally used to produce a firm surface. The fields were divided in four 40*30 m² plots allowing adequate replications. Three samples were taken in each plot (12 samples in each field and 24 samples total) to identify soil texture. The results are given in table 7.1. The mean values of moisture content are shown in table 7.2. The detailed data are given in appendix 3, table A3.1.

Table 7.1. Soil classification data

Condition	Loose				Firm			
Plots	1	2	3	4	1	2	3	4
Clay %	28	32	30	32	28	30	32	34
Silt %	48	44	42	44	54	46	48	44
Sand %	24	24	28	24	18	24	20	22
Class	C.L.	C.L.	C.L.	C.L.	Si.L.	C.L.	Si.C.L.	C.L.

Table 7.2. Moisture content in both fields before and after operations

	Before operation				After operation			
Depth(mm)	0 - 300		300 - 600		0 - 300		300 - 600	
Conditions	Loose	Firm	Loose	Firm	Loose	Firm	Loose	Firm
M.C.(%) (mean)	13.53	11.13	18.79	17.60	15.57	12.70	19.50	17.62

7.2.3. Treatments and methodology

Two John Deere tractors model 3140 were used to investigate the effects of spacing between the dual wheels. Due to technical limitations in the chosen site to change the spacing between dual wheel tractor, two single tractors were used. This allowed a wider range of spacings to be arranged and investigated between the rear wheels than was possible with a dual wheel tractor. New rear tyres were fitted to ensure the same condition on both tractors in terms of all characteristics, particularly lug height. The tractors were driven side by side at the required spacing between the rear wheels (see Figure 7.1).



Figure 7.1. Two single tractors driven side by side at varied spacings

The speeds of both tractors were kept constant manually. A travel line was also marked by chalk to allow the drivers to keep the required distance apart.

The rear wheels of each tractor were adjusted to give the maximum distance between them before starting the tests. The front wheels were also adjusted minimising the distance between them to avoid any interaction between rear and front tyres. Figure 7.2 shows their positions before and after the adjustment.

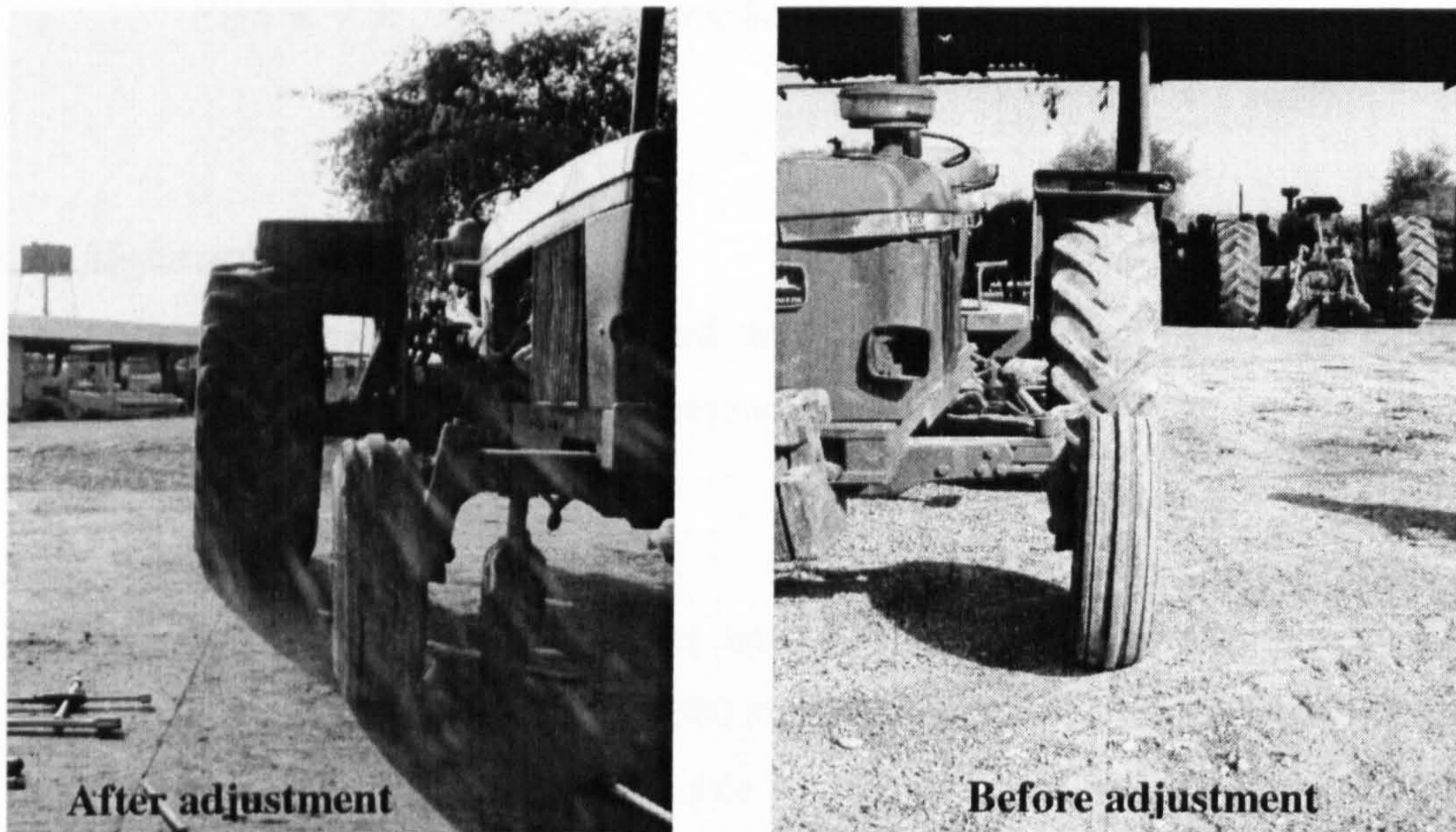


Figure 7.2. Front and rear wheel adjustments to avoiding interaction

Four different spacings between the wheels were investigated providing a varied range of possible interactions between dual arrangements. The spacing measured was between the outside of the tyres (see Figure 7.3).

A single tyre was also tested carrying twice the load as one wheel of the dual. The load was applied using extra weight as well as mounted implements.

The treatments were as follows:

- A) Dual wheels with 50 mm spacing ($L = 50$ mm)
- B) Dual wheels with 200 mm spacing ($L = 200$ mm)
- C) Dual wheels with 350 mm spacing ($L = 350$ mm)

- B) Dual wheels with 200 mm spacing($L=200$ mm)
- C) Dual wheels with 350 mm spacing($L=350$ mm)
- D) Dual wheels with 500 mm spacing($L=500$ mm)
- E) Single tyre carrying the same load

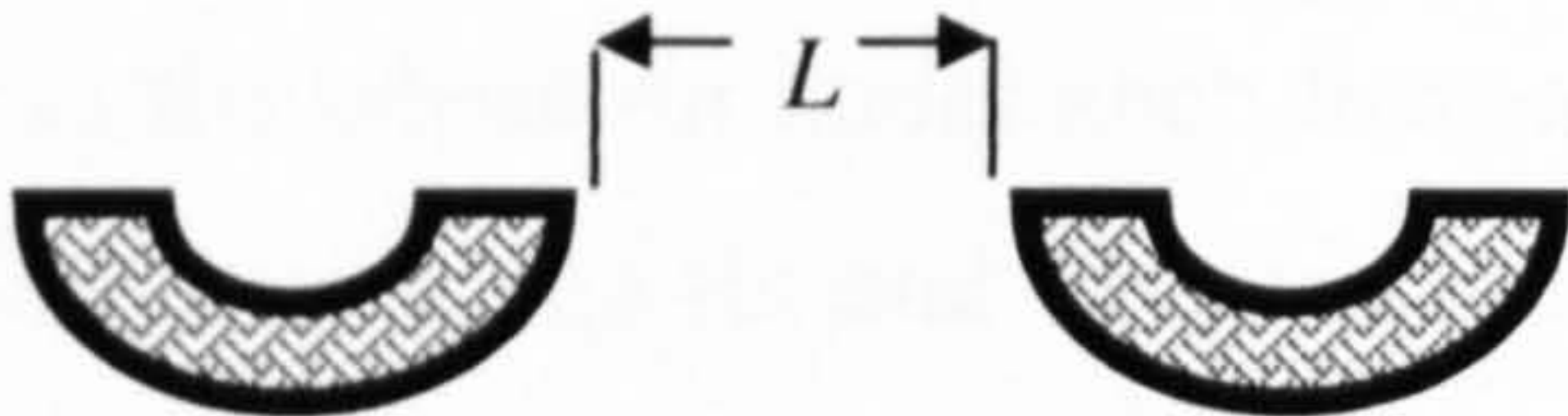


Figure 7.3. Applied spacing between the dual tyres

7.2.4. Measured parameters

The measured parameters were divided into two sections, firstly soil related parameters and secondly tractor related parameters as explained below.

7.2.4.1. Soil related parameters

Bulk density: The dry bulk density was determined using core sampler within three depth ranges of 0-150, 150-300 and 300-600 mm before the experiments. The average values are given in table 7.3 and full data for all replications are given in appendix 3, table A3.2. The density after the tests in both fields was also measured in the wheel rut area, the results are discussed in the next section.

Table 7.3. Bulk density in both fields at all depth ranges

Depth(mm)	0-150		150-300		300-600	
Conditions	Loose	Firm	Loose	Firm	Loose	Firm
B.D.($Mg.m^{-3}$)	1.26	1.37	1.48	1.51	1.59	1.60
(mean)						

Penetration resistance: A SP1000 model penetrometer made by Findley Irvin Company was used to measure the penetration resistance before and after the tests. The measurements could be made up to 500 mm depth with a minimum reading interval of 10 mm. There was an audible alarm if the maximum load

was exceeded. A 30° cone with 12.83-mm base diameter was used in this experiment. The technical specification and drawing are given in Appendix 3, Figure A3.1.

The values of penetration resistance before the tests in both fields are given in appendix 3, tables A3.4 and A3.5. The resistances after the experiments were measured across the wheel rut under each treatment, enabling comparisons to be made of the values in the rut and between them which are discussed in the next section.

Wheel sinkage: The sinkage of the wheels was measured under each arrangement with reference to a standard datum. The results are discussed in the next section.

7.2.4.2. Tractor related parameters

Contact area: The tyre contact area was measured under both the dual wheel (one wheel) and single tyre on a concrete surface. Chalk was spread around the tyre and the area calculated after removing the wheels.

Axle load: A 5 kN load cell model TC-21K made by Tokyo Sokki Kenkyujo Company was used to measure the axle loads. For more detail including the specification and function keys see appendix 3, Figure A3.2. Additional parts were made to enable the load cell to be used under the tractor axle as shown in Figure 7.4. The load was measured to be 15.7 – 15.8 kN on each of the dual wheels. The load on the single wheel test was 31.3 kN.

Inflation pressure: The tyre pressure was adjusted to 137.9 kPa or 1.38 bar, which was the factory recommended pressure for ploughing operation with 18.4-34 tyre size.

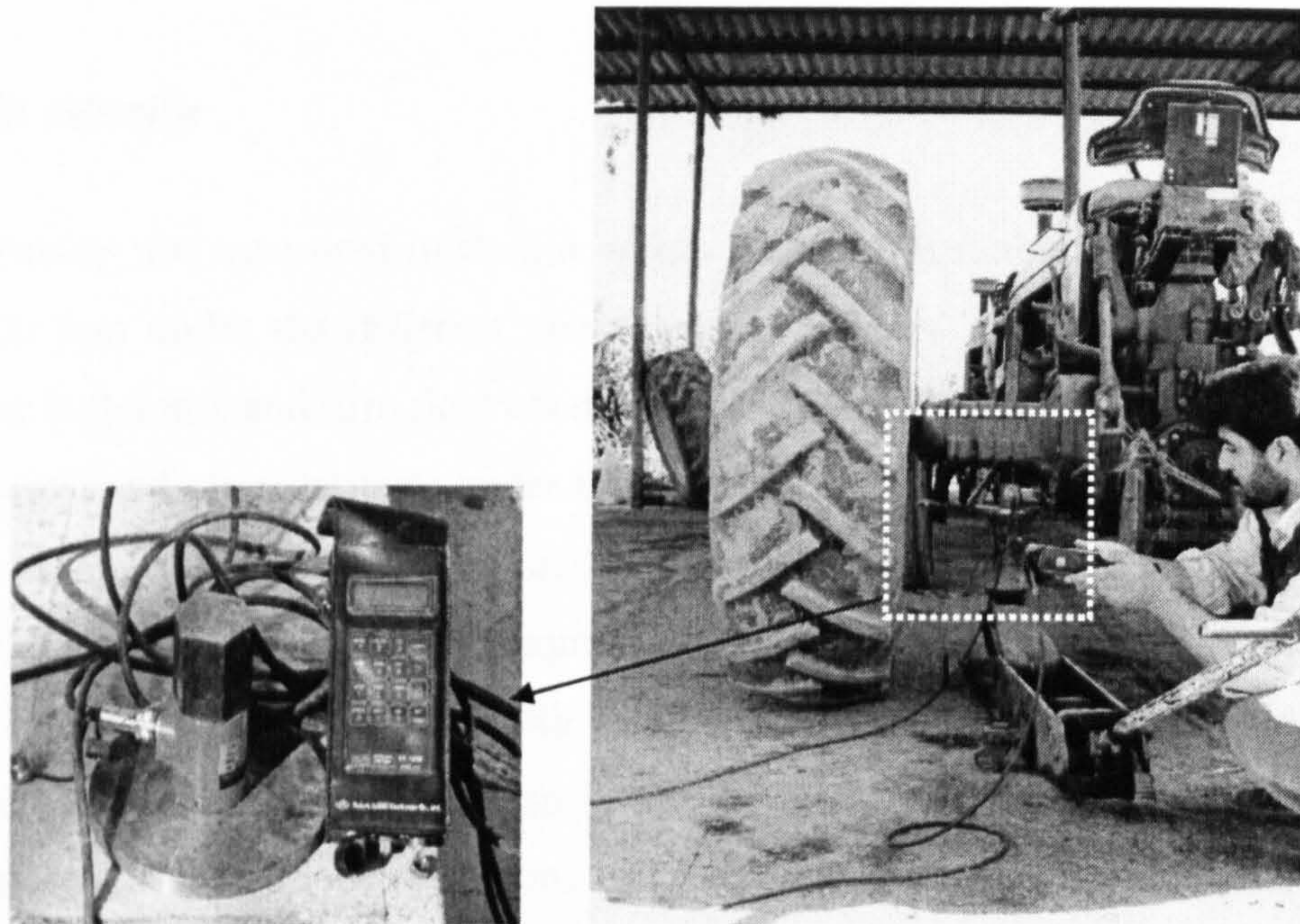


Figure 7.4. Axle load measurement and load cell components

7.4. Results and discussions

7.4.1. Contact area

The contact area under the single and dual wheels was measured on a concrete surface using chalk. The areas were calculated to be 0.24 and 0.18 m^2 under single and dual wheels (one wheel) respectively with the same inflation pressure. This meant that there was a larger contact area under the single wheel than under one of the dual wheels. The stress applied to the soil was also calculated to identify the difference between them, it was follows.

Single tyre

$$\text{Area} = 0.24 \text{ m}^2$$

$$\text{Load} = 31.4 \text{ kN}$$

$$\text{Stress} = \frac{31.4}{0.24} = \mathbf{131.5 \text{ kPa}}$$

Dual tyre

$$\text{Area} = 0.18 \text{ m}^2$$

$$\text{Load} = 15.7 \text{ kN}$$

$$\text{Stress} = \frac{15.7}{0.1794} = \mathbf{87.7 \text{ kPa}}$$

7.4.2. Bulk density

The bulk density was measured in the rut within three depth ranges 0-150, 150-300 and 300-600 mm under the different arrangements. Figures 7.5 and 7.6 show the results under both loose and firm field conditions. The comparison between the results before (control) and after the tests under the arrangements indicated that there were differences in the 0-150 and 150-300 mm depth ranges in the loose field and in the 0-150 mm depth range in the firm field (compare control with the others in Figures 7.5 and 7.6). Comparing the controls in both the firm and loose fields showed that the density in the firm field was higher than in the loose one in the depth range 0-150 mm. This meant that the tillage operations had created different conditions in the top layer of both fields.

The results in the loose field indicated that the major difference between the treatments occurred in the 0-150 mm depth range. A higher density was found under the arrangements with wider spacings of 350 and 500 mm than under the smaller spacings of 50 and 200 mm in this depth range (see “a” in both Figures 7.5 and 7.6).

From the glass sided tank studies it was likely that an interaction between the wheels at smaller spacings created a static zone in the middle supporting a greater load. It was most probable that dual wheels with wide spacing performed individually without interaction or with very weak interaction imposing more stress in the rut.

The results from an analysis of variance given in tables 7.4 and 7.5 showed that there was no significant difference between treatments in the loose field, but a significant difference was found between the treatments in the firm field.

Table 7.4. ANOVA test for bulk density in the loose field

Source	df	SS	MS	F
Arrangements	4	0.019	0.0047	2.97 <i>n.s.</i>
Error	10	0.016	0.0016	
Total	14	0.035		

n.s. = Non significant difference

Table 7.5. ANOVA test for bulk density in the firm field

Source	df	SS	MS	F
Arrangements	4	0.0205	0.00513	5.98 *
Error	10	0.0087	0.00087	
Total	14	0.0292		

* = Significant difference with 95% confident

Therefore a LSD test was carried out to reveal where the difference was. The comparison between the treatment means using the LSD test in the firm field, indicated that the difference was between the dual wheel at the largest spacing (500 mm) and the smallest spacing (50 mm). The LSD analysis also showed that there was a significant difference between the single tyre and the dual wheel with the smallest spacing carrying the same load. The results of LSD analysis are described below.

LSD (%5) = 0.054

$\bar{X}_{200} - \bar{X}_{50} = 1.427-1.397 = 0.03 \text{ n.s.}$

$\bar{X}_{350} - \bar{X}_{50} = 1.44-1.397 = 0.043 \text{ n.s.}$

$\bar{X}_{500} - \bar{X}_{50} = 1.48-1.397 = 0.083 *$

$\bar{X}_{single} - \bar{X}_{50} = 1.49-1.397 = 0.093 *$

n.s. = Non significant difference * = Significant difference with %95 confident

No significant difference was found between the treatments in the 150-300 and 300-600 mm depth ranges in both fields.

The results showed that there was a step increase in density above the 200-mm spacing (350 and 500 mm) in the loose field for depth levels of 0-150 and 150-300 mm. This step occurred a little later in the firm field, above the 350-mm spacing (500 mm) at similar depth levels, because of the soil condition. It is suggested that some changes in terms of interaction could have occurred between the wheels at that spacing.

See tables A3.2 in appendix 3 for bulk density data of all plots and replications after the tests.

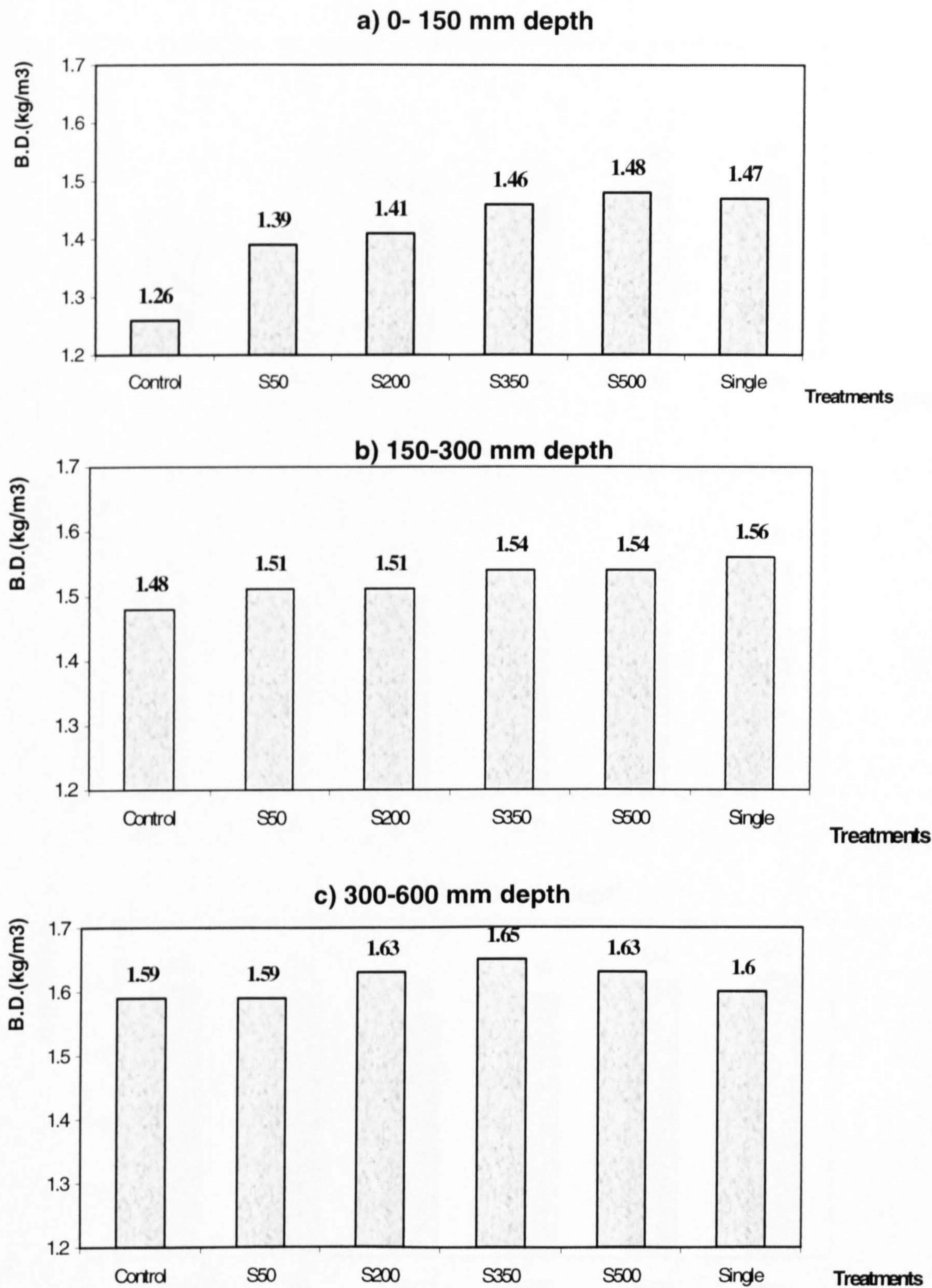


Figure 7.5. Bulk density($Mg.m^{-3}$) in the loose field at different depth levels
S50=50 mm spacing S200=200 mm spacing S350=350 mm spacing S500=500 mm spacing

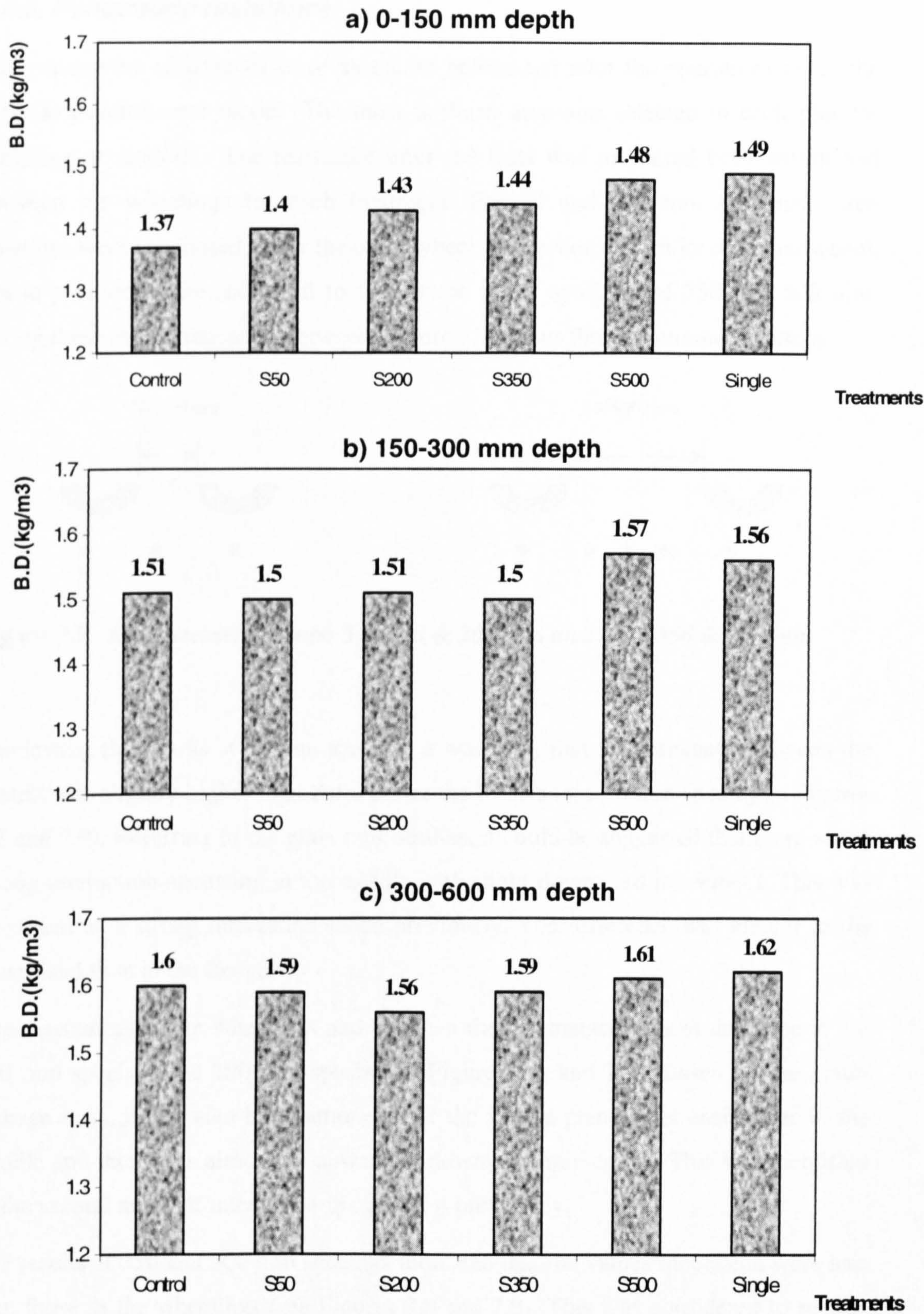


Figure 7.6. Bulk density($Mg.m^{-3}$) in the firm field at different depth levels
S50=50 mm spacing S200=200 mm spacing S350=350 mm spacing S500=500 mm spacing

7.4.3. Penetration resistance

The penetration resistances were measured before and after the operations using the SP1000 penetrometer model. The most uniform area was selected in each plot for sampling at random. The resistance after the tests was measured both within and between the wheelings for each treatment. For 50 and 200 mm spacings, three positions were monitored under the outer wheel, inbetween and under the inner wheel. These positions were increased to five at the wider spacings of 350 and 500 mm, giving three measurements inbetween. Figure 7.7 shows the measurement pattern.



Figure 7.7. Measurement points: 3 for 50 & 200 mm and 5 for 350 & 500 mm

Reviewing the results at 50 mm spacing, it was clear that the resistance between the wheels was slightly higher than those under the wheels (see 50 mm spacing in Figures 7.8 and 7.9). Referring to the glass tank studies, it could be suggested that there was a strong interaction occurring in the middle with slight downward movement. This was identified as a strong interaction mode previously. The difference was clearer in the loose field than in the firm one.

The resistances in the wheelings and between them remained almost the same at the 200 mm spacing (see 200 mm spacing in Figures 7.8 and 7.9). Based on the plate-sinkage tests, it can also be mentioned that the failure planes met each other in the middle and there was almost no upward or downward movement. This was identified as the second mode of interaction in chapter 4 previously.

The results at 350 and 500 mm spacings indicated that the values inbetween were less than those in the wheelings (see Figures 7.8 and 7.9). This was considered to be due to weak interaction and upward movement in the middle. This was identified as a first mode of interaction previously in the glass tank tests.

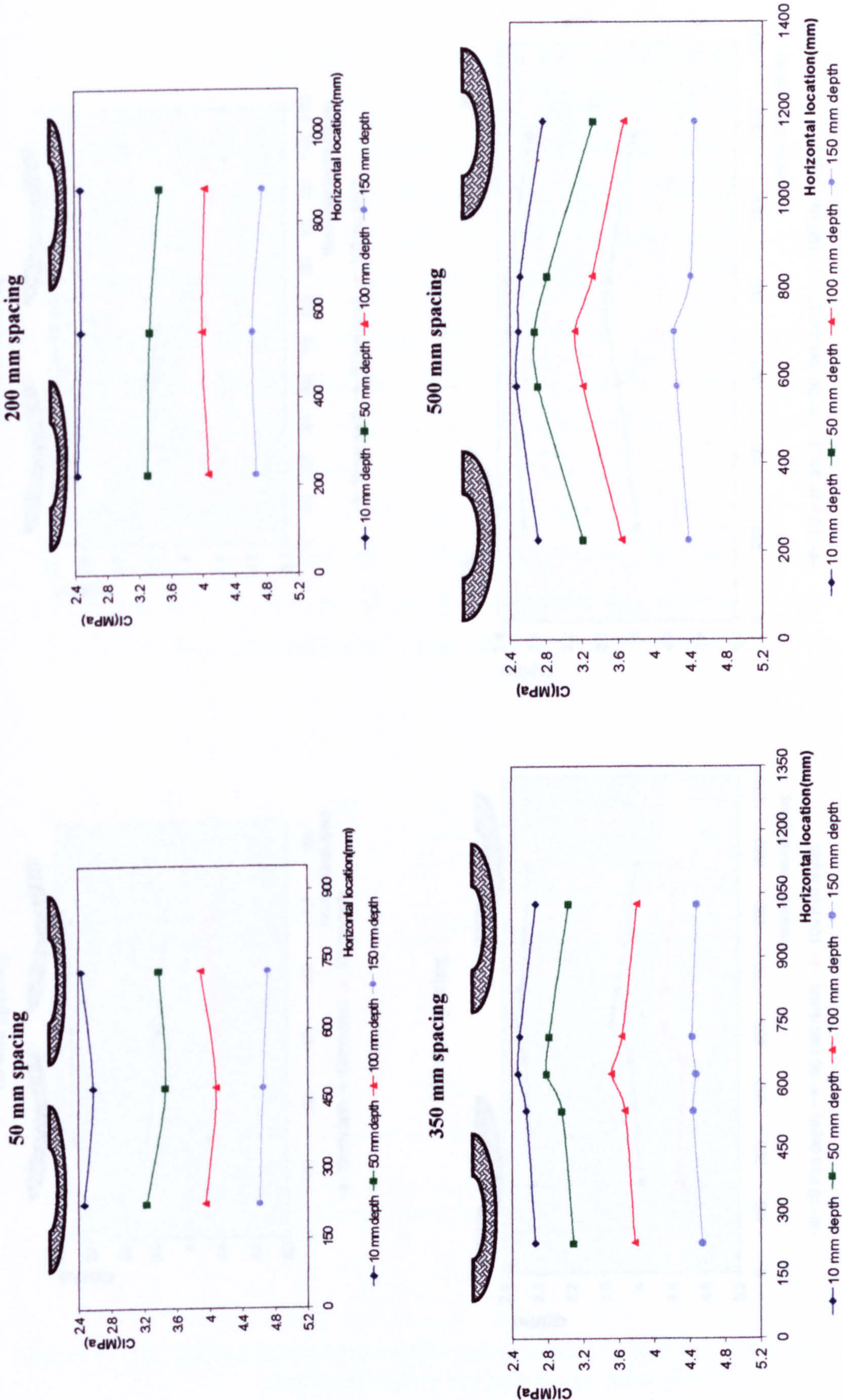


Figure 7.8. The penetration resistance under dual arrangements in the loose field

CI = Cone Index

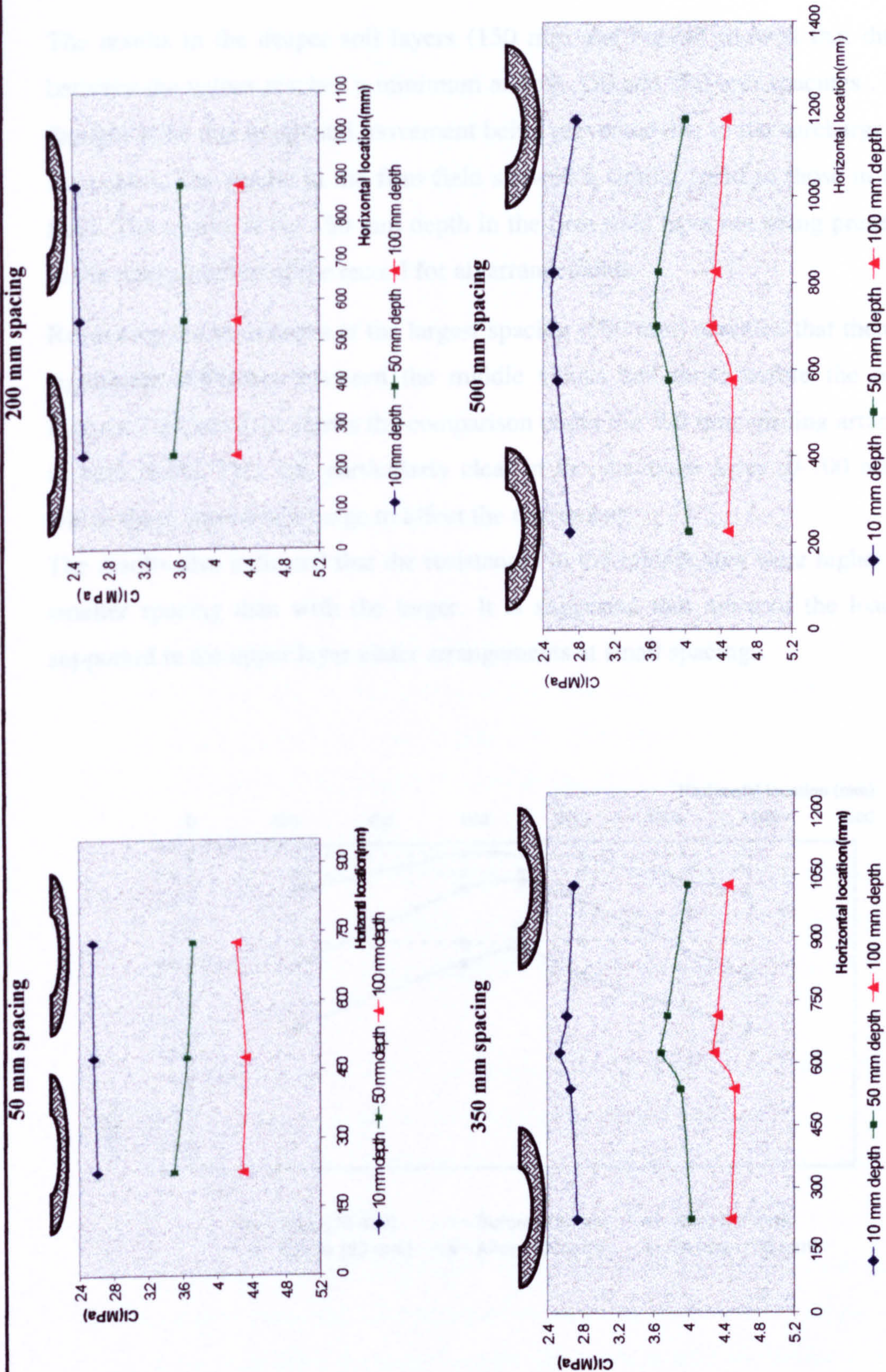


Figure 7.9. The penetration resistance under dual arrangements in the firm field

CI = Cone Index

The results in the deeper soil layers (150 mm and below) showed that differences between the values reached a minimum at both 350 and 500 mm spacings . This was thought to be due to upward movement being prevented due to the surcharge effect in the centre. The results in the firm field showed a similar trend to those in the loose field. The results at the 150 mm depth in the firm field have not being presented due to the unavailability of the record for all arrangements.

Reviewing the resistances at the largest spacing (500 mm) revealed that there was no significant difference between the middle values and those before the operation. Figures 7.10 and 7.11 shows the comparison under the 500 mm spacing arrangements in both fields. This was particularly clear in the shallower layer (0-100 mm depth) where there was no surcharge to affect the movement.

The results also indicated that the resistances in the middle area were higher with the smaller spacing than with the larger. It is suggested that more of the load can be supported in the upper layer under arrangements at small spacings.

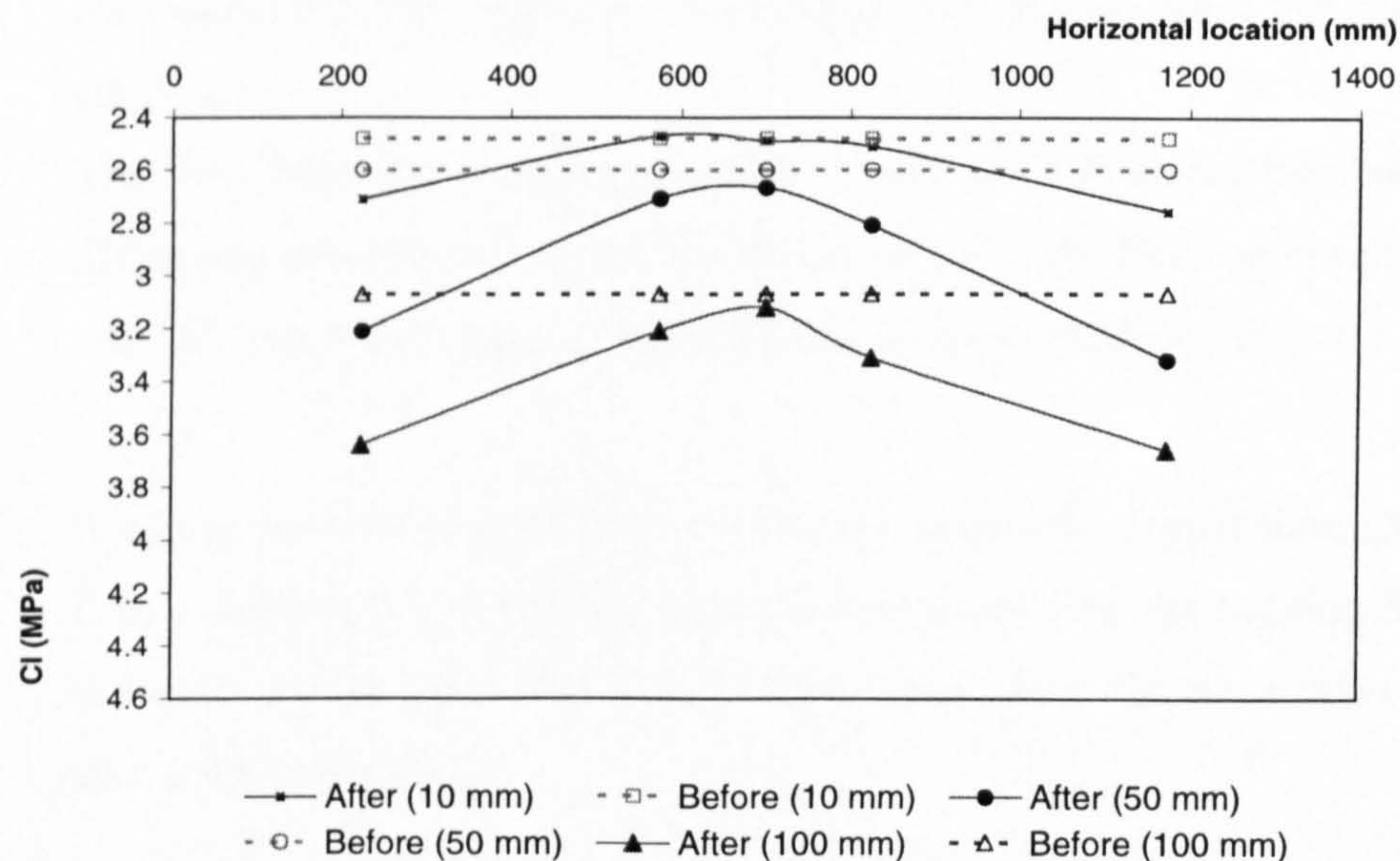


Figure 7.10. Comparison of the middle values under the 500 mm arrangement with those before the tests in the loose field

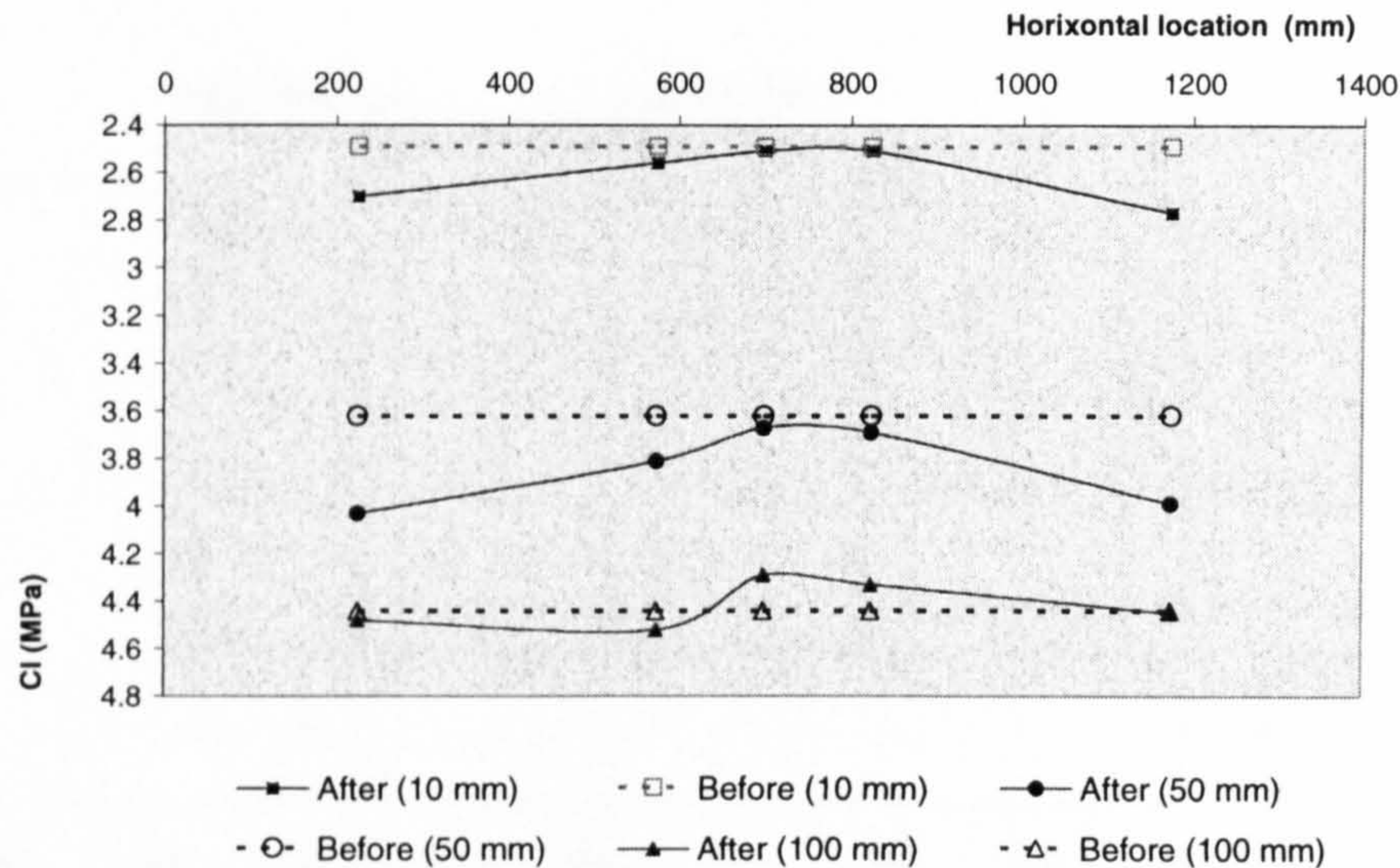


Figure 7.11. Comparison of the middle values under the 500 mm arrangement with those before the tests in the firm field

The single tyre test result indicated that the penetration resistance in the wheelings was higher when compared with the dual wheels, particularly at the small spacing. (compare Figure 7.12 with Figure 7.8). The values of density before the operation are also showed in the Figure 7.12 revealing the changes after the operation under the single tyre.

The firm field showed similar results to the loose field but there was no significant difference between the values under the wheel with those before operation in the 50 and 100 mm depth range compared with the loose field (see Figure 7.13).

It was impossible to record the penetration resistance deeper than 150-200 mm in the firm condition because of the penetrometer exceeding the limiting 50 kN force. This however proved not to be a serious problem, since the interaction mostly occurred above that depth range.

The data plotted in Figures 7.8-7.13 was obtained from one representative plot for each condition to avoid making errors by using the average of all plots. The full data for the other plots are given in appendix 3, tables A3.6 for the loose field and A3.7 for the firm field. The data in the other plots showed a similar trend.

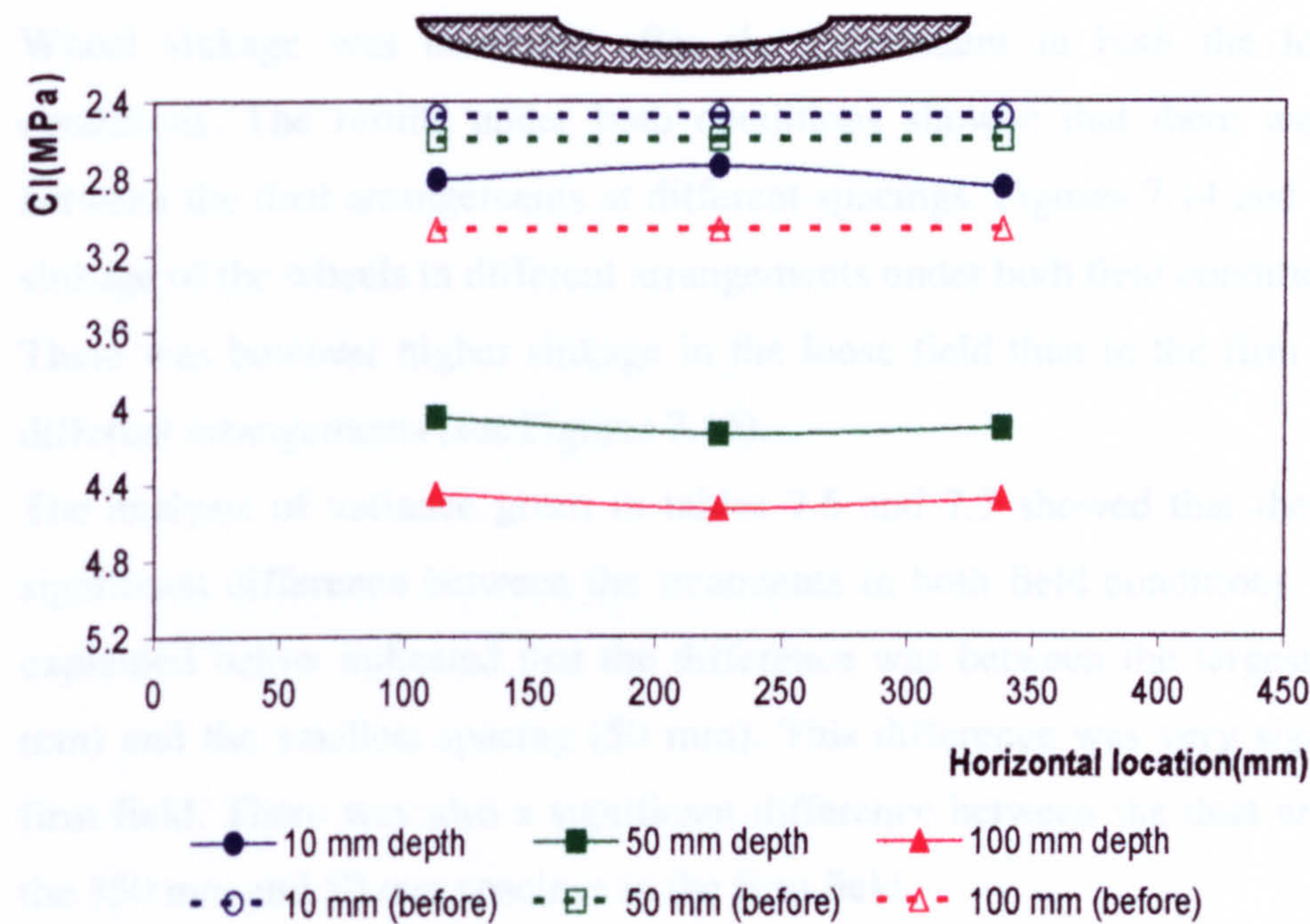


Figure 7.12. Penetration resistance under single tyre in the loose field

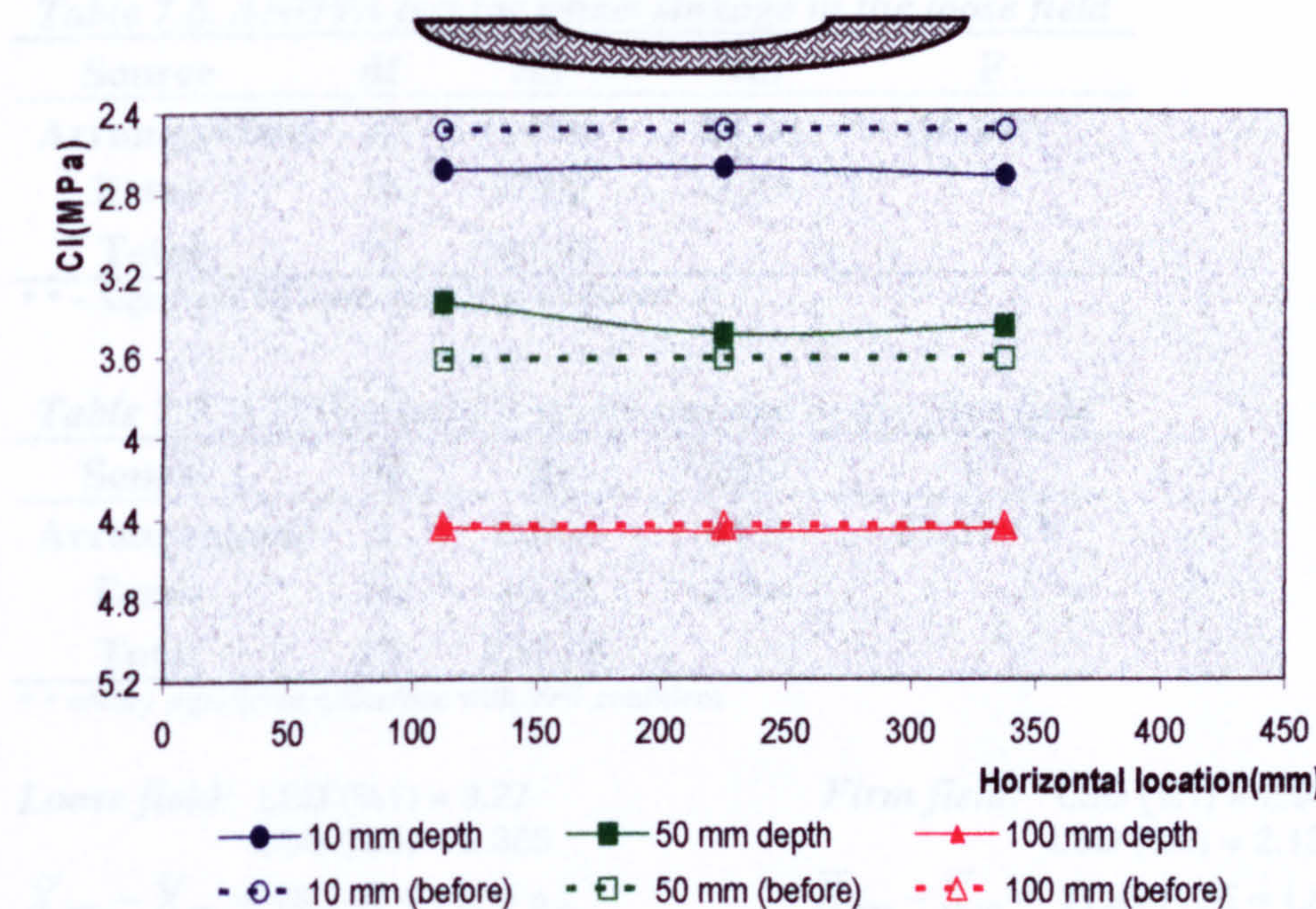


Figure 7.13. Penetration resistance under single tyre in the firm field

7.4.4. Wheel sinkage

Wheel sinkage was measured after the experiment in both the loose and firm conditions. The results under both conditions showed that there were differences between the dual arrangements at different spacings. Figures 7.14 and 7.15 show the sinkage of the wheels in different arrangements under both field conditions.

There was however higher sinkage in the loose field than in the firm one under the different arrangements (see Figures 7.16).

The analysis of variance given in tables 7.6 and 7.7 showed that there was a very significant difference between the treatments in both field conditions. The LSD test explained below indicated that the difference was between the largest spacing (500 mm) and the smallest spacing (50 mm). This difference was very significant in the firm field. There was also a significant difference between the dual arrangements at the 350 mm and 50 mm spacings in the firm field.

The LSD test revealed that there was a very significant difference between the single tyre and all the dual arrangements at varied spacings in both fields.

Full data of replications in both fields are given in appendix 3, tables A3.8 and A3.9.

Table 7.6. ANOVA test for wheel sinkage in the loose field

Source	df	SS	MS	F
Arrangements	4	104.33	26.08	10.56 * *
Error	15	37.02	2.47	
Total	19	141.35		

* * = Significant difference with 99% confident

Table 7.7. ANOVA test for wheel sinkage in the firm field

Source	df	SS	MS	F
Arrangements	4	207.6	51.9	25.37 * *
Error	15	30.15	2.01	
Total	19	237.75		

* * =Very significant difference with 99% confident

Loose field: LSD (%1) = 3.27
LSD (%5) = 2.365

$\bar{X}_{200} - \bar{X}_{50} = 28.3-27.4 = 0.95 \text{ n.s.}$
 $\bar{X}_{350} - \bar{X}_{50} = 29-27.4 = 1.6 \text{ n.s.}$
 $\bar{X}_{500} - \bar{X}_{50} = 30.4-27.4 = 3 *$
 $\bar{X}_{\text{single}} - \bar{X}_{50} = 34-27.4 = 6.6 **$

Firm field: LSD (%1) = 2.947
LSD (%5) = 2.131

$\bar{X}_{200} - \bar{X}_{50} = 21.83-19.95 = 1.88 \text{ n.s.}$
 $\bar{X}_{350} - \bar{X}_{50} = 22.2-19.95 = 2.25 *$
 $\bar{X}_{500} - \bar{X}_{50} = 22.93-19.95 = 2.98 **$
 $\bar{X}_{\text{single}} - \bar{X}_{50} = 29.4-19.95 = 9.45 **$

n.s. = Non significant difference * = Significant difference with 95% confident * * = Very significant difference with 99%

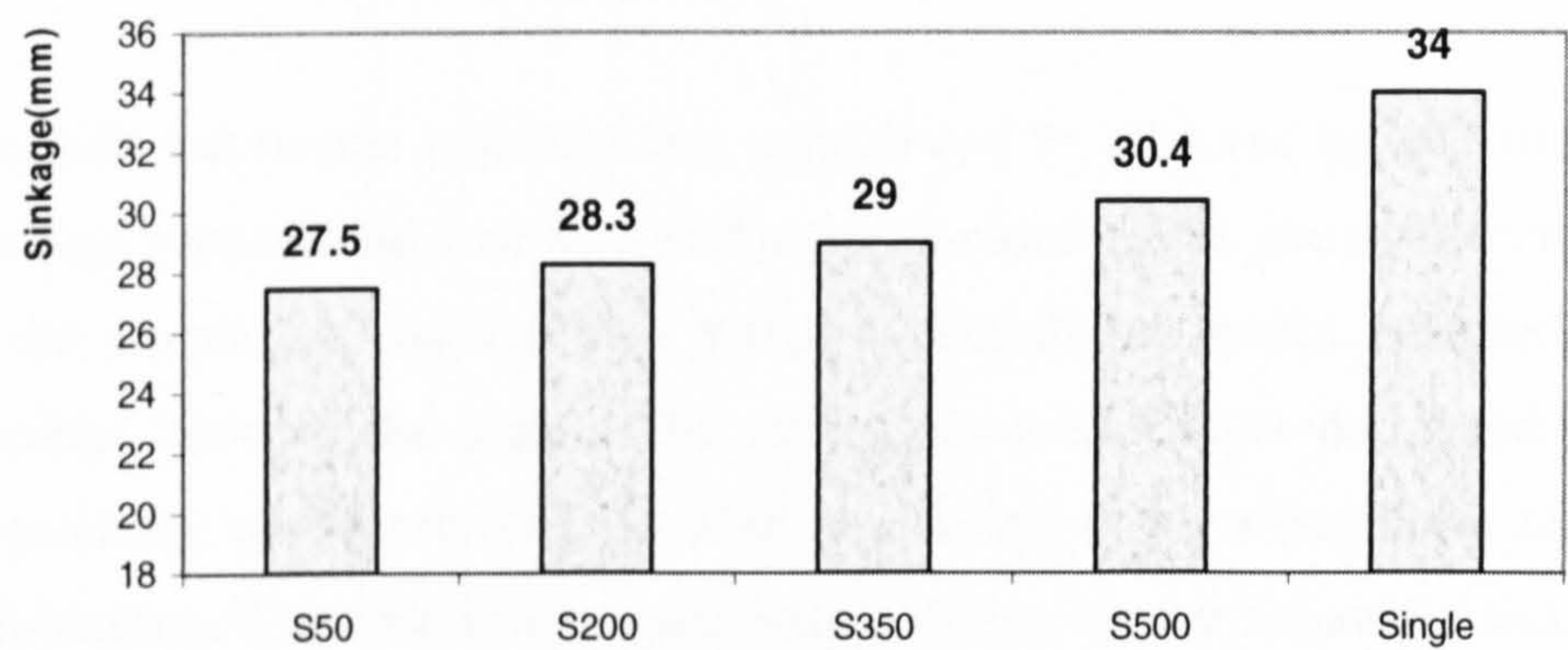


Figure 7.14. Wheel sinkage under different treatments in loose field

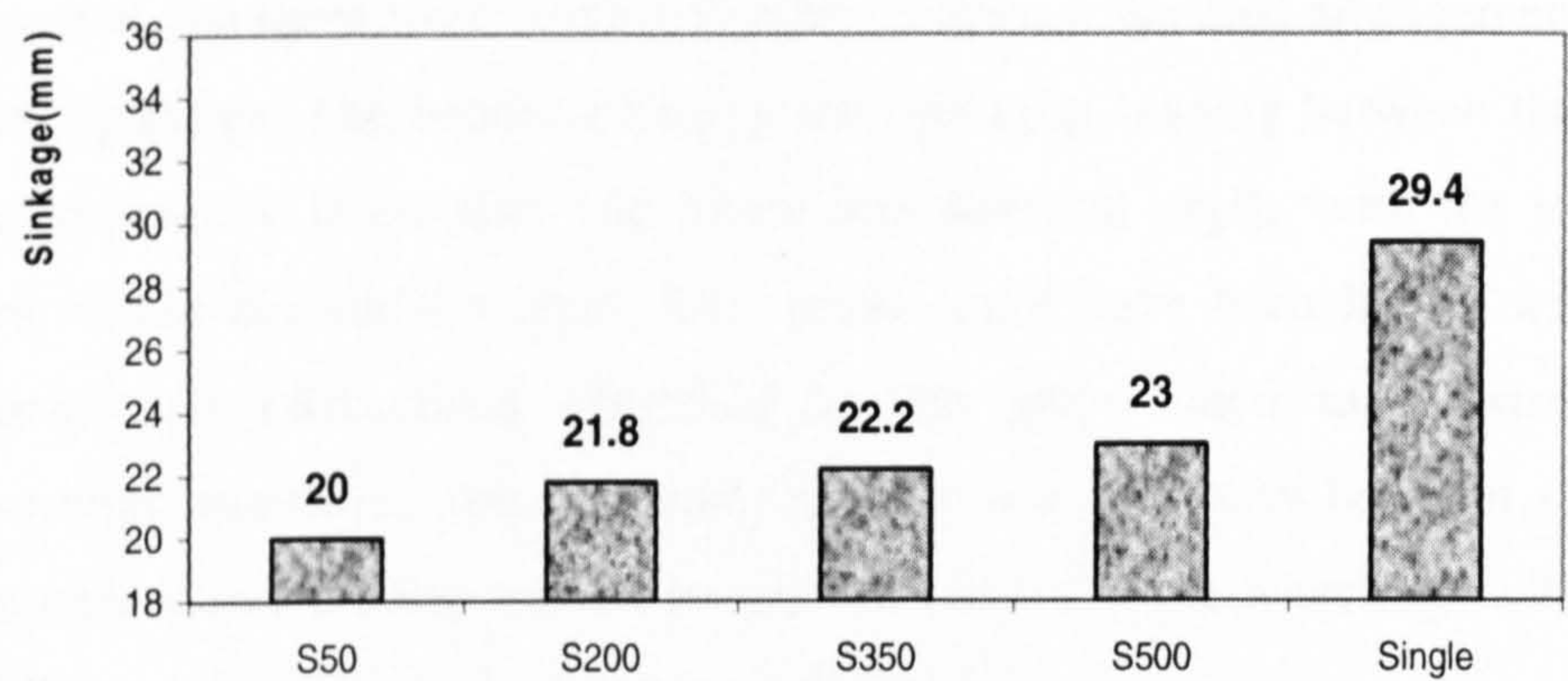


Figure 7.1 5. Wheel sinkage under different treatments in firm field

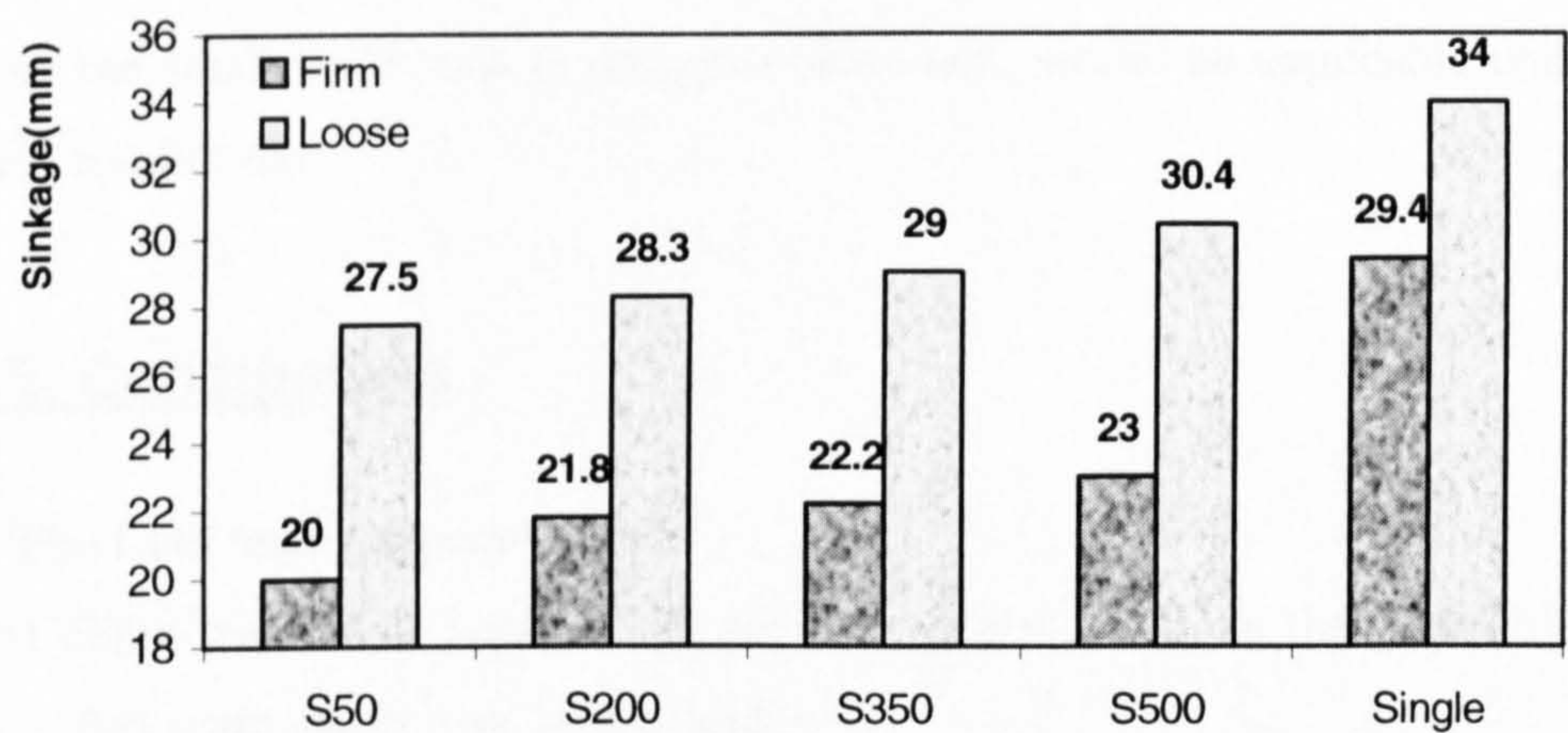


Figure 7.16. Wheel sinkage comparison in both loose and firm fields

7.4. Summary of discussions

The field test results indicated that benefit can be achieved by selecting appropriate spacings between the dual wheels. Previous studies in the glass sided tank (explained in the chapter 4) showed that different interaction modes occurred at different spacings between the plates. The interaction modes were numbered from 0 to 3 representing no- interaction to strong interaction which affected the forces and soil deformation. The field test was expected to show similar behaviour linking the glass tank tests with practical situations.

The results of bulk density, penetration resistance and wheel sinkage measurements suggested that there were some differences between the dual arrangements at different wheel spacings. The benefit of using the optimum spacing between the dual wheels offered positive interaction and hence less stress at depth, with the load supported more within the surface layer. This trend could have been linked with the failure patterns and interactions identified in the glass sided tank experiments. The penetration resistance results clearly identified a similarity between the field glass tank tests where a comparison between the values in the wheelings with those in the middle revealed different interaction behaviour.

The major interaction and its effects were found to be in the 0-150 mm depth range under both field conditions.

This chapter therefore provides evidence that the fundamental knowledge obtained from the small scale tests in the glass sided tank would be applicable under practical field conditions.

7.5. Conclusions

1. The field tests suggested that:

- a) There was a link between the small scale test results in the glass sided tank and full scale wheel tests in the field.
- b) Some benefits could be achieved by selecting the appropriate spacing between the dual wheels to provide maximum support in the surface layers.

- c) The major differences occurred in the 0-150 mm depth range, where the greatest interaction was expected to occur.

2. The bulk density results indicated that:

- a) There was a difference between the dual wheels at the smallest and the largest spacings in the 0–150 mm depth range.
- b) As the spacing increased, a step increase was visible beyond the 200 mm spacing in loose soil and the 350 mm spacing in firm soil, suggesting possible changes in the type of interaction.

3. The penetration resistance results claimed that:

- a) There was no significant difference between the readings in the wheelings and in the middle at the 50 and 200-mm spacing in both loose and firm conditions, although the middle points were slightly higher.
- b) There was a difference between the values in the wheelings and those in the middle at the 350 and 500-mm spacings.
- c) There was no significant difference between the middle values before and after the test at the larger spacing but there was within the wheelings.
- d) The resistance between the wheels at the smallest spacing was higher than with the largest, suggesting more of the load could be supported in the upper layer at the smallest spacing

4. The wheel sinkage measurements showed that:

- a) There was a significant difference between the dual arrangements at the largest and the smallest spacings under both loose and firm conditions.
- b) There was a very significant difference between the dual wheel arrangements and the single tyre.

5. The contact area results concluded that:

- a) Although the contact area under the single tyre was measured to be 1.33 times bigger than under the dual tyre (one wheel), due to double the load it did not have a major effect.
- b) The stress transmitted to the soil under the single tyre was calculated to be 1.5 times bigger than under each wheel of dual.

Chapter 8. A force prediction model for interacting shallow footings

8.1. Introduction

The main objective of this chapter was to develop a model for predicting the vertical force under interacting footings. The model aimed at estimating the resultant force under dual or triple plate arrangements responsible for creating different interaction modes at varied spacings.

Some mathematical solutions for predicting forces have been available for two dimensional failure patterns for wide tines suggested by Osman (1964), Seimens and Weber (1965) and Hettiaratchi et al. (1966) and for three dimensional failures with narrow tines by Payne (1956), O'callaghan and Farrelly (1964) and Hettiaratchi and Reece (1967). A model was also developed for very narrow tines by Godwin and Spoor (1977).

From the literature there was no model to predict the resultant force under different dual and triple footings with interaction. The only model suggested for interacting implements was for very narrow tines developed by Godwin et al. (1984).

Force development and failure patterns in the glass tank showed that the vertical force under a single plate could be predicted using the Terzaghi general bearing capacity equation (Eqns 1) or Meyerhof solution for shallow footing (Eqns 2).

$$Q_d = w(cN_c + qN_q + 1/2w\gamma N_\gamma) \quad (8.1)$$

$$Q_d = w(cN'_c + qN'_q) \quad (8.2)$$

where: Q_d = Force per unit length ($kN.m^{-1}$) γ = unit weight ($kN.m^{-3}$)
 q = Surcharge ($kN.m^{-2}$) w = width of the footing (m)
 N_c, N_q, N_γ, N'_c & N'_q = Dimensionless numbers obtained from relative graphs
which are function of c and ϕ

The graphs to find the N values for both equations are given in appendix 4.

Meyerhof (1948 and 1951) developed a logarithmic spiral technique within a shallow footing model that deviates only marginally from the more complex numerical solution of Sokolovski (1965). The experimental results under a single plate in dry

sand indicated that the failure planes were likely to follow the semi logarithmic spiral patterns, developed by Meyerhof. Therefore the model was developed based on the Meyerhof solution.

The model aimed to predict the extra force created through the interaction between footings. This extra force could then be added to the resultant force of non-interacting footings predicted individually by the Meyerhof equation. The model evaluation showed an acceptable level of agreement with the glass tank experimental results.

8.2. Rupture distance calculation

It was necessary to calculate the rupture distance (f) at the first stage to identify the plate spacing at which interaction started (see Figure 8.1). Previous research has shown that the resultant force on a footing was relatively insensitive to the degree of mobilisation of shear stress along the face AE, therefore shear stresses on this face were neglected. To meet this condition, the angle of DAE must be $(45 - \varphi/2)$ and the angle CBA considered to be $(45 + \varphi/2)$ [Hettiaratchi and Reece 1967].

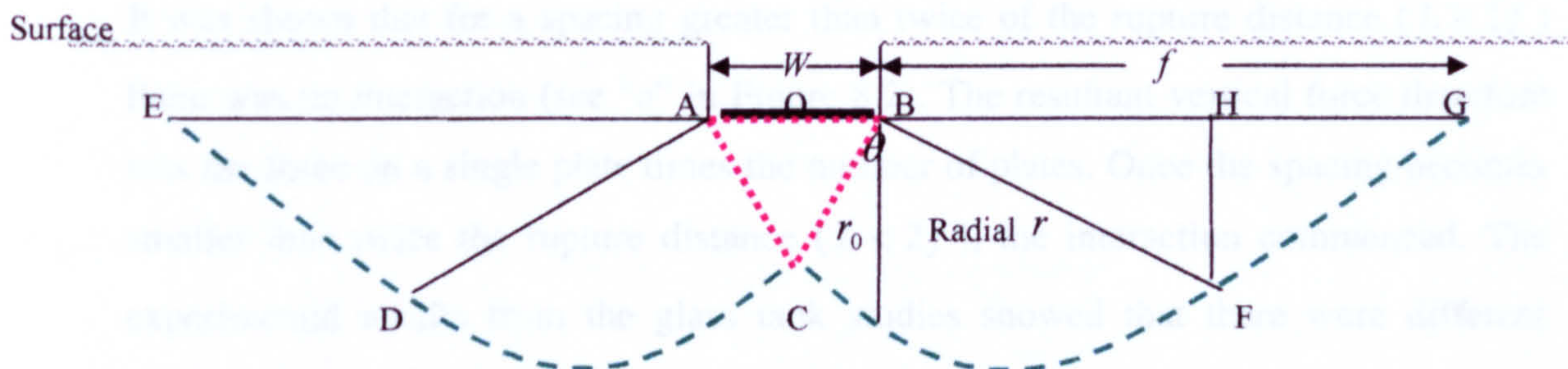


Figure 8. 1. The failure pattern and zones under a shallow footing

From the logarithmic spiral equation, the radius r in the radial zone can be calculated:

$$r = r_0 e^{\theta \tan \varphi} \quad \theta \text{ and } \varphi \text{ in radians} \quad (8.3)$$

where: $\theta_{\max} = \frac{\pi}{2}$ and $\varphi =$ The angle of soil internal friction

$$\text{From OBC: } \cos(45 + \frac{\varphi}{2}) = \frac{w/2}{r_0} \Rightarrow r_0 = \frac{w}{2 \cos(45 + \varphi/2)} \quad (8.4)$$

$$\text{Substituting Eqns (8.4) into (8.3)} \quad r = \frac{we^{\theta \tan \varphi}}{2 \cos(45 + \varphi/2)} \quad (8.5)$$

$$\text{From BFH: } \cos(45 - \frac{\varphi}{2}) = \frac{f/2}{r} \Rightarrow f = 2r \cos(45 - \frac{\varphi}{2}) \quad (8.6)$$

$$\text{Substituting Eqns (8.5) into (8.6)} \quad f = \frac{we^{\theta \tan \varphi} \cos(45 - \varphi/2)}{\cos(45 + \varphi/2)} \quad (8.7)$$

f = rupture distance at each side of the footing

By knowing θ and φ , the rupture distance can be calculated using equation 8.7.

Therefore it was possible to conclude that when (L) is the spacing between the plates

$L \geq 2f$ then there is *no interaction* and when

$L < 2f$ then there is an *interaction*

For the same φ and θ the rupture distance for different footings or plate widths can be obtained from the equation:

$$f_{w2} = f_{w1} \times \frac{w_2}{w_1} \quad (8.8)$$

8.3. Identifying interaction zones

It was shown that for a spacing greater than twice of the rupture distance ($L \geq 2f$) there was no interaction (see “a” in Figure 8.2). The resultant vertical force therefore was the force on a single plate times the number of plates. Once the spacing becomes smaller than twice the rupture distance ($L < 2f$), the interaction commenced. The experimental results from the glass tank studies showed that there were different modes of interaction and soil movement depending on the spacing.

It was assumed that an imaginary failure boundary was formed between the interacting footings, separating a wedge shaped zone of soil (see “b” and “c” in the Figure 8.2). The surface of this imaginary wedge was considered to be a real footing whose top width can be varied depending on the spacing between the footings and rupture distance overlap and can be found from:

$$w_i = 2f - L \quad (8.9)$$

Where: w_i = width of imaginary wedge

f = Rupture distance

L = Spacing

Therefore the extra force due to this imaginary footing had to be added to the force on the single plates, assumed to be acting without interaction, as follows.

$$Q = nQ_s + (n-1)Q_i \quad (8.10)$$

Where: Q_s = Force on single footing (kN)

Q_i = Extra force on imaginary footing (kN)

n = number of footings

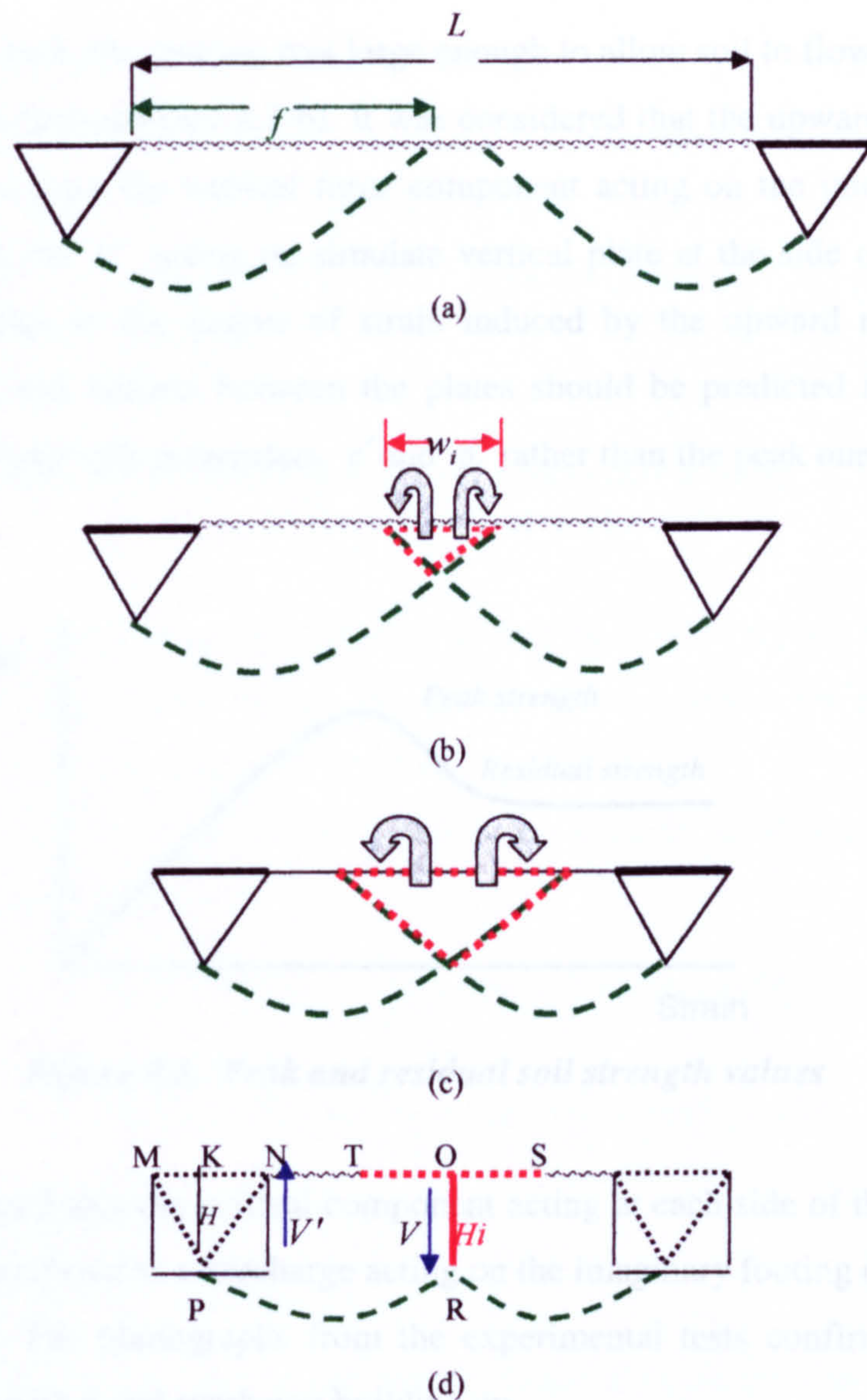


Figure 8.2. Interaction zones under dual footings with a range of spacings

- a) $L > 2f$ there is no interaction b) Interaction with upward movements
c) Achieving Transitional point d) $V > V'$ Stopping upward movements

The model had to predict the extra force on the imaginary footing for different interacting cases. Two different approaches were taken to estimate this extra force, the first approach, when upward soil movement was occurring and approach 2 when upward movement ceased.

8.4. Force prediction Model

8.4.1. Approach 1: surcharge and cohesion effects with upward movement

In this approach, the spacing was large enough to allow soil to flow and move upward between the footings (see 8.2-b). It was considered that the upward movements were occurring because the vertical force component acting on the interacting wall V is smaller than the V' acting on simulate vertical plate at the side of the real footings (see 2-d). Due to the degree of strain induced by the upward movement the soil movements and failures between the plates should be predicted by considering the residual soil strength parameters, c' and ϕ' rather than the peak one (see Figure 8.3).

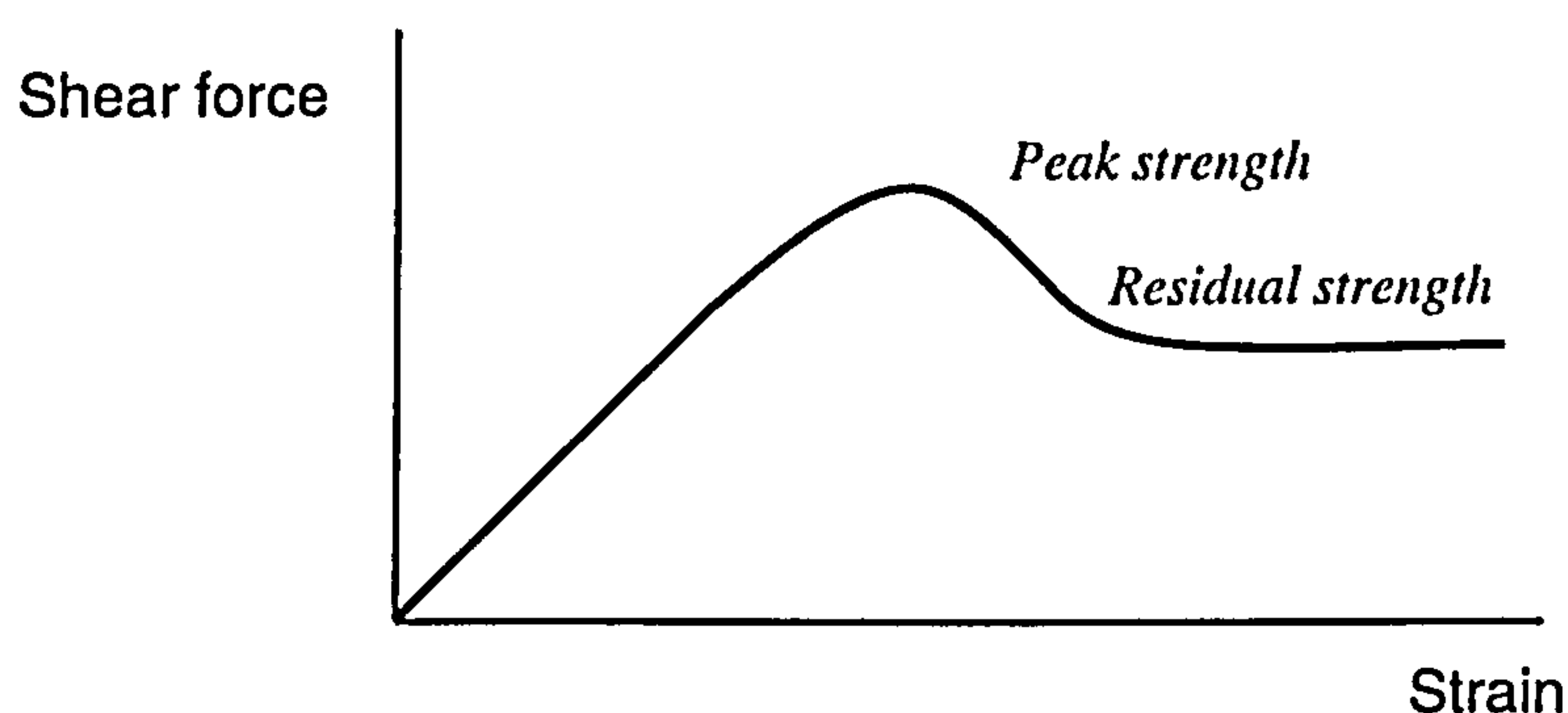


Figure 8.3. Peak and residual soil strength values

It was assumed that the vertical component acting at each side of the interacting wall could be considered as a surcharge acting on the imaginary footing (see “b” and “c” in Figure 8.2). The photographs from the experimental tests confirmed these upward movements with a soil surcharge building up.

Therefore the extra force due to interaction would be the surcharge term acting on the imaginary wedge plus the residual cohesion term in the Meyerhof equation as follows.

$$Q_i = (w_i q_i N'_q)l + l(w_i c' N'_c) \quad (8.11)$$

Where: q_i = Surcharge on the imaginary wedge ($kN.m^{-2}$)

c' = Residual cohesion ($kN.m^{-2}$)

l = Length the footings (m)

Considering the force on the single plates without interaction plus the extra force, the equation to predict the total force would be:

$$Q = n[l(wcN'_c + wqN'_q)] + (n-1)[l(w_i c' N'_c + w_i q_i N'_q)] \quad (8.12)$$

It is clear that for smaller spacings between the footings, w_i and therefore Q_i are small but become larger spacing increase. As this trend continues, V (the vertical force on imaginary wall) will get larger until the transitional point is reached where the vertical component V is equal to V' . The transitional point and spacing case are explained in the next section.

8.4.2. Approach 2: Surcharge and cohesion effects with no upward movement

This situation starts when V becomes greater than V' after the transition point. In this case the interaction becomes stronger and the soil denser, the soil in between can no longer flow or move upward (see d in Figure 8.2).

The first step in this situation is to find an equation to identify where the transition point is. In the Figure 8.2-d :

$$\text{From PNK} \quad \tan(45 + \varphi/2) = \frac{H}{w/2} \Rightarrow H = \frac{w}{2} \tan(45 + \varphi/2) \quad (8.13)$$

$$\text{From ORS} \quad \tan(45 - \varphi/2) = \frac{H_i}{w_i/2} \Rightarrow H_i = \frac{w_i}{2} \tan(45 - \varphi/2) \quad (8.14)$$

The transition point is where $H = H_i$ or

$$w \tan(45 + \varphi/2) = w_i \tan(45 - \varphi/2) \quad (8.15)$$

The parameters w , w_i and φ are known, hence it is possible to find the transition point. Moreover to calculate the position of the transitional point related to the spacing between the footings, the following equations were developed.

$$\text{From Eqns (8.15)} \quad w_i = \frac{w \tan(45 + \varphi/2)}{\tan(45 - \varphi/2)} \quad (8.16)$$

$$\text{Substituting Eqns (8.9) in (8.16)} \quad 2f - L = \frac{w \tan(45 + \varphi/2)}{\tan(45 - \varphi/2)}$$

$$\text{Then the transition spacing is: } L_t = 2f - w \tan^2(45 + \varphi/2) \quad (8.17)$$

By knowing w and φ and calculating f (rupture distance), it is possible to find the transitional spacing immediately.

Therefore it was possible to conclude that for any spacing smaller than the transitional spacing $L < L_t$, approach 2 is applicable and for wider spacings greater than transitional spacing $L > L_t$, approach 1 is applicable.

In the case of spacings smaller than the transition spacing, soil effectively does not move and hence the peak cohesion rather than the residual value must be used in the cohesion term of the general equation. Thus the imaginary wedge in this situation generates extra force due to both surcharge and peak cohesion. Therefore the extra and total force equations for this situation are:

$$Q_i = [l(w_i c N'_c + w_i q_i N'_q)] \quad (8.18)$$

$$Q = n[l(w c N'_c + w q N'_q)] + (n-1)[l(w_i c N'_c + w_i q_i N'_q)] \quad (8.19)$$

The model can be applied for a wide range of dual and triple arrangements with a range of spacings. In the triple case there are more interaction boundaries between each two sets of plates (even outer plates) and these need to be determined. Figure 8.4 shows the imaginary wedges under triple arrangements. In these arrangements three imaginary boundaries can be identified, two wedges between the inner plates and possibly one between the outer plates. To predict the resultant force, approach 2 is applicable considering all three wedges. Therefore the equation would be:

$$Q = n[l(w c N'_c + w q N'_q)] + (n-1)[l(w_{i1} c N'_c + w_{i2} q_i N'_q)] + (n-2)[l(w_{i2} c N'_c + w_{i2} q_i N'_q)] \quad (8.20)$$

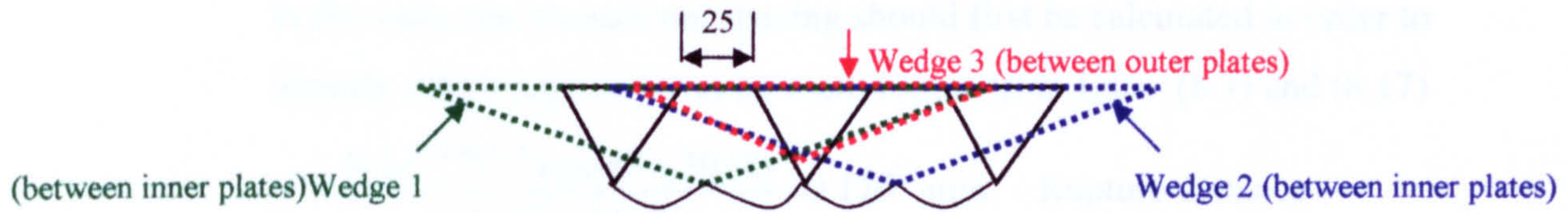


Figure 8.4. Triple plates with three imaginary wedges

It was clear that the imaginary footings become significantly greater in width for small spacings between the plates as shown in the Figure 8.4.

8.5. Model evaluation

The Model was evaluated and compared with the experimental results in the glass-sided tank for a range of spacings and plate sizes. The soil strength parameters were measured as follows:

$$\varphi = 31 \quad c = 0.5 \text{ kN.m}^{-2} \quad c' = 0.0 \text{ kN.m}^{-2} \quad \gamma = 16 \text{ kN.m}^{-3}$$

It has to be mentioned that the residual value of cohesion c' was found to be zero.

The N factors for these soil strength parameters, from Meyerhof graph given in the appendix 4, are: $N'_c = 65$ and $N'_q = 40$

φ is assumed to be 30 deg for simplicity to calculate in radians.

8.5.1. Wide plate ($w=100 \text{ mm}$ $l=150 \text{ mm}$)

8.5.1.1. Single plate

The Meyerhof general equation was used to estimate the vertical force on the single plate at 40 mm sinkage ($Z=40$). From Eqns (8.2)

$$Q_d = w(cN'_c + qN'_q) \quad q = \gamma z \Rightarrow q = 16 \times 0.04 = 0.64 \text{ kN.m}^{-2}$$

$$Q_d = 0.1(0.5 \times 65 + 0.64 \times 40) = 5.71 \text{ kN.m}^{-1}$$

$$Q = Q_d \times l = 5.71 \times 0.15 = 0.86 \text{ kN} \quad \text{Predicted force on single plate}$$

8.5.1.2. Dual plates

In this case, the transitional spacing should first be calculated in order to identify which approach can be used. Hence from Eqns (8.7) and (8.17)

$$f = \frac{0.1e^{\pi/2 \tan \pi/6} \cos(45-30/2)}{\cos(45+30/2)} = 0.176 \text{ mm} \quad \text{Rupture distance}$$

$$L_t = 2f - w \tan^2(45+\phi/2) = 2 \times 0.176 - 0.1 \tan^2(45+30/2) = 0.051 \text{ m} = 51 \text{ mm}$$

Therefore for spacings wider than 51mm, approach 1 should be used and for spacings smaller than 51 mm, approach 2 should be used.

a) **300 mm spacing:** This spacing was bigger than the transitional point then approach 1 was used. Hence the extra force from Eqns (8.9) and (8.10)

$$w_i = 2f - L = 2 \times 0.176 - 0.3 = 0.052 \text{ m} \quad \text{the width of imaginary wedge}$$

$$Q_i = (n-1)(w_i q N'_q) l = (0.52 \times 0.64 \times 40) 0.15 = 0.2 \text{ kN} \quad \text{the extra force}$$

(Note: The $l(w_i c' N'_c)$ term is zero).

b) **200 mm spacing:** Using same approach and equations, the extra force is:

$$w_i = 2f - L = 2 \times 0.176 - 0.2 = 0.152 \text{ m}$$

$$Q_i = (n-1)(w_i q N'_q) l = (0.152 \times 0.64 \times 40) 0.15 = 0.58 \text{ kN} \quad \text{the extra force}$$

c) **120 mm spacing:** Using same approach and equations, the extra force is:

$$w_i = 2f - L = 2 \times 0.176 - 0.12 = 0.232$$

$$Q_i = (n-1)(w_i q N'_q) l = (0.232 \times 0.64 \times 40) 0.15 = 0.89 \text{ kN} \quad \text{the extra force}$$

8.5.1.3. Triple plates

In this arrangement three wide plates with 25 mm separation were investigated. The spacing was smaller than the transitional point, therefore approach 2 was used. Figure 8.4 shows that there were three imaginary wedges under this arrangement. Two bigger wedges due to interaction between the inner footings at 25 mm spacing (footings 1&2 and 2&3). The

third wedge was between the outer footings with 150 mm separation (footings 1&3). In this case w_i for all three boundaries should be considered.

Hence from equations (8.9) and (8.20) the extra force is:

$$w_{i1} = 2f - L = 2 \times 0.176 - 0.025 = 0.327 \text{ m}$$

$$w_{i2} = 2f - L = 2 \times 0.176 - 0.15 = 0.202 \text{ m}$$

$$Q_i = (n-1) [l(w_{i1}cN'_c + w_{i2}qN'_q)] + (n-2) [l(w_{i2}cN'_c + w_{i2}qN'_q)] \text{ or}$$

$$Q = (3-1) [0.15(0.327 \times 0.5 \times 65 + 0.327 \times 0.64 \times 40)] + (3-2) [0.15(0.202 \times 0.5 \times 65 + 0.202 \times 0.64 \times 40)] = 7.46 \text{ kN}$$

The extra force

8.5.2. Narrow plate ($w=70 \text{ mm}$ $l=150 \text{ mm}$)

8.5.2.1. Single plate

The same approach was applied as the wide plate using Meyerhof general equation (2).

$$Q_d = 0.07(0.5 \times 65 + 0.64 \times 40) = 4.07 \text{ kN/m}$$

$$Q = Q_d \times l = 4.07 \times 0.15 = 0.61 \text{ kN}$$

8.5.2.2. Dual plates

The transitional point for this plate can be calculated using same approach as the wide plate:

$$f = \frac{0.07 e^{\pi/2 \tan \pi/6} \cos(45 - 30/2)}{\cos(45 + 30/2)} = 0.123 \text{ mm} \quad \text{rupture distance}$$

$$L_t = 2f - w \tan^2(45 + \phi/2) = 2 \times 0.123 - 0.07 \tan^2(45 + 30/2) = 0.036 \text{ m} = 36 \text{ mm}$$

a) **200 mm spacing:** using approach 1 and from Eqns (9) and (10), the extra force was calculated:

$$Q_i = (n-1)(w_i q N'_q) l = 0.18 \text{ kN}$$

b) *120 mm spacing*: using same approach Equations the extra force is:

$$Q_i = (n-1)(w_i q N'_q)l = 0.48 \text{ kN}$$

8.5.2.3. Triple plates

In this arrangement three narrow plates with 35 mm (smaller than the transitional point) separations were investigated. Therefore approach 2 was used to predict the force. There are three imaginary wedges under this arrangement and the same approach as the triple wide plates was followed.

$$w_{i1} = 2f - L = 0.211$$

$$w_{i2} = 2f - L = 0.106$$

therefore $Q_i = 4.6 \text{ kN}$

Table 8.1 summarises of the comparison between experimental and predicted extra forces for a range of spacings and sizes.

Also Figure 8.5 shows the comparison between the predicted and experimental total force under dual arrangements for two different footing sizes at various spacings. The graph indicates an acceptable level of agreement between the predicted and measured resultant forces.

Table 8.1: The predicted and experimental results for a range of spacings and sizes

Treatments	Spacing (L)	Transitional spacing L_t	Approach using	Predicted extra force	Measured extra force
<i>Single-wide</i>	-	-	Meyerhof	0.87	0.95
<i>Dual-wide</i>	300	51	1	0.20	0.25
<i>Dual-wide</i>	200	51	1	0.58	0.60
<i>Dual-wide</i>	120	51	1	0.89	0.85
<i>Triple-wide</i>	25	36	2	7.46	7.10
<i>Single-narrow</i>	-	-	Meyerhof	0.60	0.48
<i>Dual-narrow</i>	200	36	1	0.18	0.15
<i>Dual-narrow</i>	120	36	1	0.48	0.40
<i>Triple-narrow</i>	35	36	2	4.60	3.60

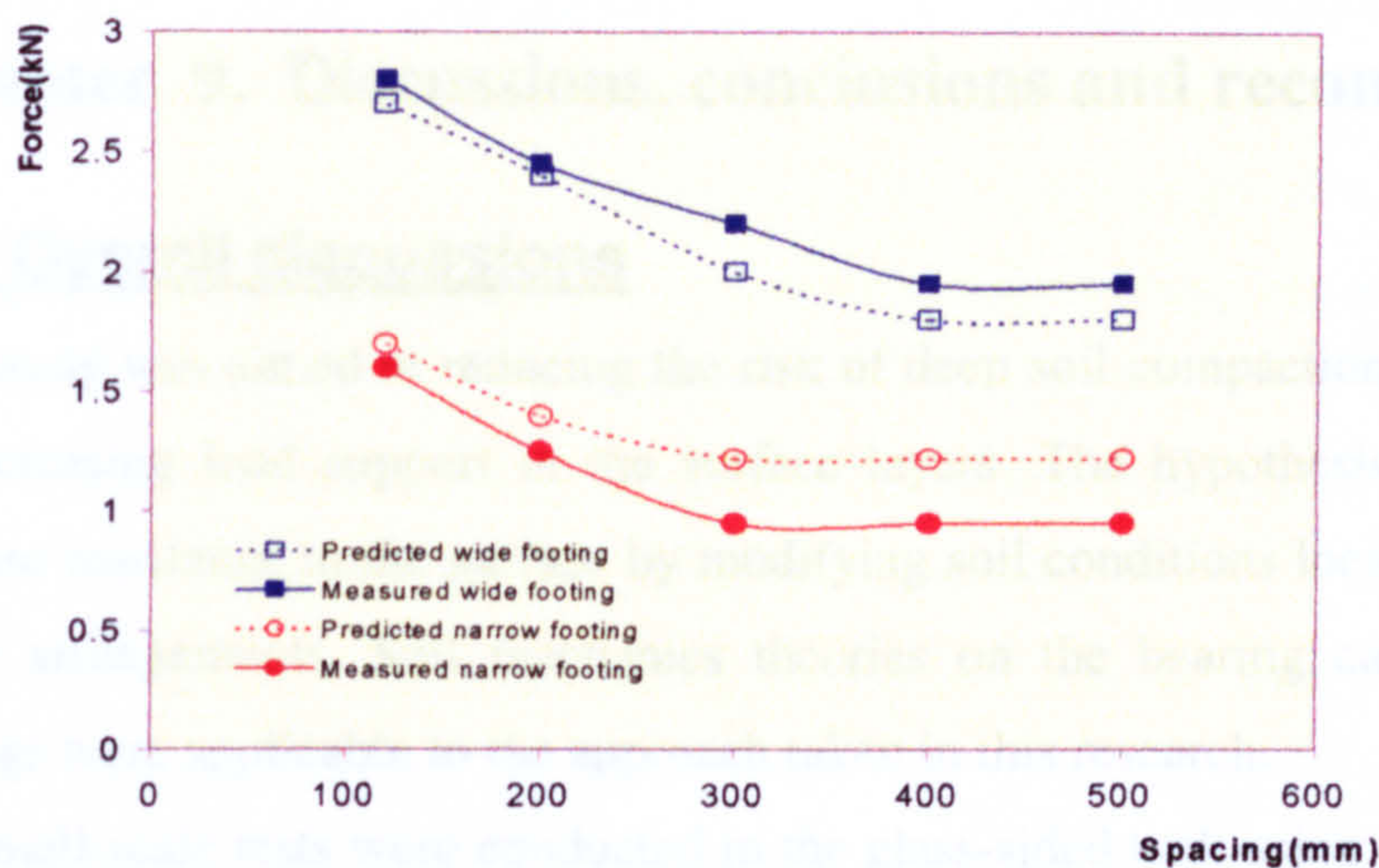


Figure 8.5. Comparison of predicted and experimental results under two different sizes of dual arrangements at varied spacings

8.6. Summary of procedure

To predict the extra force using the model for interacting plates ($L < 2f$) the following steps should be taken:

- 1) Calculate the rupture distance (f) using Equation 8.7.
- 2) Calculate the transitional distance using Equation 8.17.
- 3) If the spacing between the footings (L) is greater than the transitional distance(L_t) then approach 1 and Equation (8.12) should be used.
- 4) If the spacing between the footings (L) is smaller than the transitional distance(L_t) then approach 2 and Equations (8.19) and (8.20) should be used.
- 5) Other Equations to estimate the width of the imaginary wedge (8.9) have been also developed within the model.

Chapter 9. Discussions, conclusions and recommendations

9.1. Overall discussions

This study was aimed at reducing the risk of deep soil compaction and displacement by increasing load support in the surface layers. The hypothesis therefore was to increase resistance in the surface by modifying soil conditions locally under different wheel arrangements. Soil mechanics theories on the bearing capacity of shallow footings were applicable to the approach taken in this research.

The small-scale tests were conducted in the glass-sided tank using plates followed by large-scale tests in the soil bin and field using wheels. The link between both scales allowed investigations to be continued with similar concepts in the full-scale tests.

The investigations on the soil failure patterns generally indicated that the size of the active wedge and passive failure planes under a footing were largely dependent on footing width. It was also shown that some benefits could be achieved by using spaced arrangements. Dual footing tests for a wide range of spacings revealed that there were different modes of interaction occurring between the passive side planes depending on the spacing. For very wide spacings, larger than twice the size of the side passive planes or rupture distance ($L > 2f$), there was no interaction and each failure zone acted individually (**Mode 0**).

The rupture distance (f) or size of passive side plane can be estimated from equation 8.7 in chapter 8 developed during this research. From the equation, it is clear that the rupture distance has a direct relationship with footing width ($f = Kw$), hence for wider footings larger rupture distances are expected. The factor K or f/w ratio can be found for different soil conditions with varied φ values (angle of internal friction). In zero sinkage situations where θ is $\pi/2$, it was found that for the soil ranges with φ between 20-30 degree, the f/w ratio would be between 1.45-1.80. It is therefore possible to estimate the rupture distance in relation to footing width by knowing the angle of soil internal friction. In order to make the general conclusions, the spacings for different interaction modes were therefore explained relative to rupture distance.

Interaction started at closer spacings ($f < L < 2f$) when the passive planes met each other in the centre opposing each other's flow (**Mode 1**). By placing the footing even at closer spacing ($1/2f < L < f$) denser interaction took place (**Mode 2**). This mode created a locally compacted zone in the middle increasing resistance in the surface layer, as well as a little upward movement due to interaction of the passive planes. The footings when placed at closer spacings ($1/4f < L < 1/2f$) still formed the static area in the middle but with slight downward movement (**Mode 3**).

Force development graphs showed an improvement in the load-sinkage relationship under interacting footings. There was however a limit to the improvement with closer spacings between the footings, as the interaction benefit could be lost at very close spacing ($L < 1/4f$). In this case the dual footings would start to act as a single wide footing affecting greater soil depths.

In order to make a general recommendation for the spacing between dual wheels to minimise the risk of deep compaction in practical situations the following assumptions can be made. In soils with ϕ ranging between 20-30 deg when the f/w ratio is approximately 1.5 as explained earlier, the optimum spacing L is equal to 0.75 wheel width. This spacing ensures failure is within mode 2 (the smallest limit) or mode 3 (the largest limit) as shown below, where maximum support in the surface layer can be achieved.

$$\begin{aligned} \text{Mode 2: } 1/2f < L < f \quad \text{or} \quad 0.75w < L < 1.5w & \Rightarrow \text{Therefore } L = 0.75w \\ \text{Mode 3: } 1/4f < L < 1/2f \quad \text{or} \quad 0.38w < L < 0.75w \end{aligned}$$

Modes 2 and 3 of interaction in particular produced an increase in resistance in the surface layer by modifying soil conditions locally, creating a compacted zone in the centre, thus supporting the hypothesis. It was then postulated that if the surcharge on the central zone between footings could be increased, the shearing resistance in the surface layers should also increase further.

The triple configurations were then considered to increase this surcharge. By placing the third footing in the centre between the side footings (triple configuration with a raised middle footing) more load was applied on the central static zone generated by the footing interactions. Comparing the results under dual and triple with a raised middle footing arrangements, showed that improvements in the tolerated load could

be achieved under the triple arrangement for a given sinkage as compared with the dual (see Figure 5.6 and 5.7 in chapter 5). To maximise the benefit, the effective spacing between the outer footings was found to be the same as in mode 2 with slight upward movement. The spacing between the middle footing and side footings should also not be smaller than the minimum spacing in mode 3 ($>1/4f$) in order to avoid the plates acting as single wide footing, thus losing the spacing benefits. It is clear that for the f/w ratio of 1.45-1.80 in soils with ϕ values 20-30 deg, the spacing would be 0.35-0.45 of the width. It was also possible to use different widths for the middle footing in order to allow enough space. Narrower footings in the middle are suggested for the situation where there is a limit to the spacing possible between the outer footings when they are in their effective interaction mode. For instance in a soil with $\phi=20$ deg ($f/w=1.45$), footings of 100 mm width should be placed 36-73 mm apart ($1/4f < L < 1/2f$ or $0.36w < L < 0.73w$). In this case even at the largest spacing of 73 mm, it would not be possible to place the third footing of similar 100 mm width, narrower footings would therefore be necessary.

The optimum height of the middle footing would be such as to allow the side footings to sink sufficiently to allow enough interaction to occur before the surcharge is applied. The vertical height should not exceed the likely side footing sinkage. The experiments showed that the appropriate vertical height was 20-30 mm depending on the footing sinkage in the soil. The force development graph indicated that larger vertical distances would cause further sinkage for a given load.

The triple configuration with a lower middle footing was also considered but did not show promising results. The main reason for this was that the middle footing penetrated as a single footing without benefiting initially from the interaction with the side footings, which were not in contact with the soil. Once the interaction with the upper side footings occurred, greater pressure would be produced on the lower footing, increasing the resistance to deformation. Comparing this arrangement with the triple raised middle footing and also with the dual, showed greater sinkage occurred for a given load. This was because initially only one footing was penetrating

rather than two. No further investigation was therefore arranged for this configuration as surcharging benefits were the least.

When all three footings were placed at the same level, the configuration showed promise for surface support and soil deformation. The results indicated that there was less displacement at depth compared with a single very wide footing having the same overall pressure while carrying the same load. The comparison revealed that although greater displacement occurred under this arrangement than with the raised middle one, the tolerated load was significantly higher and very similar to the single very wide footing simulating a terra tyre. The effective spacings between the outer footings in this configuration can be similar to either modes 2 or 3, with similar spacings between middle and side footings as suggested for the triple raised configuration.

It can be concluded that the benefits of using narrow spaced arrangements rather than a single wide wheel supported the hypothesis in two ways. Firstly by increasing the resistance and surface support by creating a central static zone and secondly by creating individual relatively small active and passive failure zones affecting shallower depths.

The experiments also indicated that the non-uniform soil with a denser bottom layer, used in this research to simulate field conditions, modified the load-sinkage relationship. The load increased continuously with sinkage, while in the uniform homogenous soil, greater sinkage occurred for the same load after reaching a soil yield point. This indicates that non-uniform soil with a dense bottom layer has increased soil strength and load support capacity. The test conditions were not exactly the same as practical field conditions, where there is mostly a hard layer of limited thickness at tillage depth, with less firm layers above and below. This situation was difficult to simulate in the soil bin but was approached in the simulated stony soil test.

The simulated stony soil test revealed that stones could improve strength and surface resistance depending upon their dimension, position and direction in the soil. The

stones tended to simulate local hard layers of limited thickness at tillage depth similar to the practical field condition.

The approaches taken in this study as explained above, proved that by modifying soil conditions locally with specific wheel arrangements, it was possible to increase resistance and surface load support, in order to reduce the risk of compaction and displacement at depth, supporting the aim and hypothesis.

9.2. Conclusions

1. The research has shown that for a given surface load, it is possible to reduce the depth of soil displacement up to 40% by locally modifying the soil conditions, using interacting wheel configurations rather than single wheels.
2. Benefits of spaced wheel arrangements in reducing deep soil compaction are achieved through the interaction between the wheels and the modification of soil failure zones. The most promising methods for achieving these benefits are multiple dual and triple wheel arrangements as follows:

2.1. Dual wheels: Different interaction modes occur for different wheel spacings ranging from non-interaction, where the spacing (L) between the wheels is greater than twice the lateral rupture distance ($L > 2f$), to dense interaction where the spacing is smaller than the lateral rupture distance but greater than one quarter of the rupture distance ($1/4f < L < f$). The lateral rupture distance (f) can be estimated from a prediction model and has a direct relationship with the wheel's width. The dense interaction modes in particular generate a locally compacted zone in the surface layers that can tolerate a higher load. Spacings closer than one quarter of the rupture distance effectively cause dual wheels to act as a single wide wheel, losing the benefits of interaction.

2.2. Triple wheels: The soil resistance and surface load support can be increased further by using triple wheel arrangements. The promising configurations are:

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- a) *Triple with similar diameter wheels*: This arrangement tolerates a high load similar to a single wide wheel (Terra tyre) with the same overall contact pressure. Benefits of using these interacting wheels are shallower soil displacements and smaller soil failure zones than single wide wheels for a given load.
 - b) *Triple with smaller diameter middle wheel*: This arrangement causes the shallowest soil displacement similar to dual wheels whilst tolerating higher loads. The configuration also produces the most promising type of soil deformations in the surface layers. To achieve the benefits, the difference in the radius of outer and middle wheels should be less than the anticipated sinkage of the outer wheels.
3. The mechanism of interaction between the wheel arrangements has been modelled based on bearing capacity theory for shallow footings. The model predicts:
 - 3a) The extra vertical force due to interaction within $\pm 10\%$ and $\pm 20\%$ error of the measured forces for dual and triple arrangements respectively.
 - 3b) The extent of passive failure planes at the footing sides and hence the spacing requirements to optimise the load support and soil displacement.
 4. Non-uniform soil with a higher density in the lower layer than in the top layer can increase soil strength and surface load support, the load continuously increasing with sinkage. Such a condition is often found in the field at tillage depth.
 5. The presence of stones in a soil can improve the soil strength and load support. This is due to the stones behaving like small footings once displaced by the failure zones under the wheel. This increases the overall soil resistance to deformation. The stones behave in a local way similar to the effect of a firmer layer with limited thickness at tillage depth.
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9.3. Recommendations for further work

1. Investigate the potential advantages of using triple spaced wheel arrangements with similar diameter wheels and with smaller diameter middle wheels in practical field situations for heavy machinery applications such as on harvesters and transport vehicles.
2. Further investigations into the effect of stone content in fields and into the benefits of a limited hard layer at cultivation depth on surface load support, failure zones and the depth of compaction.
3. Investigations into the benefits of placing other materials such as geotextiles, timber or wood chips (simulating stones) for forestry and military interests, on load support and strain direction modification.
4. Application and evaluation of the theoretical model for the interacting arrangements and the estimation of the optimum spacings in practical field situations.

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Appendices

Appendix 1

Glass-sided tank design

Image analysis software

Glass-tank test photographs

A1.1. Design and development of a glass-sided tank

The tank comprised of four separate parts as follows (Figure A1.1 shows the first sketch):

- 1) Main frame
- 2) Glass frame
- 3) A rotatable mechanism with handle
- 4) Top cover

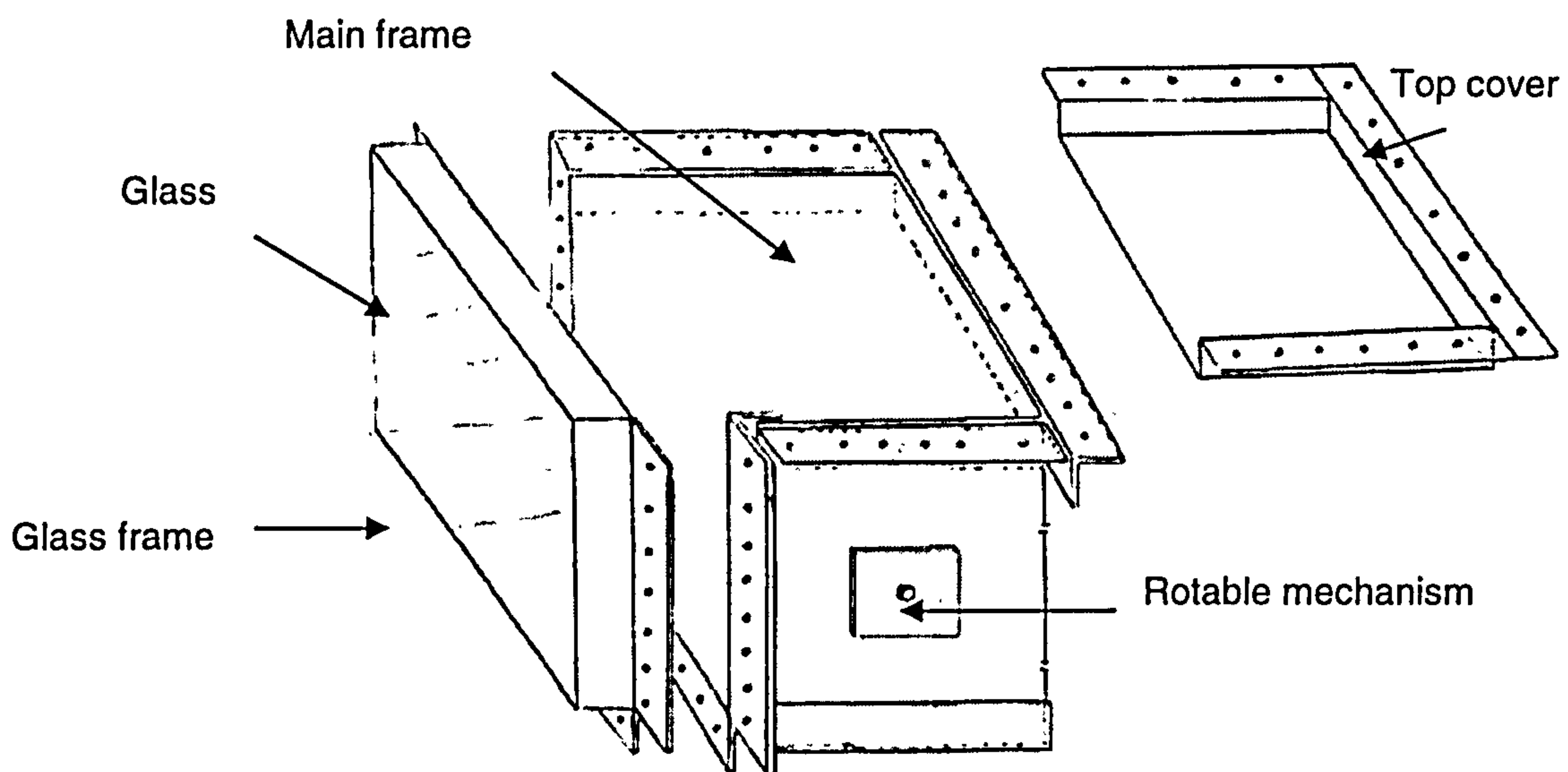


Figure A1.1. The first sketch of glass-sided tank with its parts

The main frame considered as a bin for holding soil, comprised of a box without front and top cover. The glass frame was bolted to the main frame at the front enabling soil behaviour to be observed. Lead was inserted between the metal frame and the glass to protect the glass. The rotating mechanism and handle were designed in order to lift and rotate the tank for soil processing. Rotating the tank through 90 degrees bringing the glass frame to the top, allowed the glass frame to be removed for soil preparation or any other operation on the soil. The top cover kept soil in the tank whilst rotating.

The calculations for the major dimensions, forces and moments associated with the design are explained below.

A1.1.1. Weight of the tank with soil

The total weight of the tank with soil can be found from calculating soil and tank weight separately and adding together. Therefore:

Soil mass = Volume of the tank * maximum density of the soil

Tank Vol. = Length * Width * Depth = $1.5 * 0.4 * 0.6 = 0.36 \text{ m}^3$

Maximum density was assumed to reach 2000 Mg/ m^3 hence:

Soil load = $2000 * 0.36 * 9.81 = 7.1 \text{ kN}$

Load of empty tank was found to be 2.5 kN therefore the total weight would be:

9.6 kN which was considered approximately as 10 kN .

A1.1.2. Thickness of main frame sheet

From the total weight, the load per unit length can be found from:

Load = $100 \text{ N} \implies q = w/l = 100/1.5 = 66.7 \text{ N/m}$

Two different sheet thicknesses were assessed to find the most appropriate one (D is depth and B is width of the tank section see Figure A1.2):

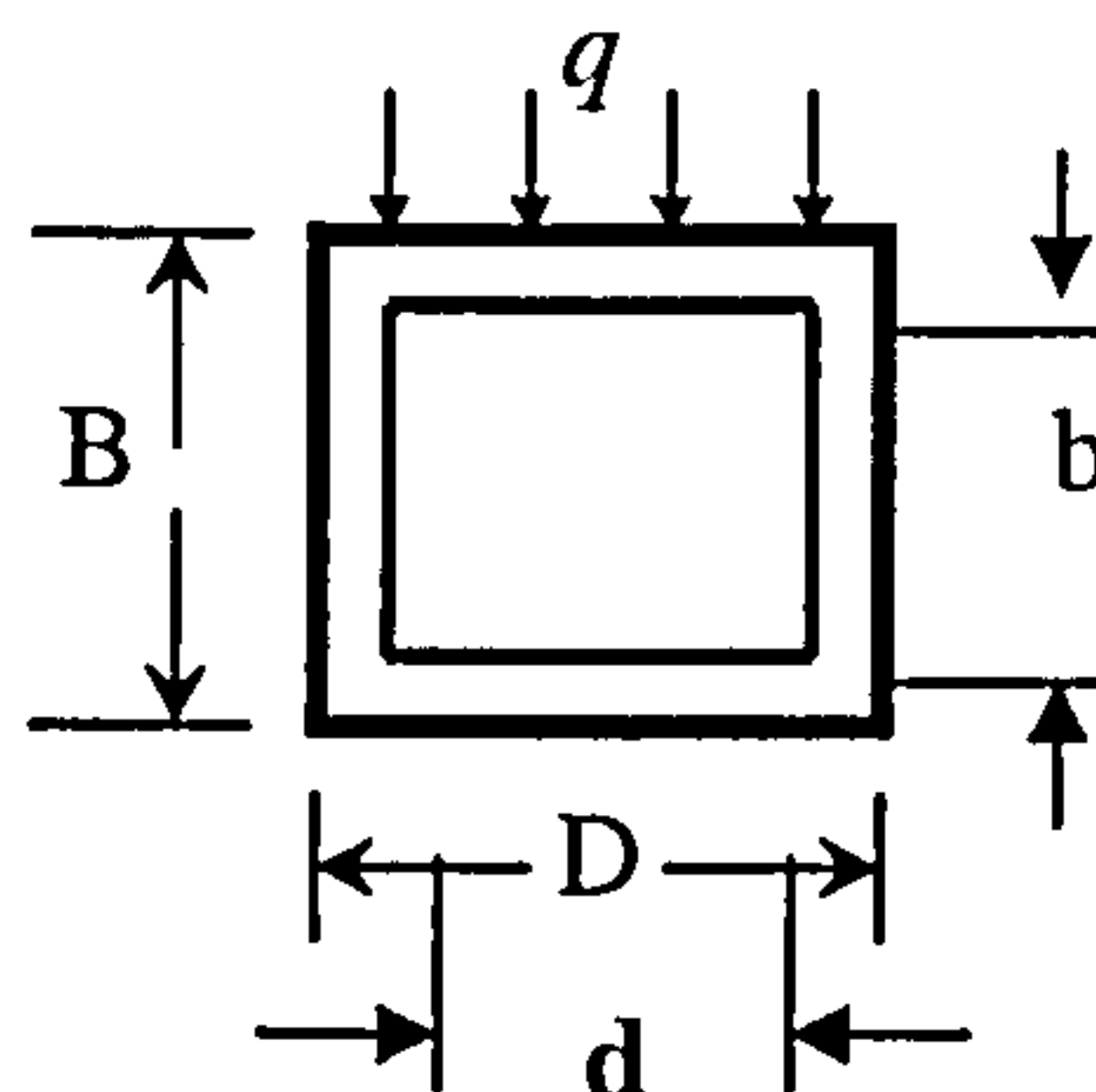


Figure A1.2. Dimension of a sheet for calculating the thickness

a) 4 mm thickness

$$\sigma = \frac{M.Y}{I} \quad (A1.1)$$

Where: σ = stress ($N.m^{-2}$)

I = second moment of area (m^4)

Y = central distance (m)

M = Bending moment ($N.m$)

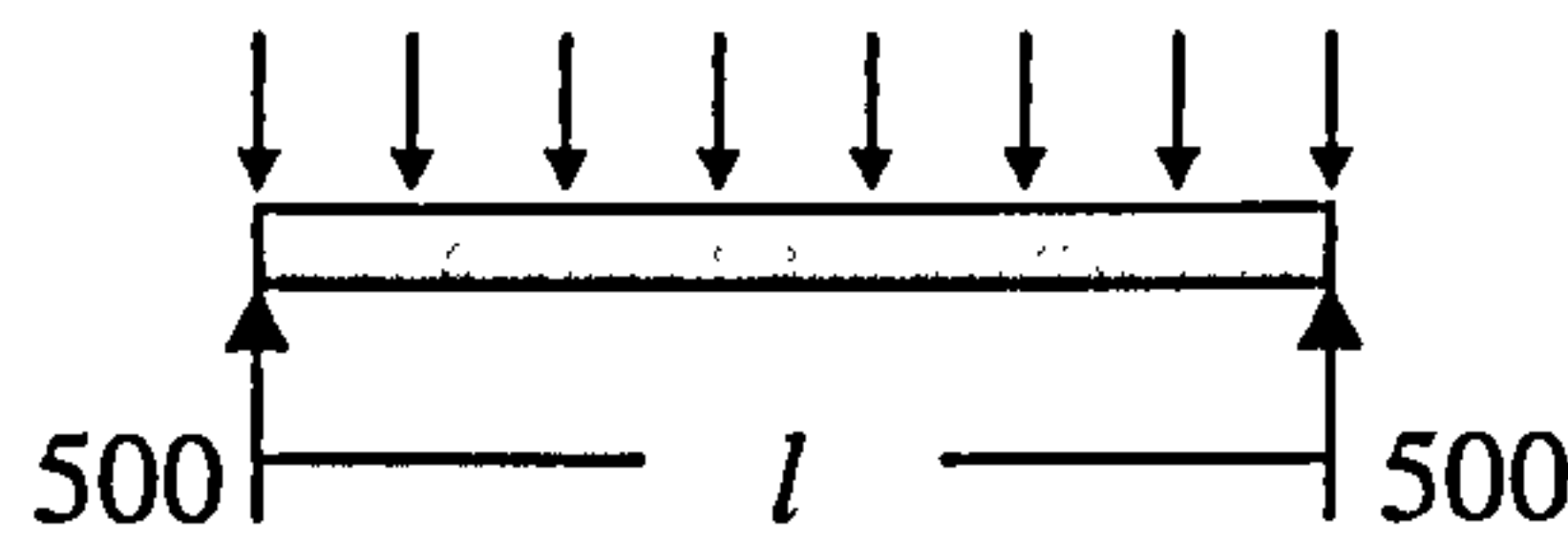


Figure A1.3. Reaction loads on a beam with uniform load

For beam with uniform load shown in Figure A1.3. the moment is [11]:

$$M = \frac{ql^2}{8} = \frac{6.7 \times 1.5^2}{8} = 1.88 \text{ kN.m}$$

$$I = (BD^3 - bd^3) = (0.4 \times 0.6^3 - 0.392 \times 0.592^3) = 5.1 \times 10^{-3} m^4$$

$$\sigma = \frac{M.Y}{I} = \frac{1839.5 \times 0.3}{5.1 \times 10^{-3}} = 0.11 MN.m^{-2}$$

When considering a safety factor SF=6 (recommended for beams and shafts)

$$\sigma = 0.11 \times 6 = 0.66 \text{ MN.m}^{-2}$$

As the standard stress limit for the sheet is 215 MN/m^2 then $0.66 < 215$ therefore the stress for this thickness is much smaller than the limit, so it is safe.

b) 3 mm thickness

$$I = (BD^3 - bd^3) = (0.4 \times 0.6^3 - 0.394 \times 0.594^3) = 3.8 \times 10^{-3} m^4$$

$$\sigma = \frac{M.Y}{I} = \frac{1839.5 \times 0.3}{3.8 \times 10^{-3}} = 0.15 MN.m^{-2} \text{ when considering a safety factor SF=6}$$

0.9 < 215 therefore stress for 3 mm thickness is still much smaller than limit and was chosen.

A1.1.3. Diameter of rotating shaft

a) Shear stress

$$\tau = \frac{L}{A} \quad \text{or} \quad \tau = \frac{L}{\pi D^2 / 4} \quad (\text{A1.2})$$

where: τ = shear stress ($N.m^{-2}$)

L = shear force (N)

A = area (m^2)

D = shaft diameter (m)

when considering $\tau_{standard} = 215 \text{ MN.m}^{-2}$ for mild steel

and $SF = 6$ from Eqn. A1.2:

$$\frac{215 * 10^6}{6} = \frac{1000 / 2 * 9.81}{\pi D^2 / 4} \Rightarrow D^2 = 29.05 \text{ or } D = 5.4 \text{ mm}$$

Therefore it is clear that shear stress is not critical for rotating shaft diameter hence bending moment should be calculated.

b) Bending moment

$$\sigma_b = \frac{M.l}{Z} \quad \text{or} \quad \sigma_b = \frac{M.l}{\pi D^3 / 32} \quad (\text{A1.3})$$

Where: σ_b = bending stress $MN.m^{-2}$ and Z = section modulus(m^3)

considering $\sigma_{standard} = 215 \text{ MN.m}^{-2}$ for mild steel

and $SF = 6$ from Eqn. A1.3:

$$\frac{215 * 10^6}{6} = \frac{500 * 9.81 * 0.03 * 10^9}{\pi D^3 / 32} \Rightarrow D = 34.7 \text{ mm}$$

Therefore a 50 mm diameter shaft was chosen to avoid bending.

A1.1.4. Thickness and deflection of the glass

The factory recommended thickness of the glass was $h = 51$ mm for $q = 250$ kN/m load on $1.5 \times 0.6 \text{ m}^2$ area of the glass tank. Equation A1.3 shows that there is a relationship between load and glass thickness as explained below.

$$\delta = \frac{5ql^4}{384EI} \quad (\text{A1.3})$$

where q = load per unit length (kN/m) l = length (m)

E = Modulus Elasticity = 70 GPa for glass I = second moment area (m^4)

$$I = bh^3 / 12 \quad (\text{A1.4})$$

Replacing Eqn.A1.3 into A1.4

$$I = \frac{5ql^4}{384E\delta} \longrightarrow bh^3 / 12 = \frac{5ql^4}{384E\delta} \longrightarrow h^3 = \frac{60ql^4}{384E\delta b} \quad \text{or}$$

$$h^3 = kq \quad (\text{A1.5})$$

Therefore by calculating the actual load for this experiment, it was possible to estimate the necessary thickness of the glass.

It was found from previous research by Earl (1993) that the maximum lateral stress in the proposed experiment could be 70 kPa maximum. It was also assumed that the maximum affected length would be half of the total length therefore:

$$\text{Max. affected area} = l/2 * D = 1.4/2 * 0.6 = 0.42 \text{ m}^2$$

$$\text{Max. lateral force} = \sigma * A = 70 * 0.42 = 29.4 \text{ kN}$$

$$\text{Force per unit length} = q = 29.4/0.7 = 42 \text{ kN/m}$$

Hence using $q = 50$ kN/m for this experiment, the thickness can be found from Eqn.A1.5 and the factory recommended thickness for $q = 250$ kN/m

$$\frac{h_1}{h_2} = \left(\frac{q_1}{q_2}\right)^{\frac{1}{3}} \quad \text{or} \quad \frac{51}{h_2} = \left(\frac{250}{50}\right)^{\frac{1}{3}} \quad \Rightarrow \quad h_2 = 29.8 \text{ mm glass thickness}$$

A1.2. Results monitoring procedure

A1.2.1. Photographic technique:

A digital camera was used in these tests to enable the photographs to be transferred to a computer for image analysis. The camera recorded the images at different levels of sinkage. A digital video recording was also made and this required an additional 500 W light placed at the side to avoid reflection in the glass.

A1.2.2. Image analysis:

All image analyses were performed using a software package called Global Lab Image (GLI) to identify the soil displacement limits accurately. The electronic sampling of the video was achieved using a device called a frame-grabber which could store and display the image. The necessary equipment were therefore a frame-grabber DT2855 which was incorporated into a personal computer and two monitors, the first to display the commands, the second to display the image. The digital camera signals could be stored, processed and converted into an array of data points. The software running under the Windows environment was menu driven. The opening screen of the software displayed a series of 14 icons or “Toolbox”, which controlled the performance of each operation during the image processing. By activating one of the icons a command window was opened allowing a further choice of actions to be taken (see Figure A1.4). To avoid unnecessary details, only the commands used in image analysis at this stage are explained below.

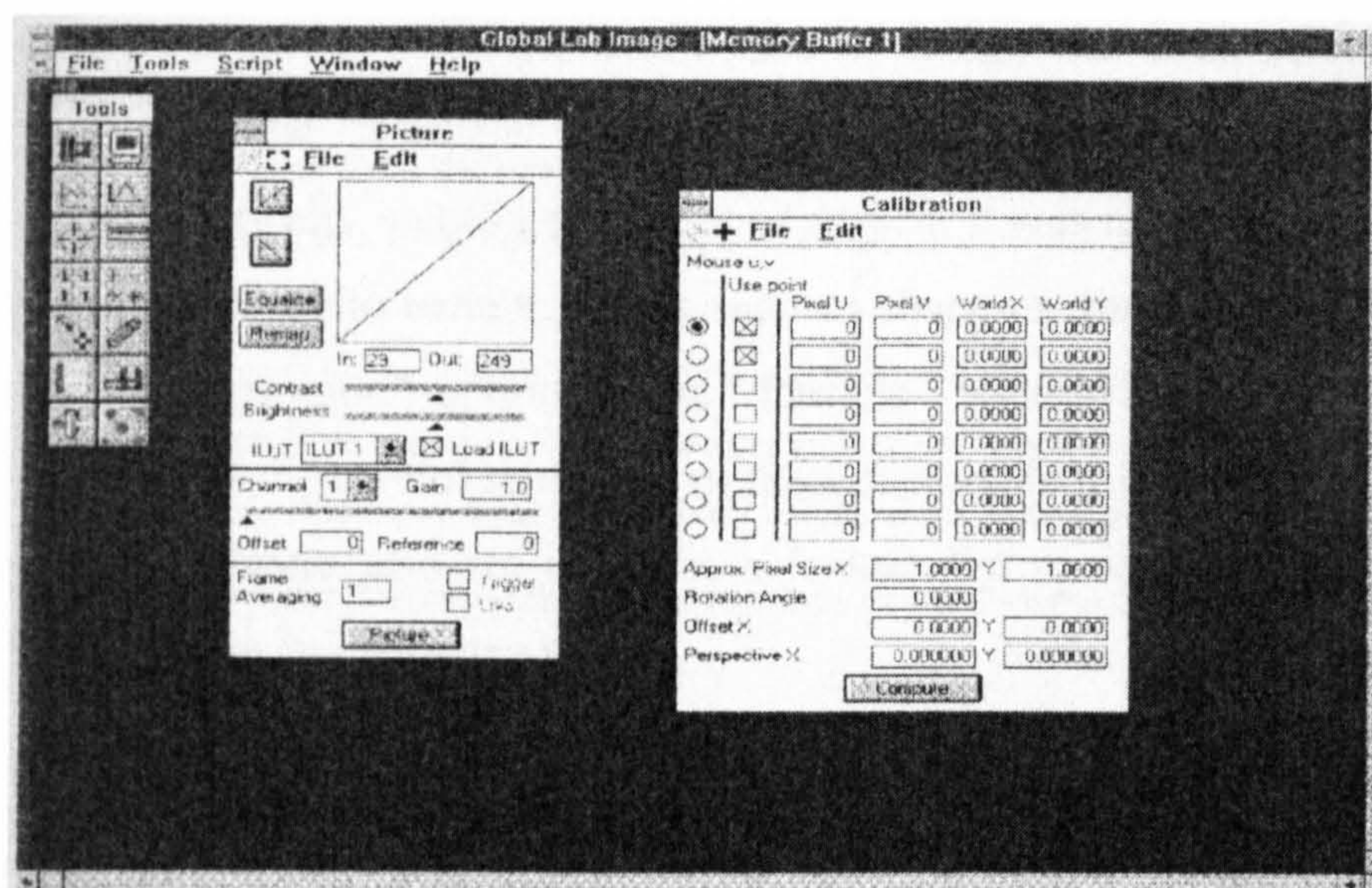


Figure A1.4. *Toolbox, Picture and Calibration windows in GLI software*

A) Image capture: The image was captured by selecting the “Picture” icon in the main menu. It was also possible to capture the image live or from a file. Once the image appeared on the second monitor, the quality could be improved using contrast sharpening techniques.

B) Calibration: Opening the “Calibration” window enabled the registration and comparison of an object of known dimensions with an image on the screen. The program adjusted for perspective tilt caused when the camera had a non-perpendicular view of the frame, distortions resulting from the rotation of the work space and also a horizon-distance effect due to the frame’s position in relation to the video source. All beads were referenced to the certain points in the grid (at least four points at corners). After inserting known points in the relative boxes, the “Compute” option was pressed to start calculations. (see the calibration window in Figure A1.4). The calibration points could be identified using different coloured images.

C) Particles: Once the desire area of image had been selected and frozen the “Particle” icon in the main menu was chosen. To automatically identify an object on screen, it was necessary to classify it according to certain factors such as shape or dimension. Activating “Configuration” option in the “Particle “window (see Figure A1.5) allowed the careful setting up of these factors. In this menu centroids X and Y were also set up from a feature list to report X and Y co-ordinates in calibrated units.

Once the “Configuration” was established and saved (make default), the option “Find Particles” was used. This initiated the process of identifying those particles which matched the established criteria, and these were assigned with a distinct colour. When the configuration was completed, the number of objects was displayed in a box of the “Particle” window. In the case of this number being different from 253 (23*11) beads, the image was readjusted and corrected until all the beads were accounted for.

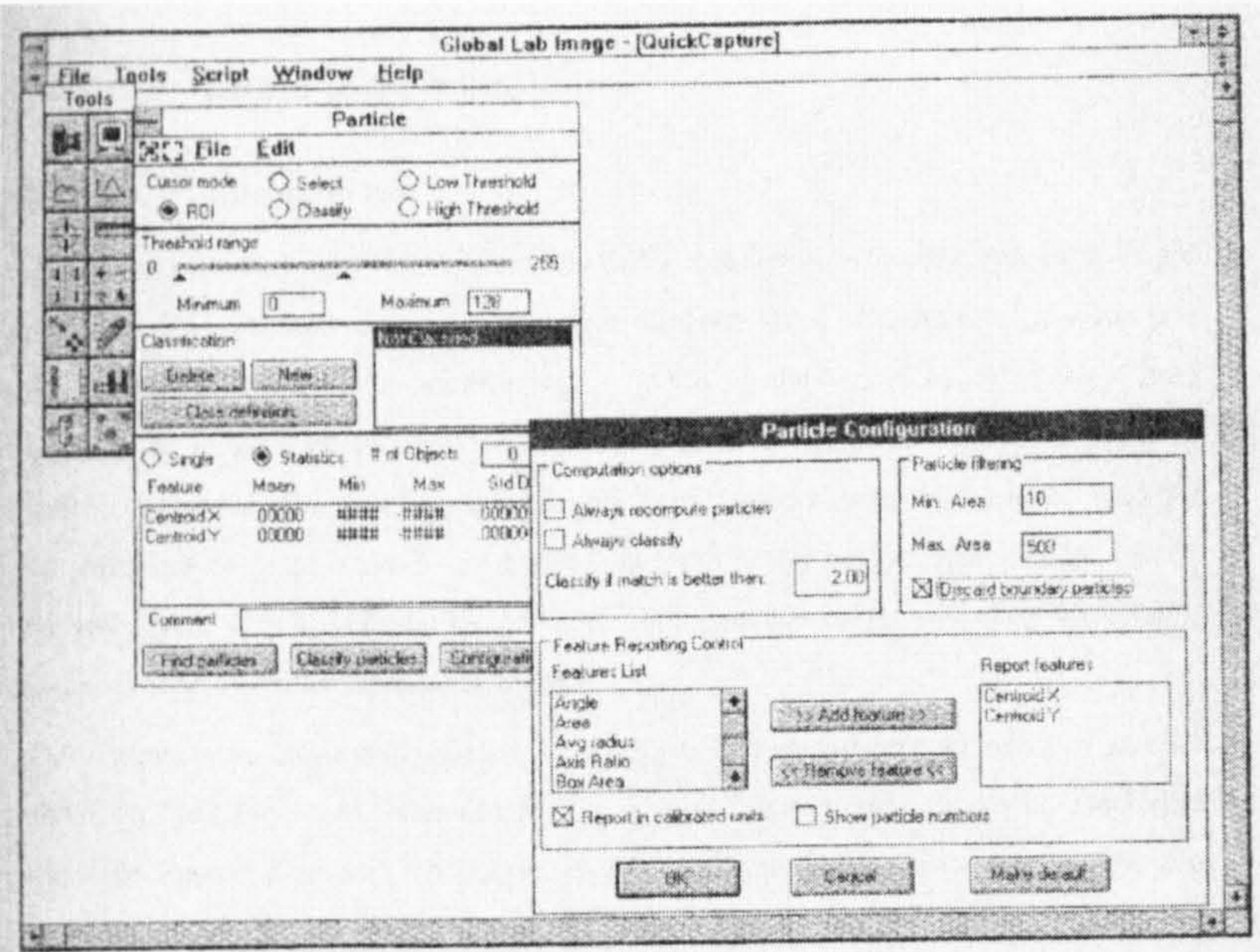


Figure A1.5. Particle and its Configuration option in GLI software

D) Data transferring: Once all beads were identified, “File” option in the “Particle” menu was chosen to log and transfer the generated numbers. The “DDE” option in the file menu could transfer the data to a pre-opened sheet in the EXCEL software. The data was then saved and a graph created to reveal the bead positions after the test. This enabled the soil movement pattern and displacement limits to be identified and compared with those of other arrangements.

A1.3 Photographs of the glass-tank tests

A1.3.1. Given 50 mm sinkage

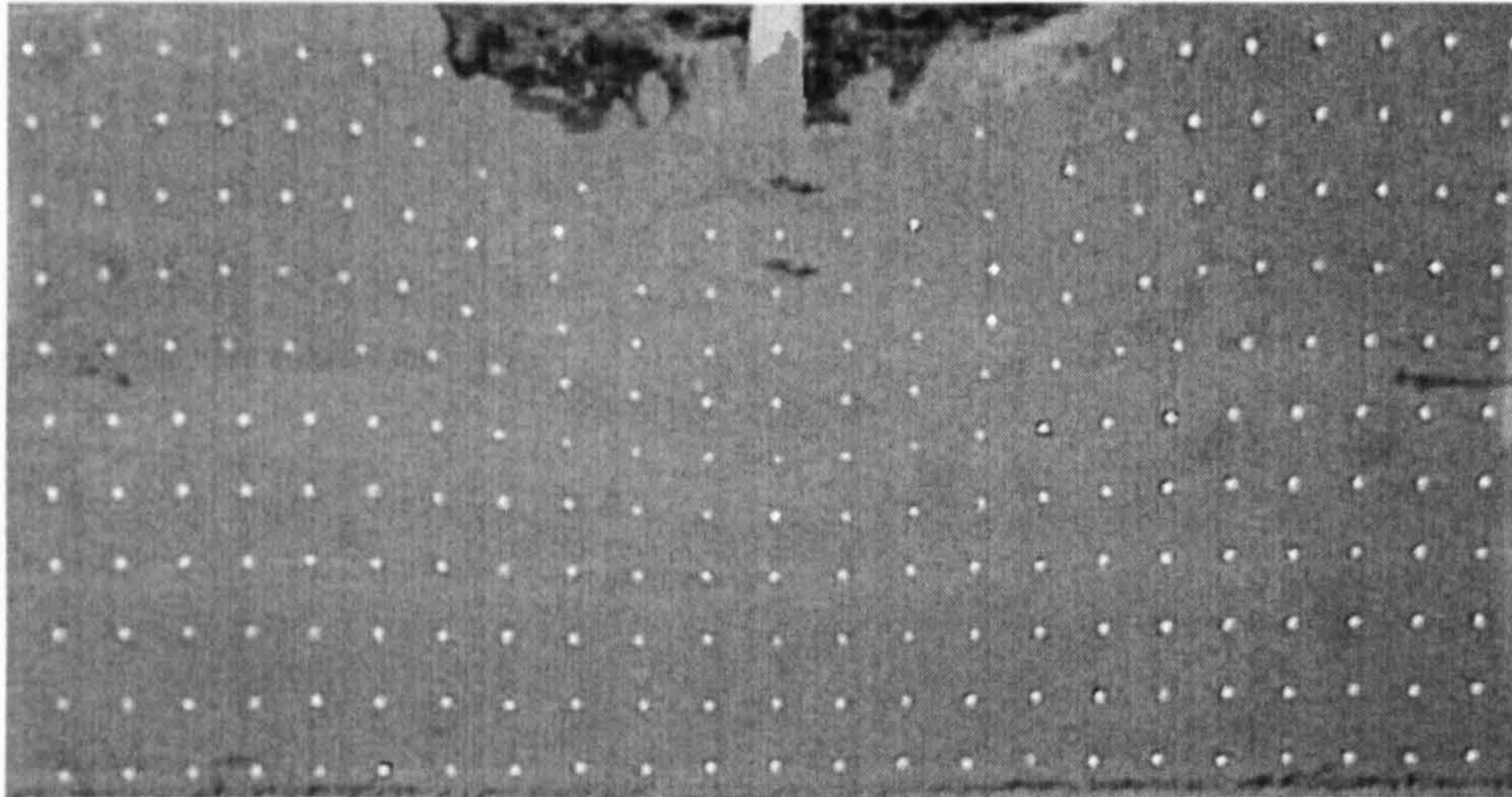


Figure A1.6. Soil movement pattern under simulating Terra tyre

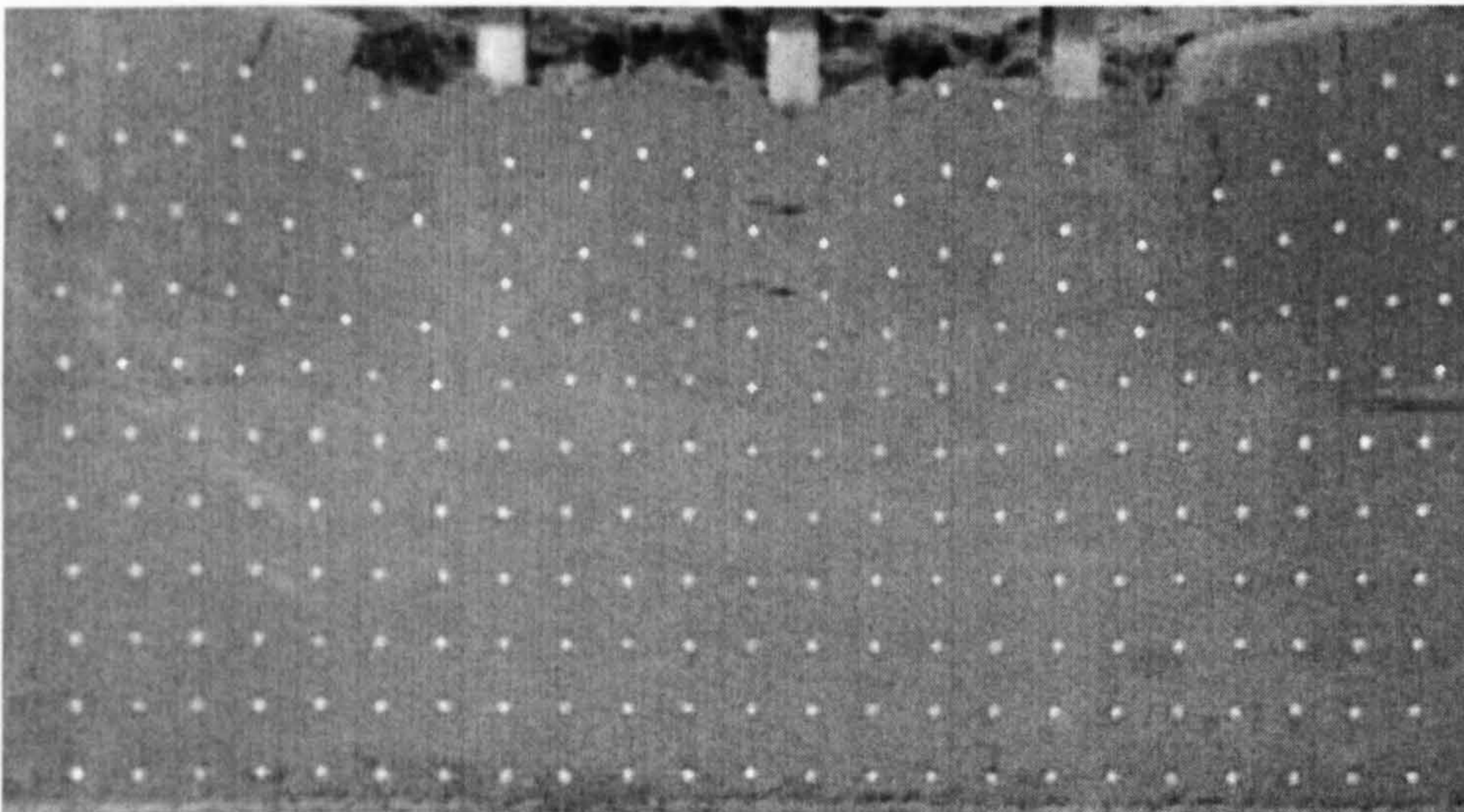


Figure A1.7. Soil movement pattern under triple with same level plates

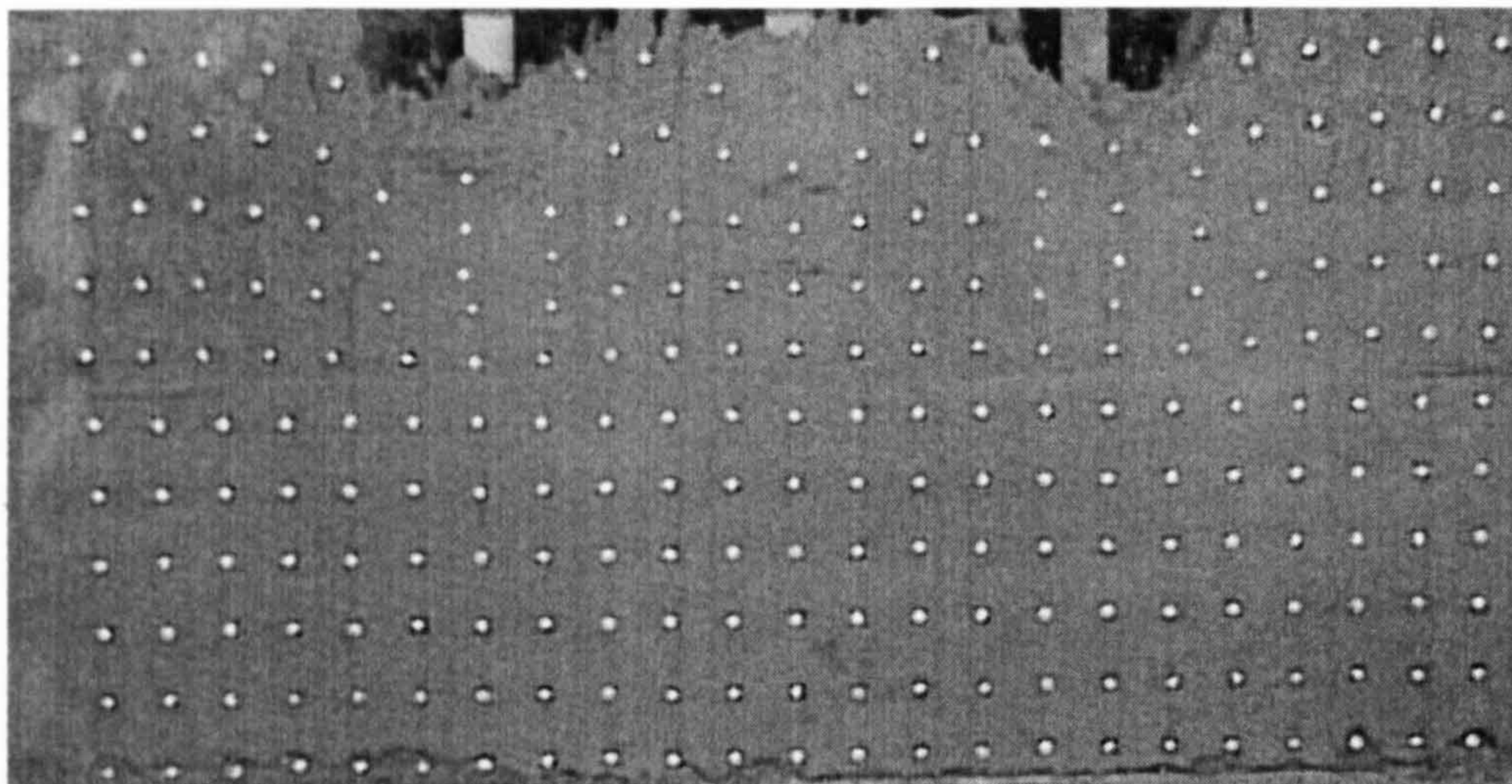


Figure A1.8. Soil movement pattern under triple with raised middle plate

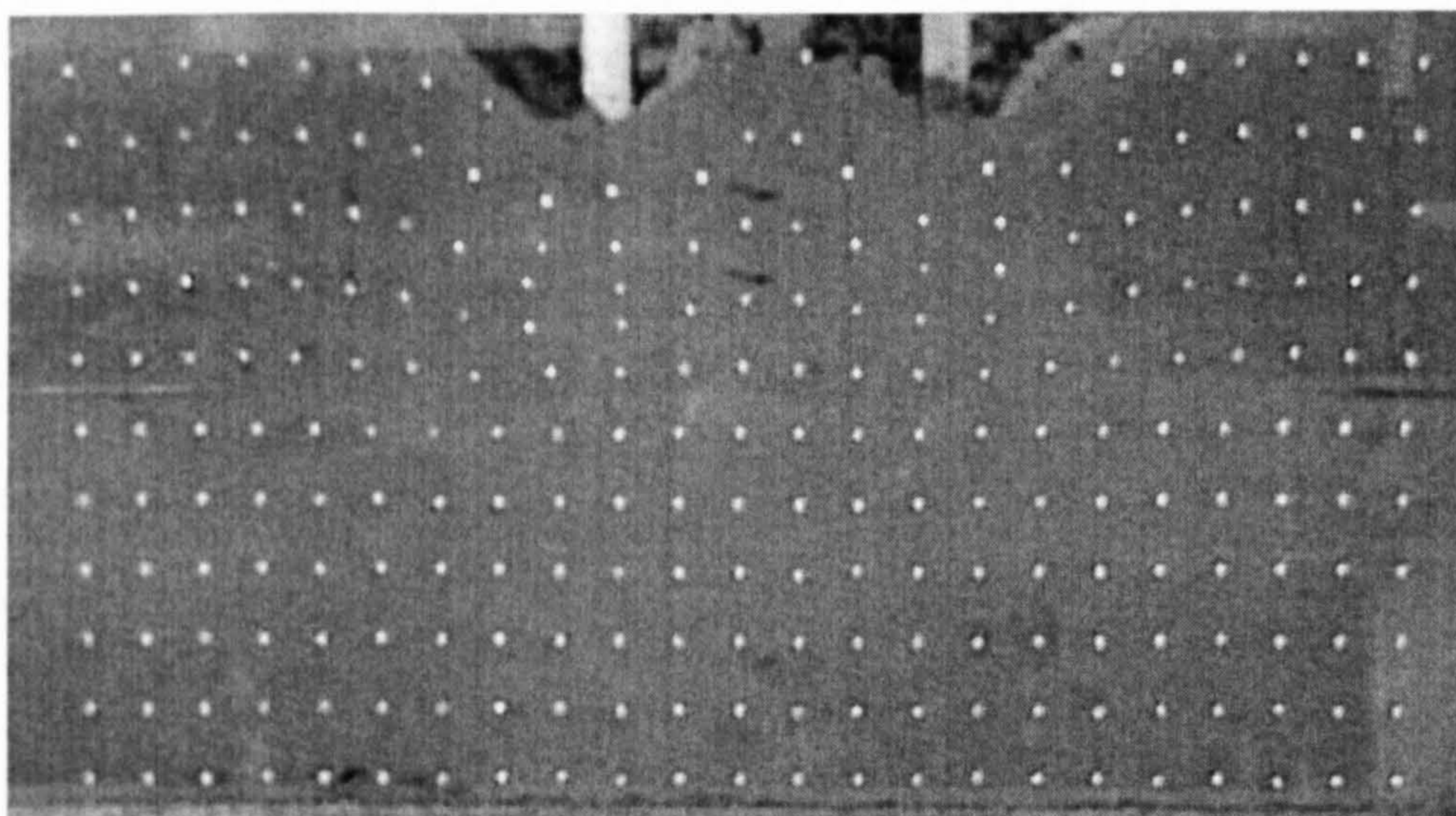


Figure A1.9. Soil movement pattern under dual plates

A1.2.2. Given 90 mm sinkage

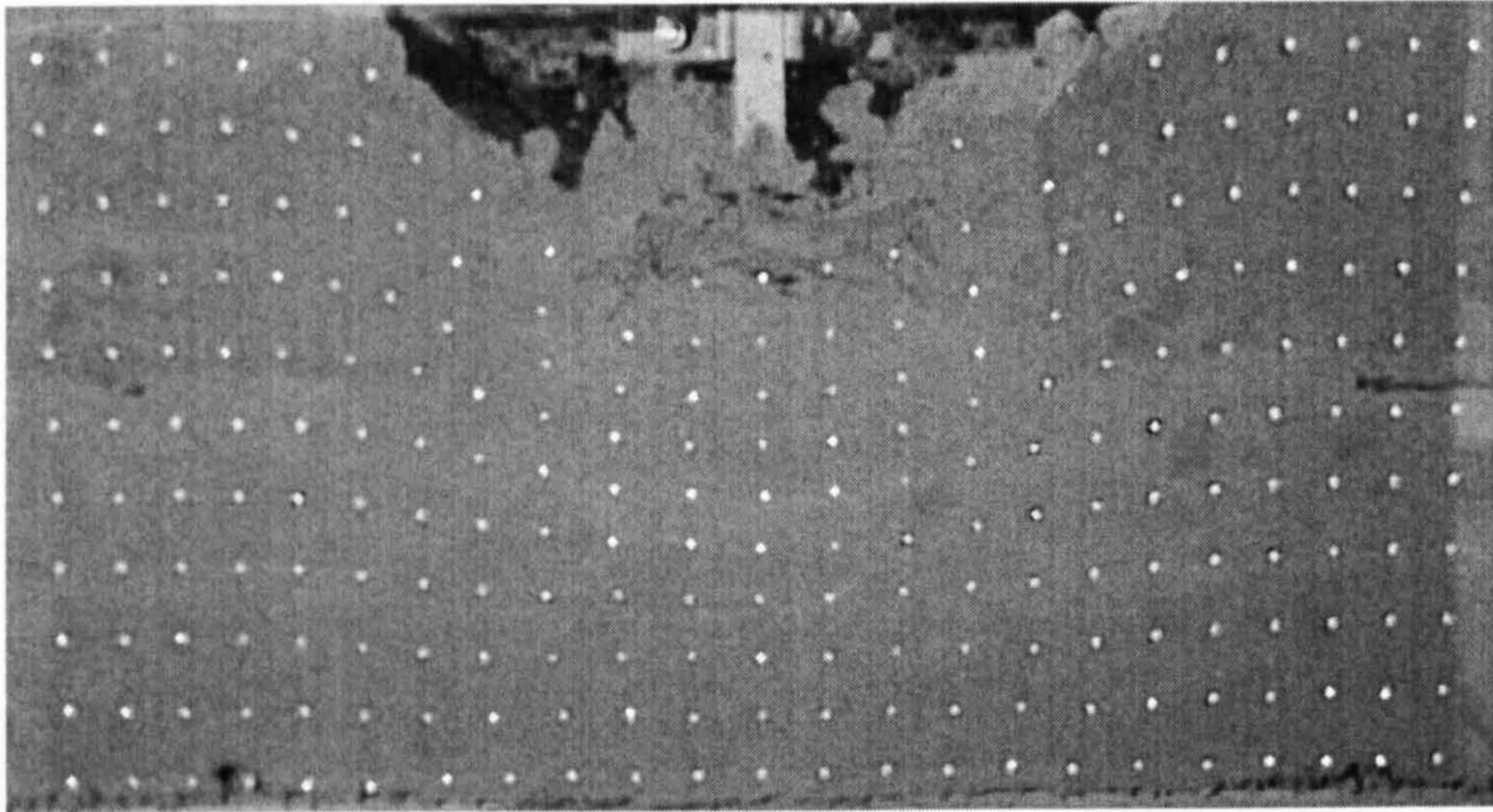


Figure A1.10. Soil movement pattern under simulating Terra tyre

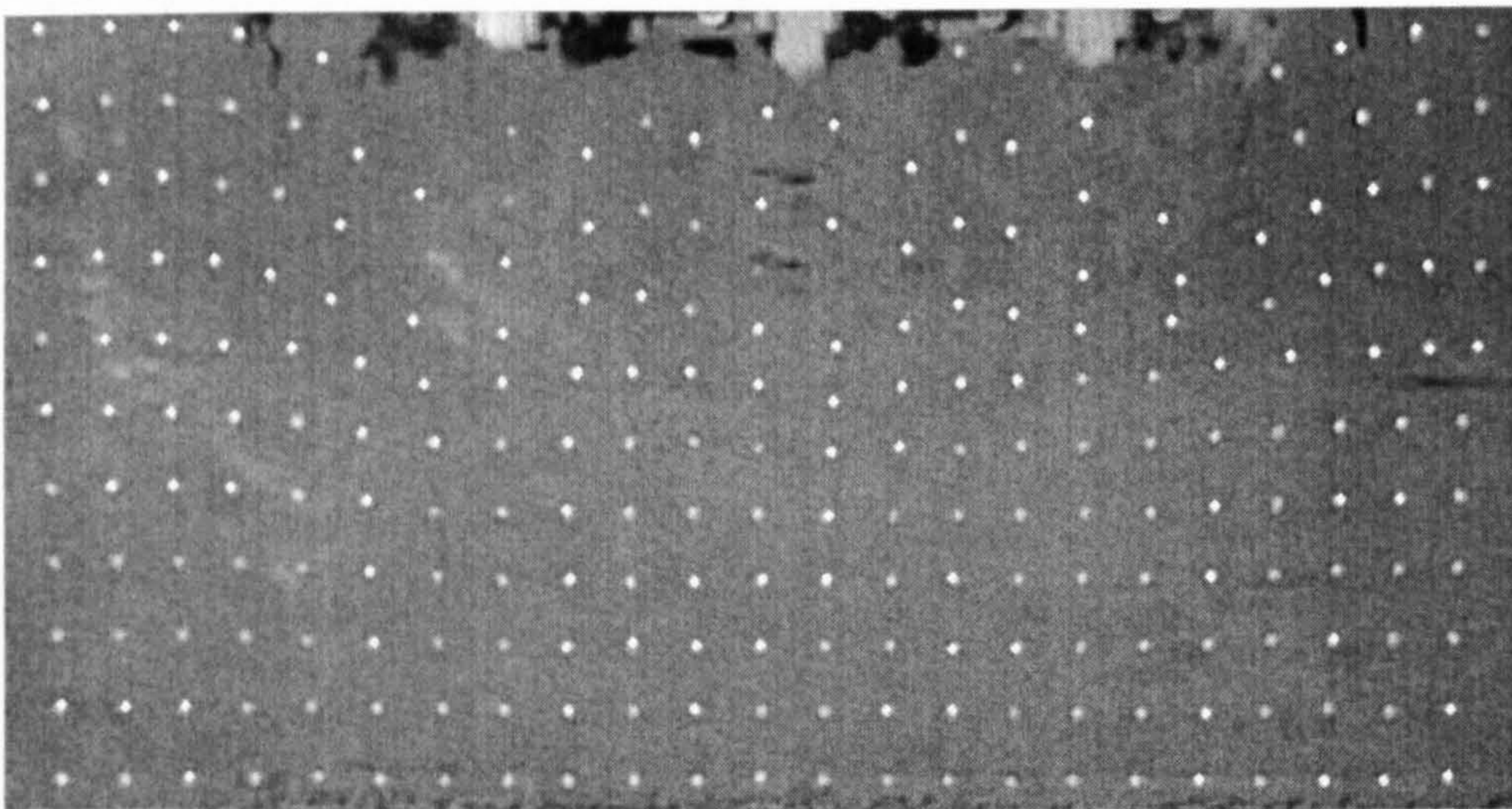


Figure A1.11. Soil movement pattern under triple with same level plates

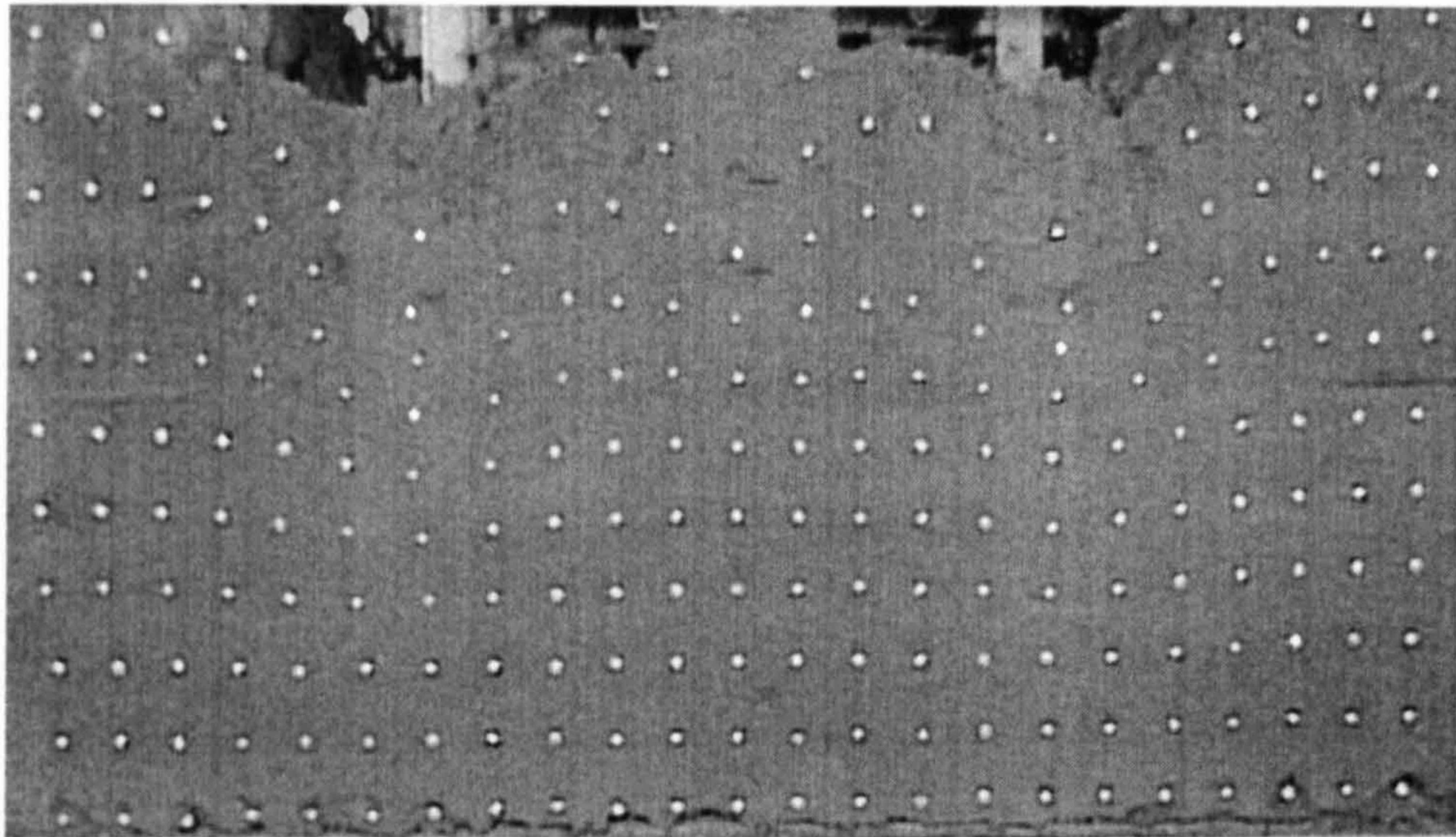


Figure A1.12. Soil movement pattern under triple with raised middle plate

Appendix 2

**Soil bin test
Photographs**

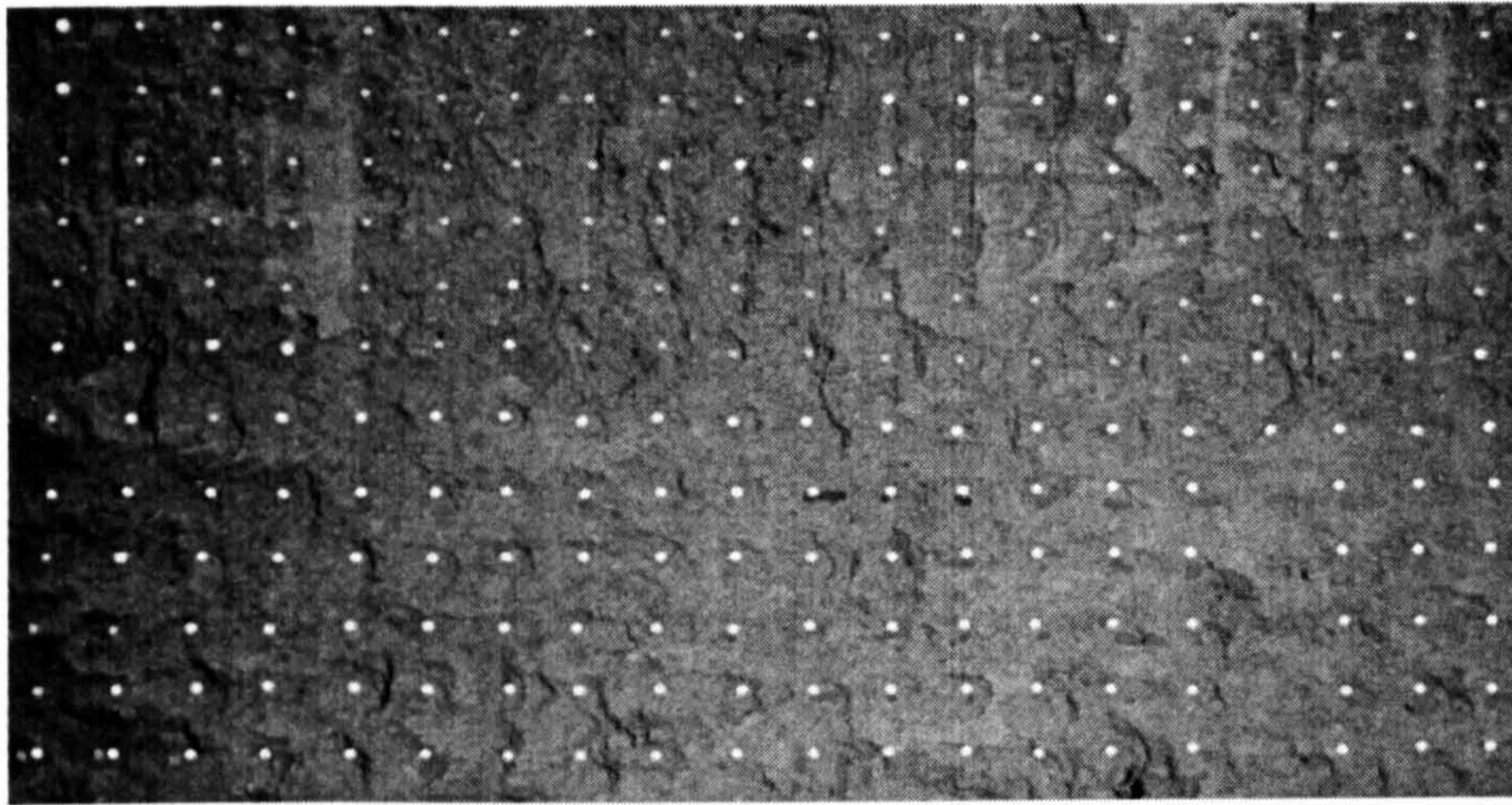
A2.1. Control profiles in all prepared bins

Figure A2.1. Control profile in the prep. 1

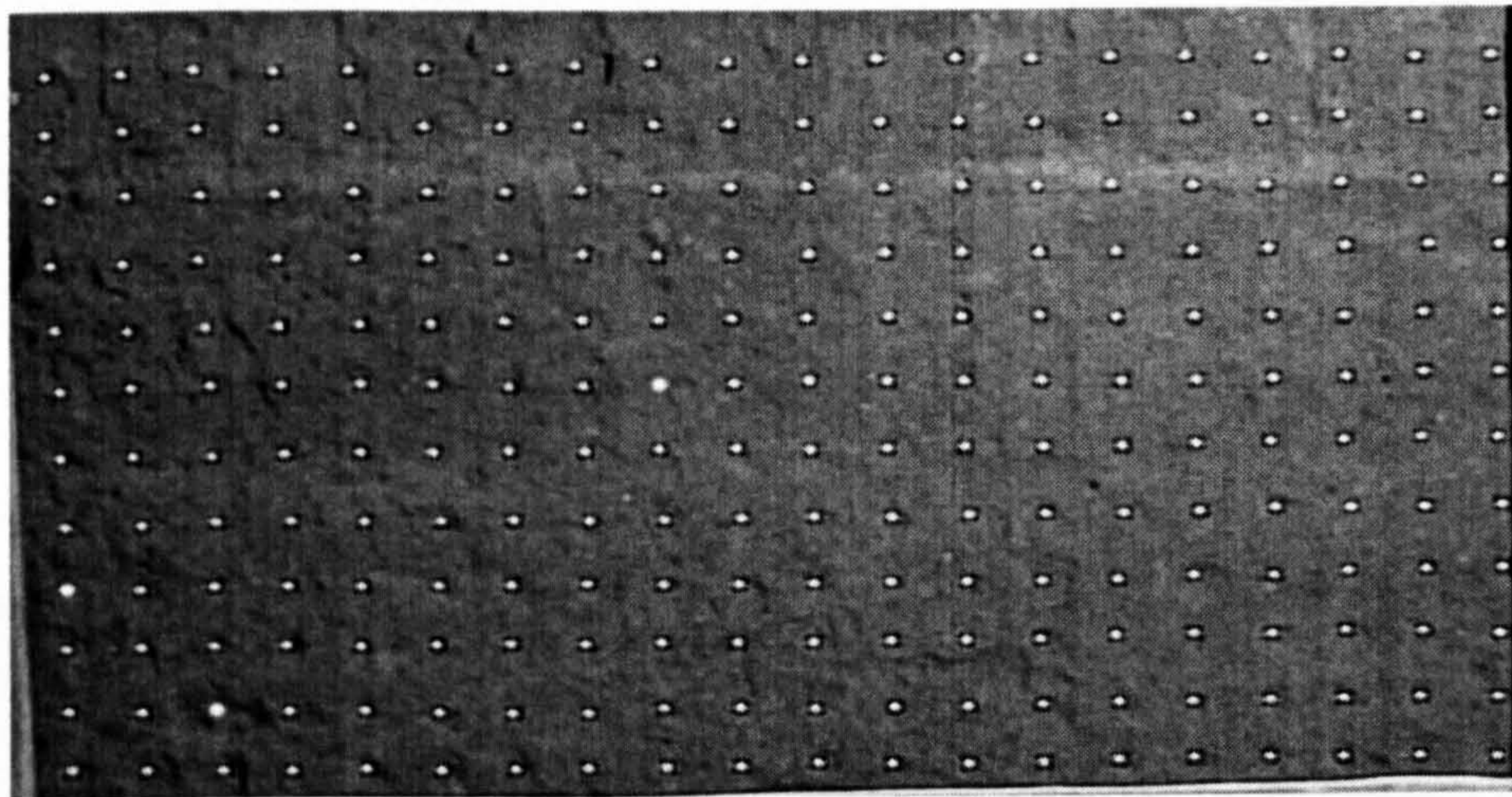


Figure A2.2. Control profile in the prep. 2

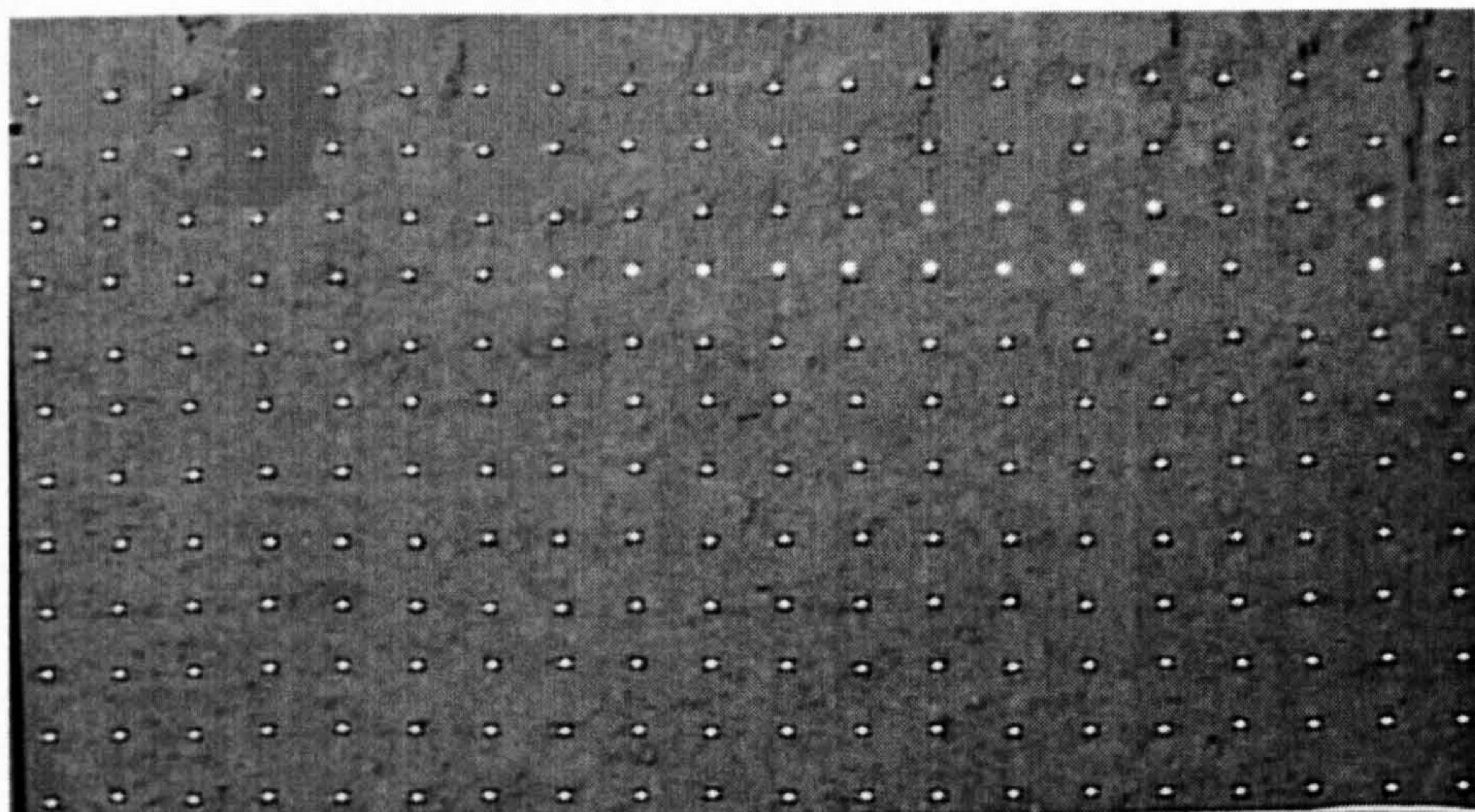


Figure A2.3. Control profile in the prep. 3

A2.2. Prep. 1 – Simulated terra and triple with same level wheels

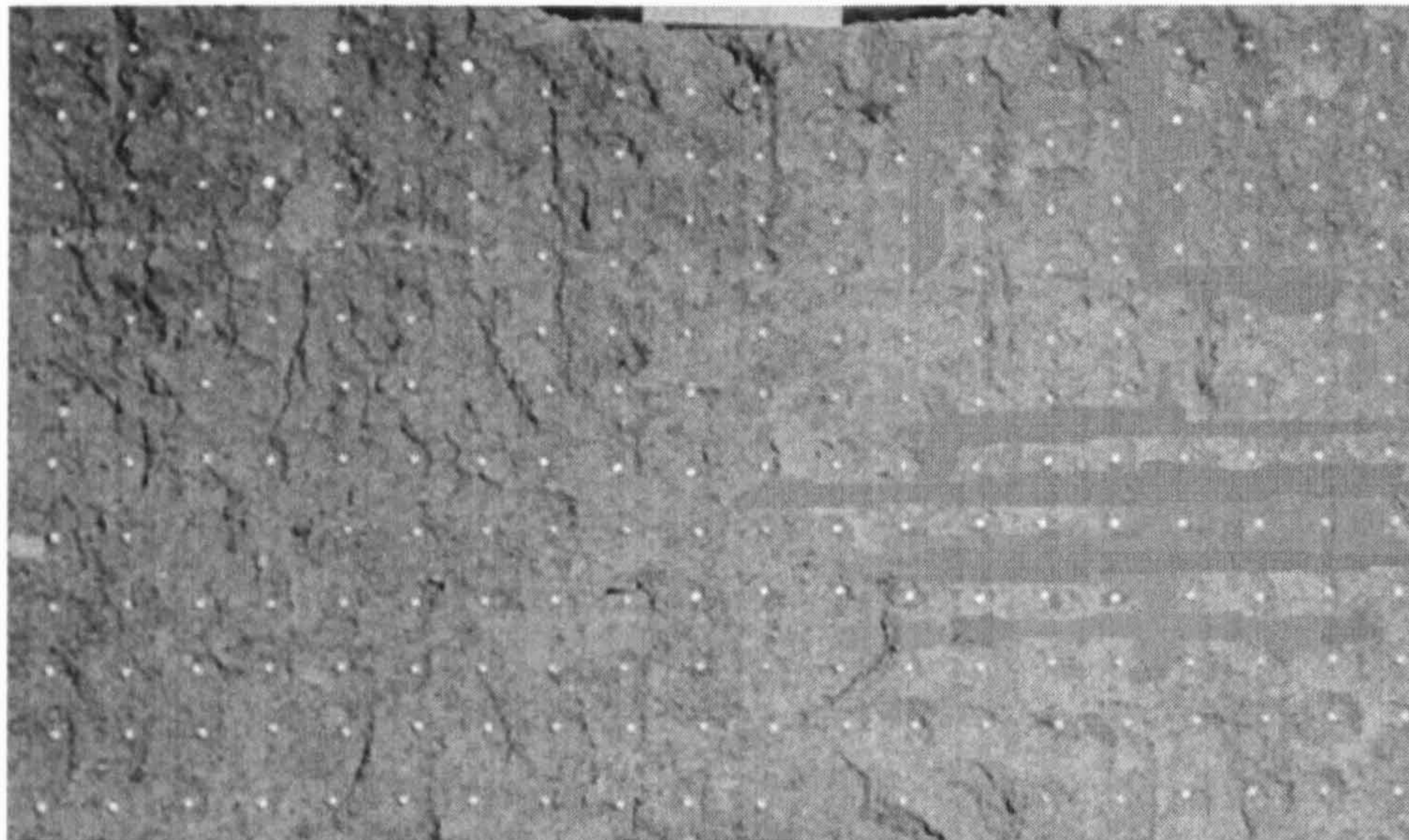


Figure A2.4. Simulated terra, Prep. 1, Rep. 1

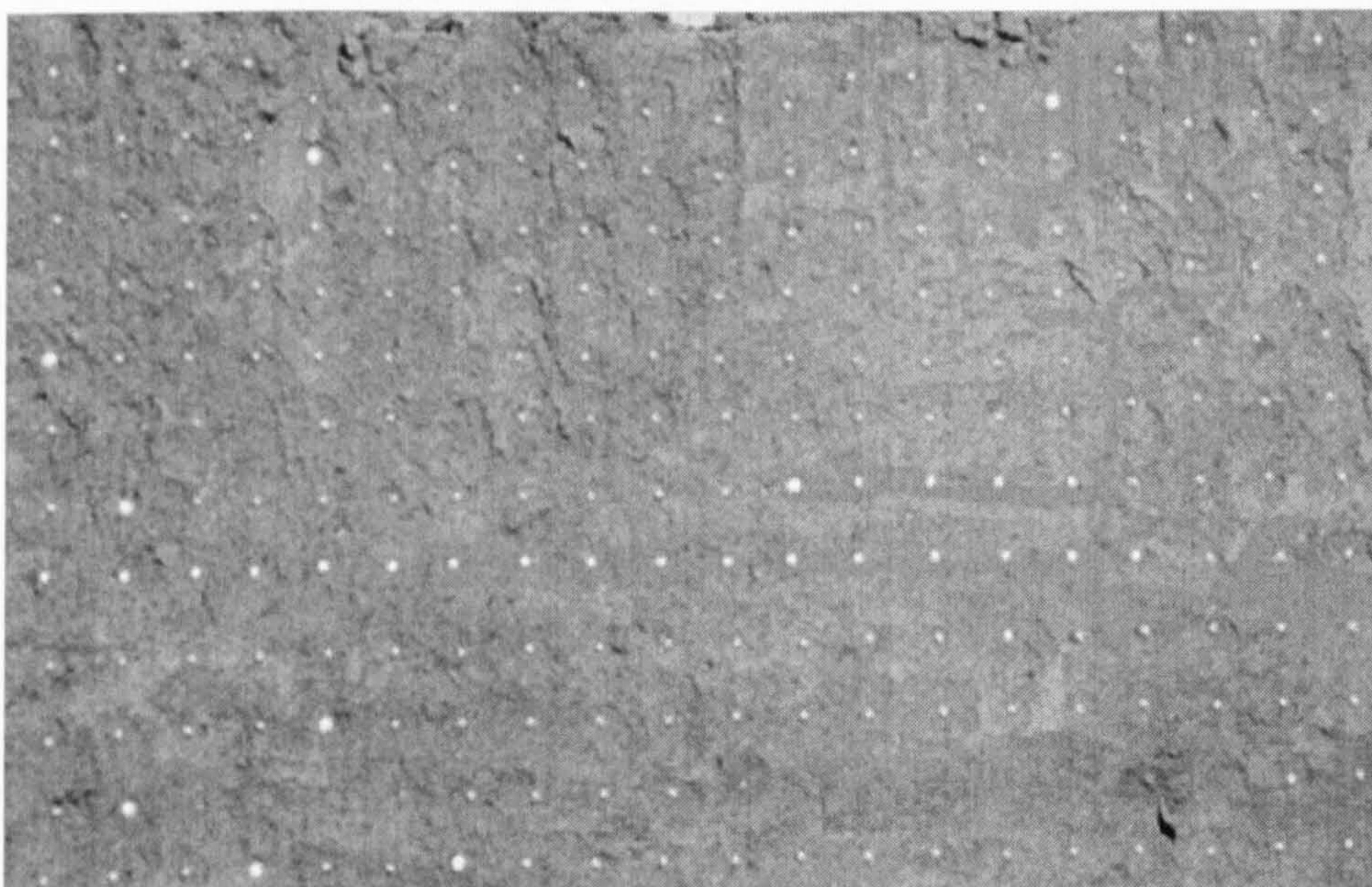


Figure A2.5. Triple with same level wheels, Prep. 1, Rep. 1

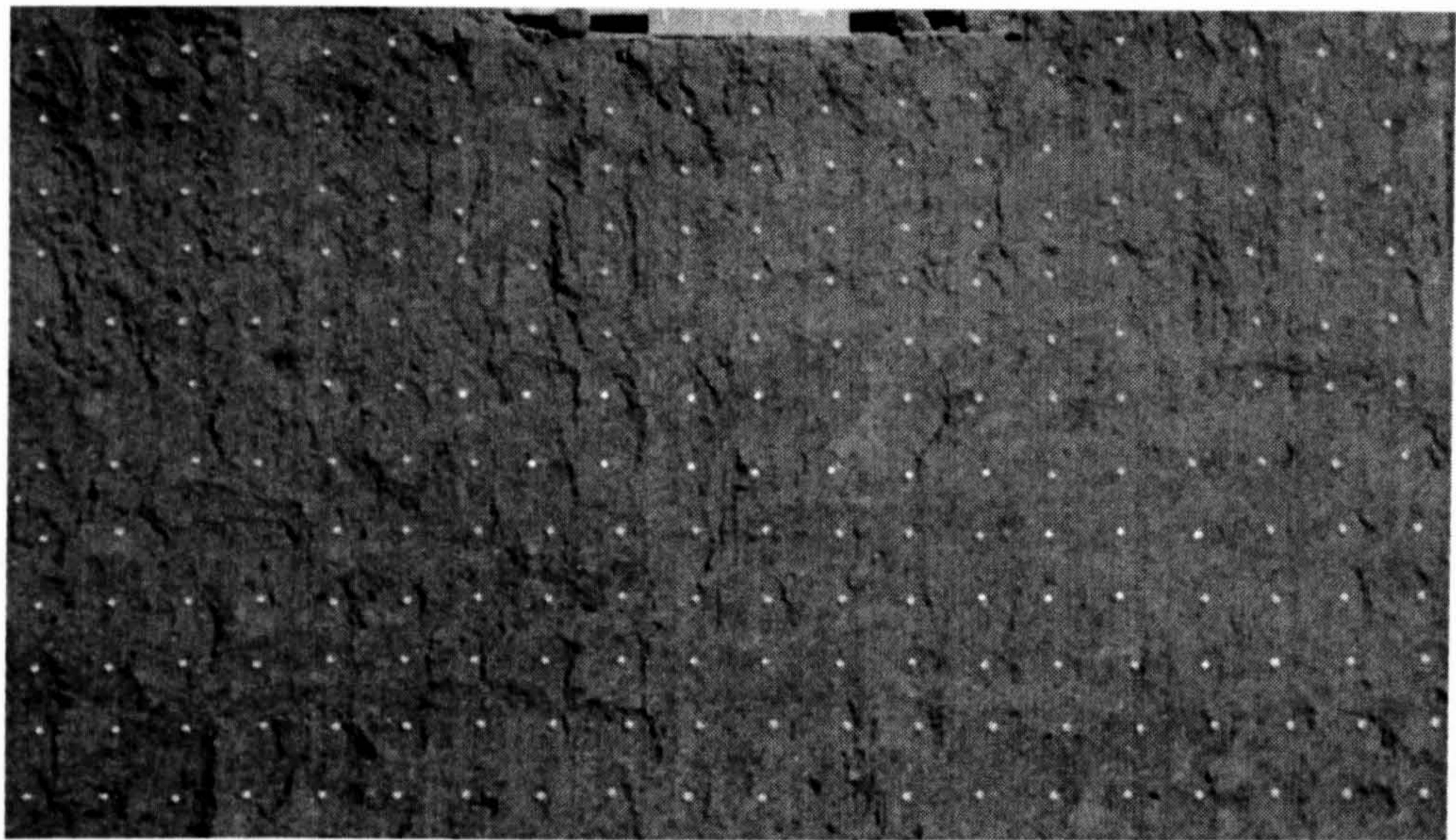


Figure A2.6. Simulated terra, Prep. 1, Rep. 2

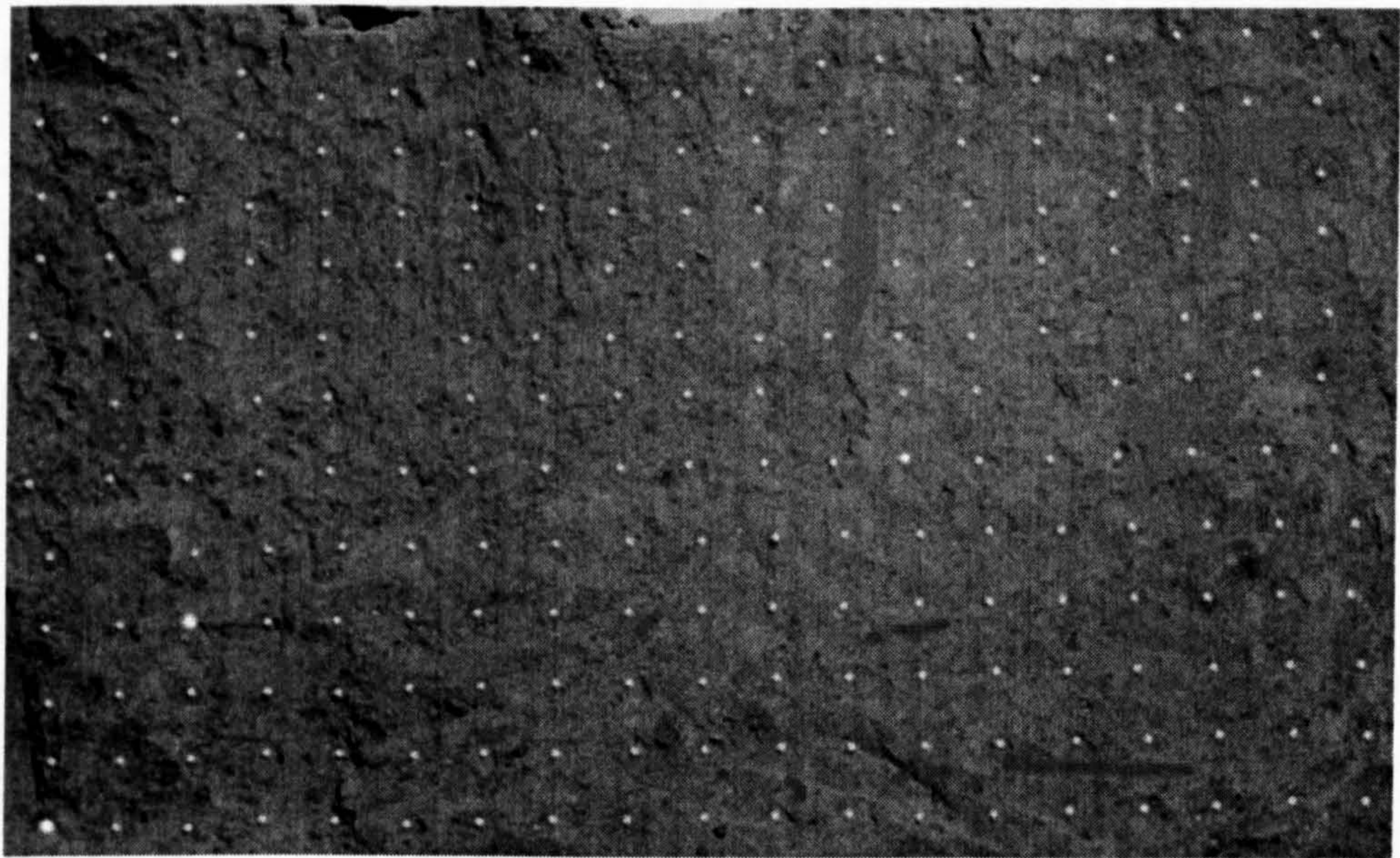


Figure A2.7. Triple with same level wheels, Prep. 1, Rep. 2

A2.2. Prep. 2 - Simulated terra and triple with raised middle wheel

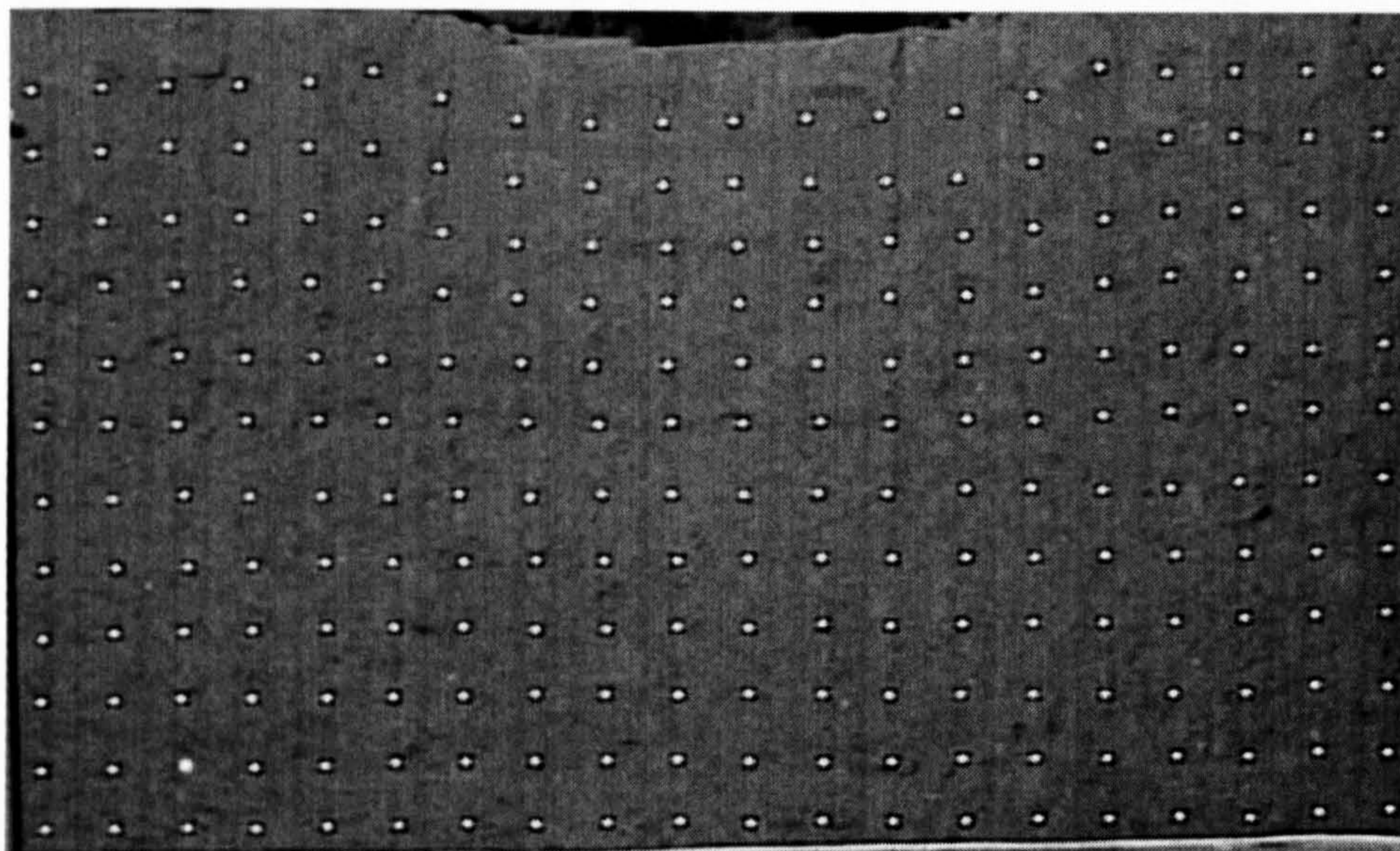


Figure A2.8. Simulated terra, Prep. 2, Rep. 1

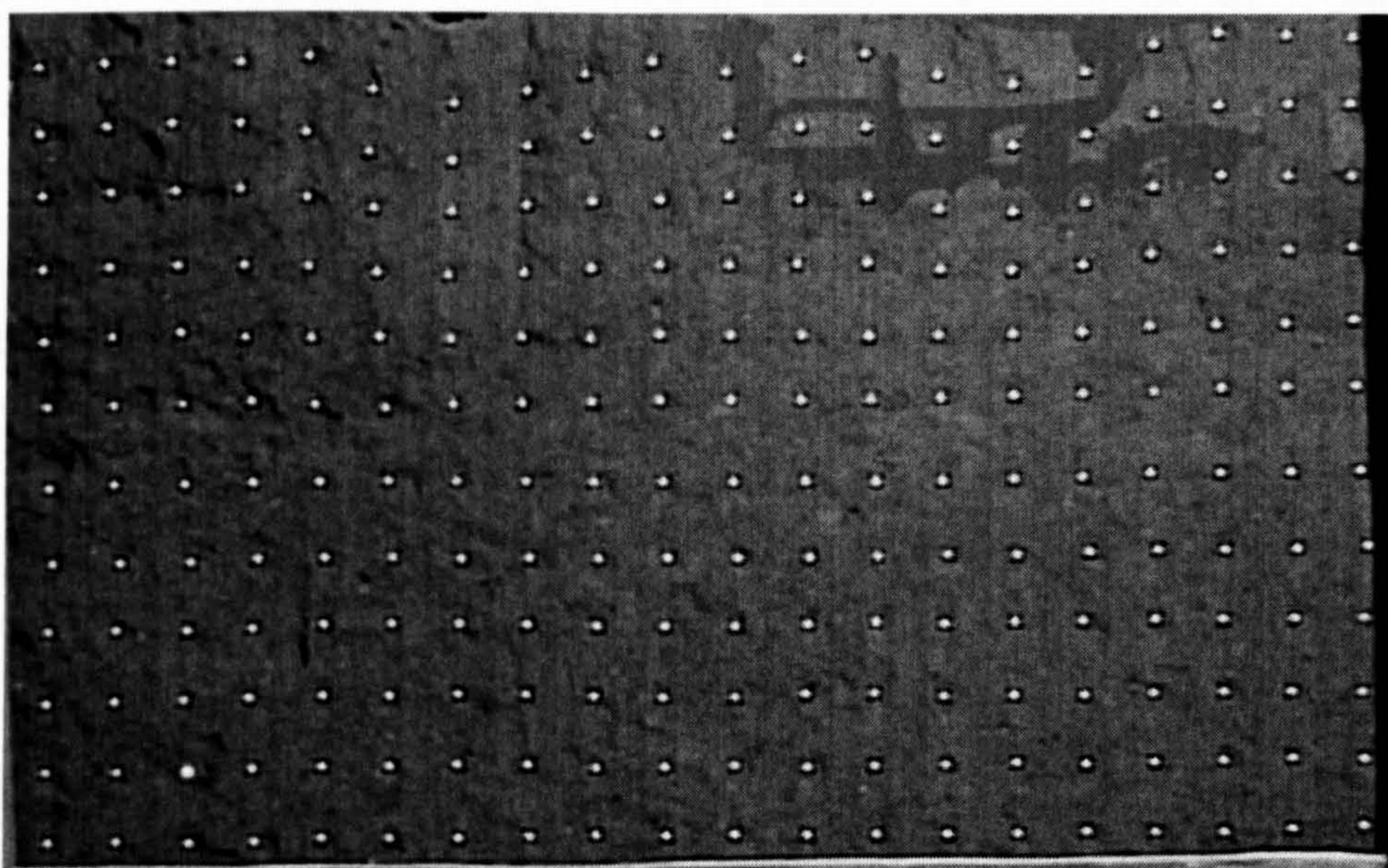


Figure A2.9. Triple with raised middle wheel, Prep. 2, Rep. 1

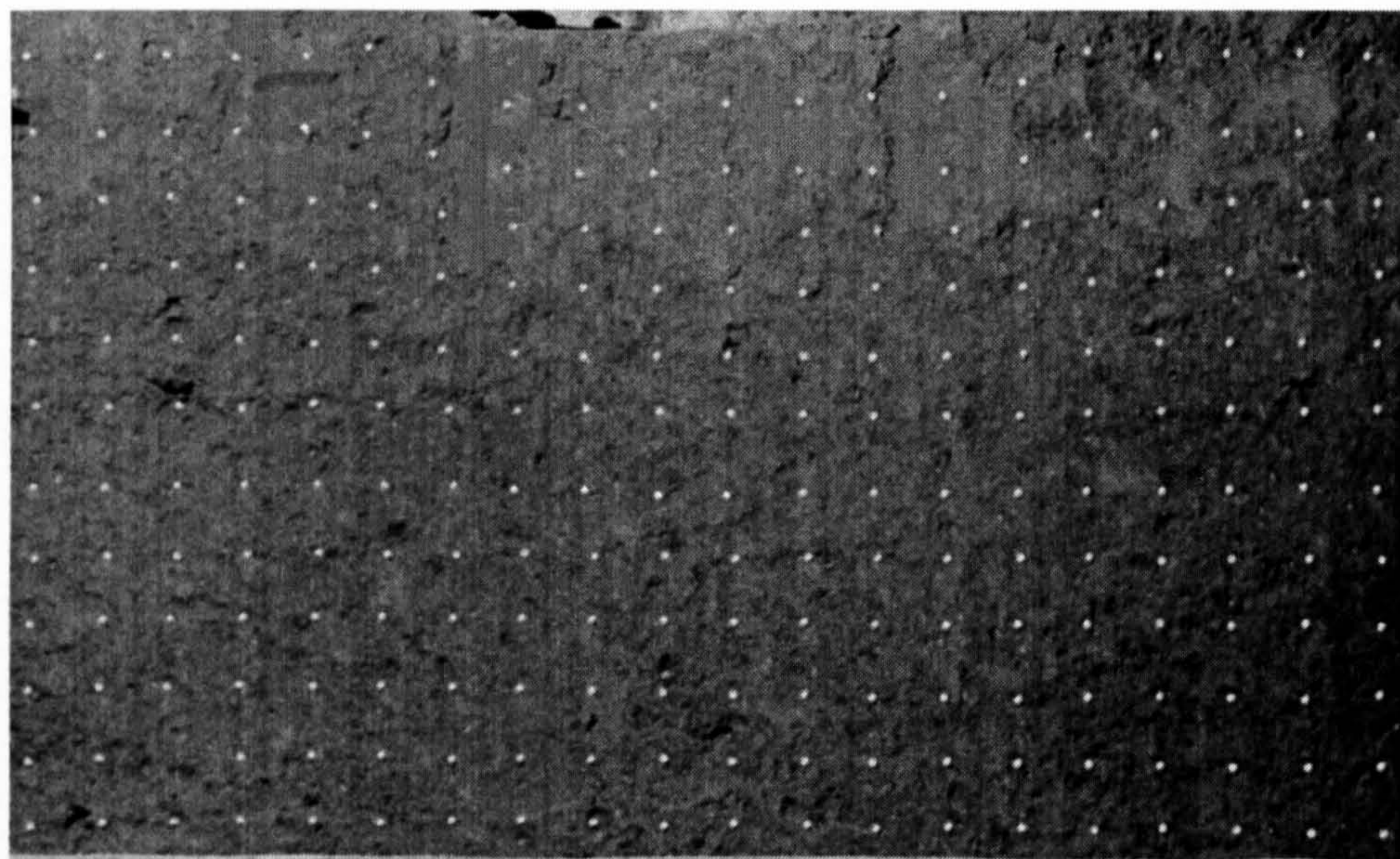


Figure A2.10. Simulated terra, Prep. 2, Rep. 2

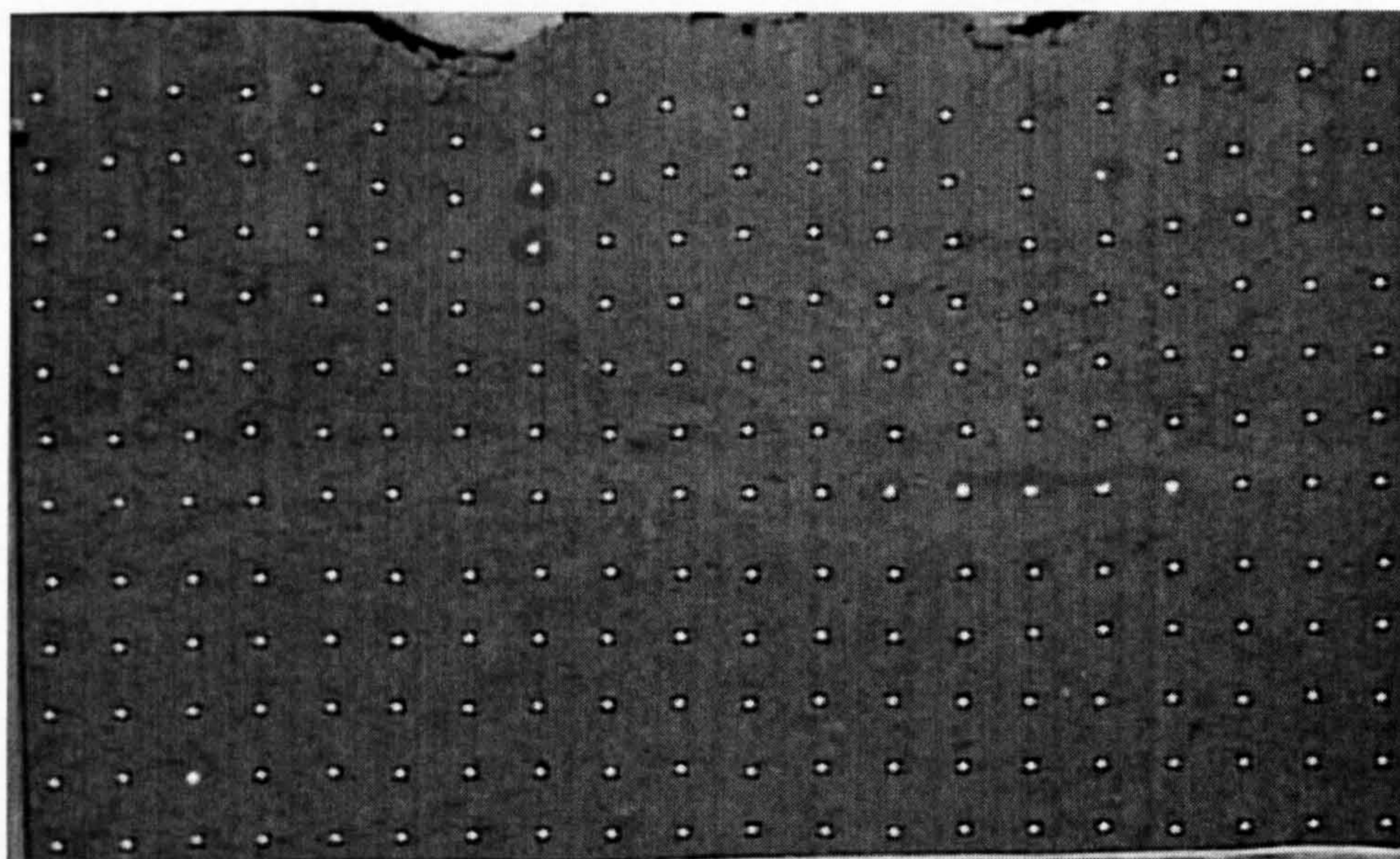


Figure A2.11. Triple with raised middle wheel, Prep.2, Rep. 2

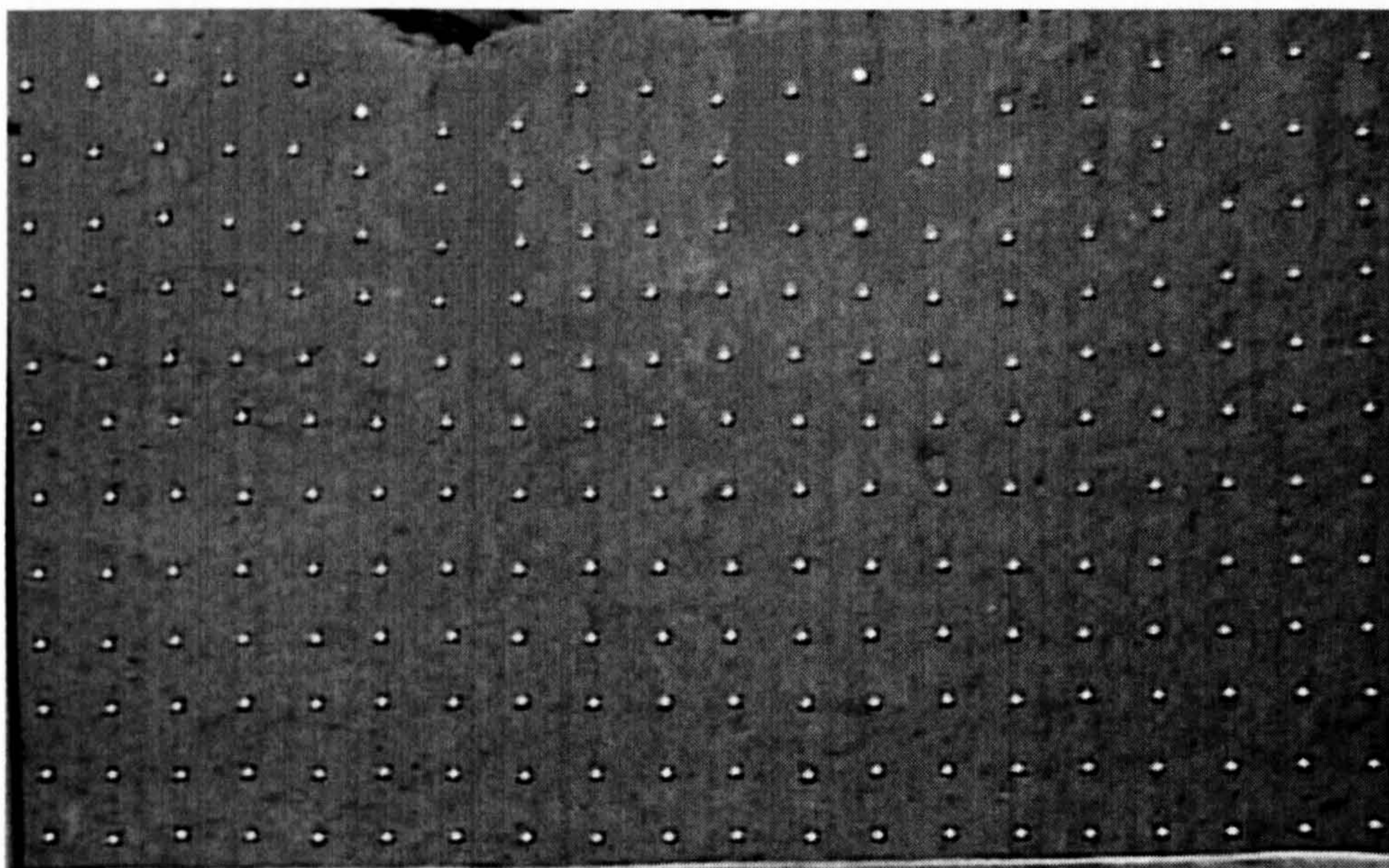
A2.3. Prep. 3 - Triple with raised middle wheel and with same level wheels

Figure A2.12. Triple with raised middle wheel, Prep.3, Rep. 1

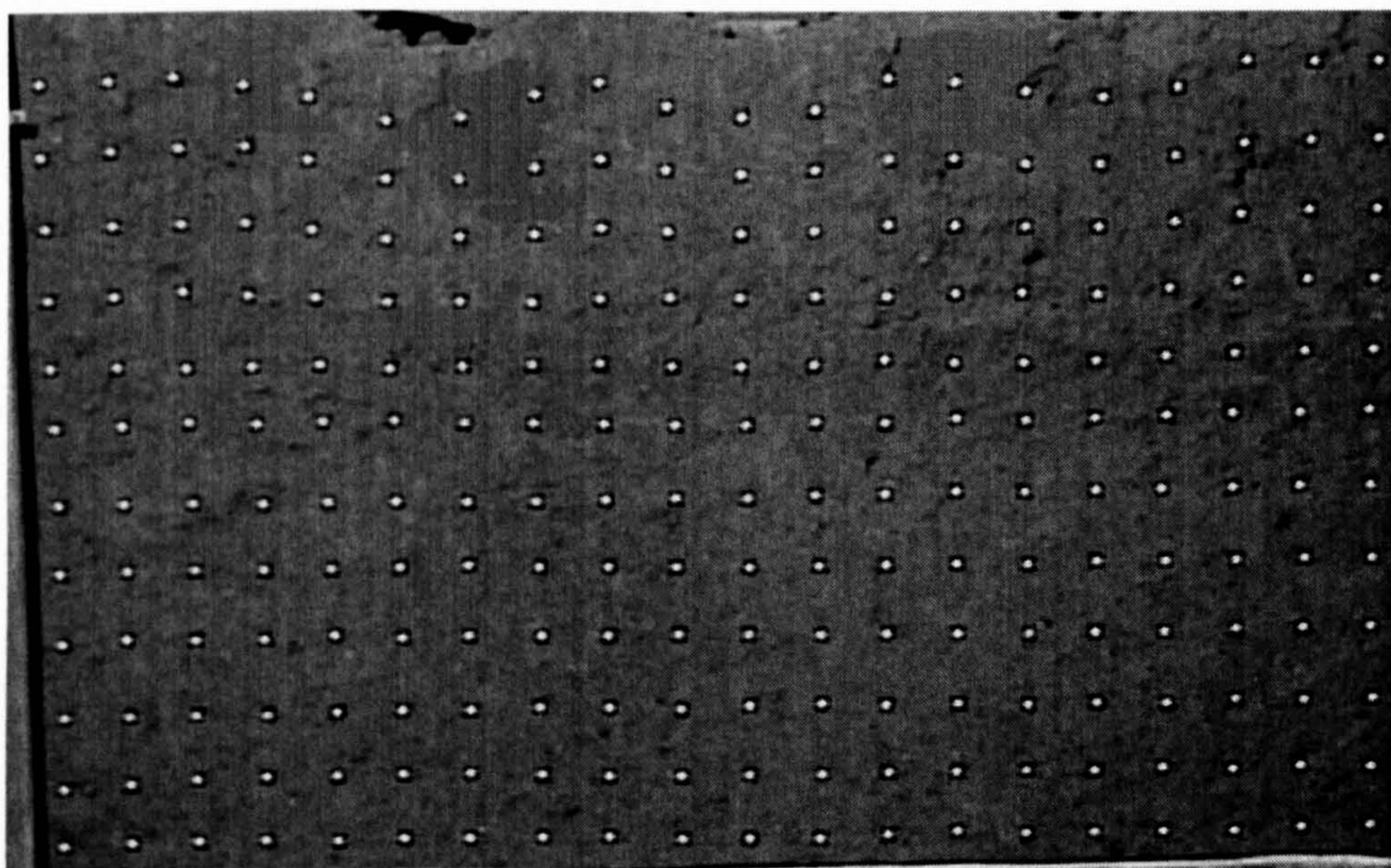


Figure A2.13. Triple with same level wheels, Prep. 3, Rep. 1

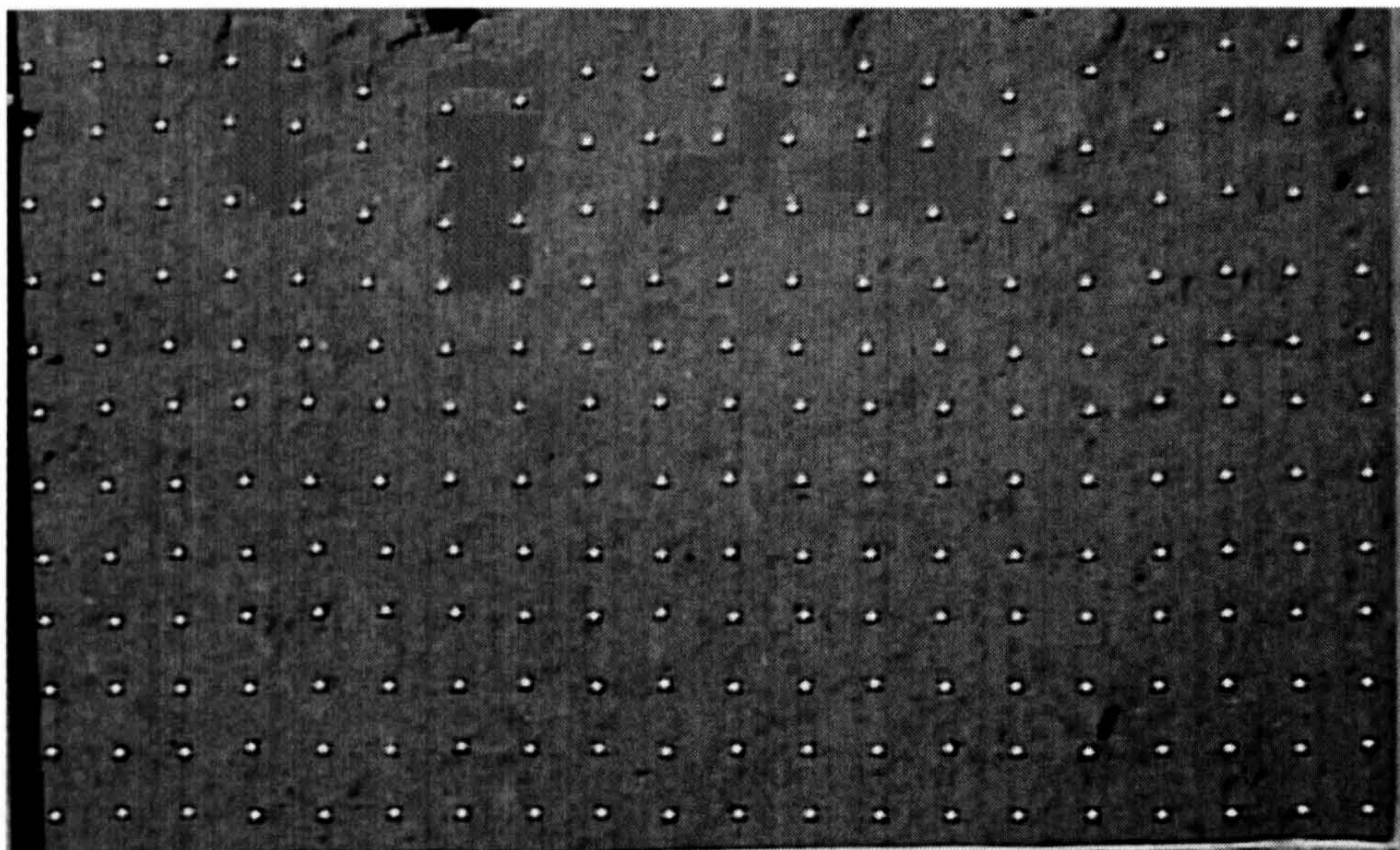


Figure A2.14. Triple with raised middle wheel, Prep.3, Rep. 2

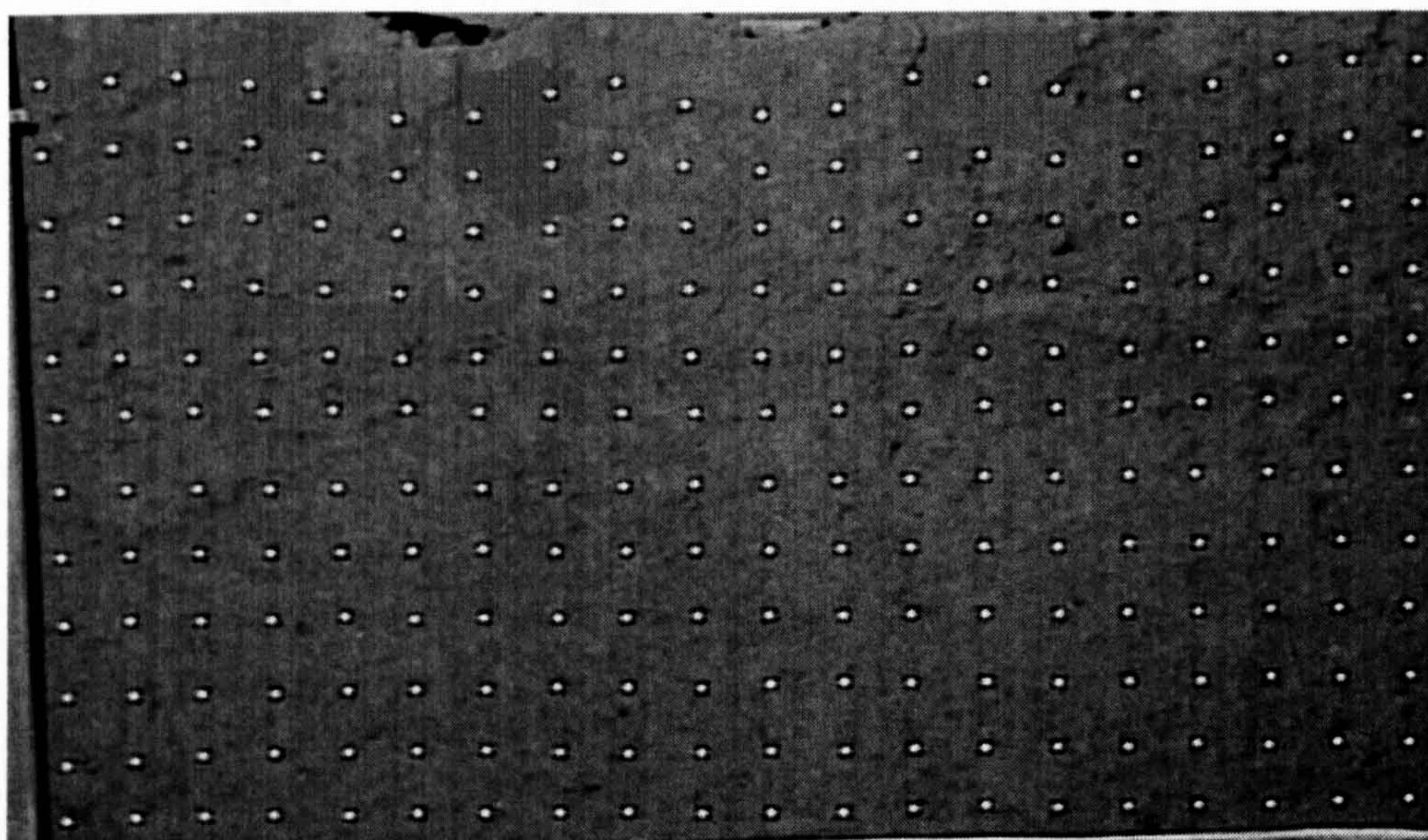


Figure A2.15. Triple with same level wheels, Prep. 3, Rep. 2

Appendix 3

Field test data

Table A3.1

Moisture content data on a dry basis

		Before operation				After operation			
Depth(mm)		0 - 30		30 - 60		0 - 30		30 - 60	
Conditions		Loose	Firm	Loose	Firm	Loose	Firm	Loose	Firm
Plot 1	R1	14.19	10.44	17.17	18.12	15.84	15.48	20.29	16.53
	R2	13.17	11.93	24.10	17.64	15.23	11.01	20.40	17.24
	R3	14.14	11.35	18.14	19.25	15.60	12.54	21.41	18.19
	R4	12.46	9.63	16.84	18.55	15.75	13.97	19.99	18.84
Plot 2	R1	14.04	9.33	18.6	13.83	12.96	9.74	16.55	15.99
	R2	14.90	12.16	20.80	18.01	13.71	12.14	16.37	18.00
	R3	11.77	12.40	17.02	18.94	13.51	12.72	17.04	17.12
	R4	14.28	11.53	16.86	17.83	16.46	13.86	21.02	17.95
Plot 3	R1	12.46	12.29	19.58	19.19	17.03	12.81	21.49	18.70
	R2	14.29	9.96	17.88	15.58	16.41	–	18.26	–
	R3	13.74	11.26	19.21	18.37	17.95	–	21.47	–
	R4	12.88	11.26	19.32	15.85	16.42	–	19.65	–
Mean		13.53	11.13	18.79	17.60	15.57	12.70	19.50	17.62

Table A3.2

Bulk density in a different depth range under treatments in both field conditions

Treatments		50 mm		200 mm		350 mm		500 mm		Single	
Field conditions		Loose	Firm	Loose	Firm	Loose	Firm	Loose	Firm	Loose	Firm
Depth(mm)		Plots									
0-150	P1	1.44	1.41	1.37	1.43	1.43	1.44	1.46	1.44	1.41	1.52
	P2	1.36	1.38	1.42	1.39	1.46	1.47	1.48	1.51	1.53	1.48
	P3	1.37	1.40	1.45	1.46	1.48	1.41	1.49	1.49	1.47	1.47
150-300	P1	1.50	1.55	1.50	1.56	1.49	1.49	1.54	1.51	1.56	1.54
	P2	1.51	1.44	1.44	1.46	1.52	1.51	1.49	1.63	1.57	1.57
	P3	1.53	—	1.58	—	1.61	—	1.59	—	1.54	—
300-600	P1	1.56	1.59	1.70	1.58	1.70	1.58	1.61	1.52	1.62	1.62
	P2	1.60	1.59	1.55	1.53	1.61	1.59	1.65	1.69	1.58	1.61
	P3	1.62	—	—	—	—	—	—	—	1.60	—

Table A3.3

Bulk densities data before tests(Mg.m⁻³)

Depth (mm)	0 -150		150 - 300		30 - 600	
Rep.	Loose	Firm	Loose	Firm	Loose	Firm
R1	1.30	1.36	1.40	1.45	1.60	1.59
R2	1.27	1.40	1.57	1.49	1.59	1.58
R3	1.28	1.38	1.49	1.50	1.58	1.61
R4	1.31	1.41	1.50	1.47	1.57	1.57
R5	1.22	1.36	1.65	1.54	1.67	1.65
R6	1.24	1.27	1.38	1.51	1.47	1.55
R7	1.27	1.33	1.46	1.55	1.62	1.67
R8	1.23	1.31	1.41	1.55	1.61	1.56
R9	1.26	1.38	—	—	—	—
R10	1.29	1.42	—	—	—	—
R11	1.23	1.41	—	—	—	—
R12	1.25	1.39	—	—	—	—
Mean	1.26	1.37	1.48	1.51	1.59	1.60

Table A3.4 *Penetration resistance before operation in loose field*

Depth/Plots	1	2	3	4	Average (MPa)
1	2.46	2.42	2.44	2.49	2.45
2	2.49	2.44	2.47	2.52	2.48
3	2.52	2.46	2.49	2.55	2.51
4	2.55	2.51	2.50	2.57	2.53
5	2.57	2.52	2.54	2.61	2.56
6	2.58	2.55	2.57	2.70	2.60
7	2.59	2.61	2.61	2.76	2.64
8	2.63	2.66	2.60	2.83	2.68
9	2.74	2.82	2.64	2.97	2.79
10	2.89	3.10	2.68	3.04	2.93
11	2.99	3.36	2.81	3.12	3.07
12	3.18	3.66	3.02	3.19	3.26
13	3.37	4.02	3.33	3.34	3.52
14	3.60	4.26	3.54	3.50	3.73
15	3.97	4.45	3.76	3.60	3.95
16	4.13	4.40	3.91	3.64	4.02
17	4.17	4.18	4.02	3.64	4.00
18	4.28	4.11	4.06	3.63	4.02
19	4.38	4.13	4.03	3.65	4.05
20	4.27	4.10	3.95	3.70	4.01
21	4.20	4.04	3.86	3.82	3.98
22	4.16	4.00	3.78	3.86	3.95
23	4.12	3.95	3.68	3.87	3.91
24	4.13	3.91	3.65	3.85	3.89
25	4.07	3.90	3.71	3.79	3.87
26	4.09	3.97	3.75	3.73	3.89
27	4.15	3.98	3.87	3.76	3.94
28	4.21	3.94	3.91	3.91	3.99
29	4.13	3.96	3.93	3.93	3.99
30	4.21	4.10	3.93	3.69	3.98
31	4.30	4.21	3.81	3.71	4.01
32	4.28	4.32	3.72	3.67	4.00
33	4.02	4.56	3.89	3.82	4.07
34	4.15	4.54	3.90	3.75	4.09
35	4.20	4.52	3.96	3.97	4.16
36	4.40	4.63	4.29	3.84	4.29
37	4.28	4.54	4.31	4.07	4.30
38	4.48	4.71	4.52	3.69	4.35
39	4.51	4.82	5.32	3.95	4.65
40	4.86	4.70	5.10	4.13	4.70
41	5.02	4.64	—	—	4.83
42	4.60	4.77	—	—	4.69
43	5.05	4.73	—	—	4.89
44	—	4.58	—	—	4.58
45	—	4.43	—	—	4.43
46	—	4.45	—	—	4.45
47	—	4.81	—	—	4.81
48	—	4.56	—	—	4.56
49	—	4.48	—	—	4.48
50	—	—	—	—	—

Table A3.5 *Penetration resistance before operation in firm field*

Depth/Plots	1	2	3	4	Average(MPa)
1	2.44	2.56	4.05	2.45	2.49
2	2.56	2.68	3.00	2.58	2.71
3	2.85	2.41	3.29	2.82	2.84
4	3.26	3.20	3.59	3.10	3.29
5	3.62	3.43	3.91	3.50	3.62
6	3.90	3.66	4.10	3.57	3.81
7	4.13	3.97	4.41	3.59	4.03
8	4.36	3.97	4.52	3.74	4.15
9	4.49	4.13	4.66	3.85	4.28
10	4.65	4.36	4.77	3.97	4.44
11	4.83	4.65	4.35	4.10	4.48
12	4.97	4.85	4.45	4.23	4.63
13	5.10	4.81	4.44	4.41	4.69
14	5.05	4.95	4.40	4.44	4.71
15	5.04	4.85	4.32	4.43	4.66
16	4.77	4.90	4.45	4.42	4.64
17	4.70	4.98	4.25	4.42	4.59
18	4.70	4.81	4.28	4.37	4.54
19	4.70	4.75	4.34	4.36	4.54
20	4.70	4.66	4.70	4.29	4.59
21	4.64	4.51	4.44	4.03	4.41
22	4.33	4.50	4.91	4.12	4.47
23	4.20	4.48	5.27	3.96	4.53
24	4.16	4.49	5.00	3.91	4.39
25	4.40	4.62	5.10	4.15	4.57
26	4.33	4.87	5.00	4.29	4.62
27	4.09	4.87	4.94	4.12	4.51
28	4.10	5.18	4.89	4.94	4.78
29	4.23	5.13	4.64	—	4.67
30	4.22	5.13	4.52	—	4.62
31	4.29	5.00	4.47	—	4.59
32	4.07	4.81	4.60	—	4.49
33	4.20	5.24	4.83	—	4.76
34	4.92	5.17	5.66	—	5.25
35	5.34	5.21	5.47	—	5.34
36	5.28	—	—	—	5.28
37	—	—	—	—	—
38	—	—	—	—	—
39	—	—	—	—	—
40	—	—	—	—	—

Table A3.6

Penetration resistance (MPa) under dual arrangements in loose field

Treatments		50 mm spacing			200 mm spacing		
Rut cross points		R*	M**	R	R	M	R
Depth(mm)	Plots						
10	P1	2.47	2.58	2.43	2.43	2.47	2.47
	P2	2.40	2.47	2.41	2.42	2.45	2.44
	P3	2.42	2.49	2.41	2.41	2.44	2.42
50	P1	3.23	3.46	3.38	3.31	3.33	3.46
	P2	3.15	3.38	3.18	3.09	3.31	3.11
	P3	3.30	3.47	3.35	3.40	3.51	3.42
100	P1	3.95	4.08	3.86	4.07	3.99	4.03
	P2	3.72	3.86	3.70	4.00	4.11	4.01
	P3	4.02	4.18	4.04	4.12	4.23	4.18
150	P1	4.61	4.65	4.71	4.67	4.62	4.75
	P2	4.22	4.31	4.16	4.21	4.24	4.18
	P3	4.59	4.64	4.61	4.71	4.69	4.73

R* = Under the wheel in the rut
M** = Between the wheels in the middle

Table A3.6 (continue)
Penetration resistance (MPa) under dual arrangements in loose field

Treatments		350 mm spacing				500 mm spacing					
Rut cross points		R*	M**	M	M	R	M	M	R		
Depth(mm)	Plots										
10	P1	2.66	2.56	2.47	2.49	2.67	2.71	2.47	2.49	2.51	2.76
	P2	2.59	2.52	2.49	2.53	2.61	2.70	2.48	2.47	2.5	2.74
	P3	2.63	2.55	2.47	2.51	2.63	2.73	2.48	2.50	2.52	2.75
50	P1	3.09	2.96	2.79	2.82	3.04	3.21	2.71	2.67	2.81	3.32
	P2	2.99	2.88	2.71	2.79	3.01	3.15	2.68	2.66	2.72	3.11
	P3	3.18	3.02	2.89	2.82	3.21	3.33	3.05	2.94	2.99	3.37
100	P1	3.78	3.67	3.52	3.64	3.81	3.64	3.21	3.12	3.13	3.66
	P2	3.69	3.60	3.51	3.62	3.70	3.57	3.22	3.14	3.17	3.56
	P3	3.98	3.86	3.77	3.83	4.04	3.74	3.43	3.32	3.36	3.81
150	P1	4.54	4.44	4.47	4.43	4.48	4.38	4.25	4.22	4.4	4.44
	P2	4.30	4.22	4.24	4.19	4.28	4.18	4.09	4.08	4.05	4.20
	P3	4.64	4.53	4.58	4.50	4.70	4.47	4.41	4.43	4.39	4.51

R* = Under the wheel in the rut
M** = Between the wheels in the middle

Table A3.7
Penetration resistance (MPa) under dual arrangements in firm field

Treatments		50 mm spacing			200 mm spacing		
Depth (mm)	Replications (Plots)	R	M	R	R	M	R
10	P1	2.61	2.57	2.55	2.51	2.47	2.42
	P2	2.50	2.52	2.47	2.52	2.49	2.48
	P3	2.59	2.63	2.61	2.60	2.58	2.63
50	P1	3.50	3.65	3.71	3.53	3.65	3.60
	P2	3.51	3.57	3.50	3.44	3.56	3.43
	P3	3.73	3.84	3.79	3.81	3.96	3.87
100	P1	4.30	4.33	4.22	4.25	4.25	4.28
	P2	4.04	4.08	4.01	4.07	4.09	4.06
	P3	4.31	4.32	4.34	4.21	4.27	4.28
150	P1	–	–	–	–	–	–
	P2	–	–	–	–	–	–
	P3	–	–	–	–	–	–

Table A3.7 (continue)
Penetration resistance (MPa) under dual arrangements in firm field

Treatments		350 mm spacing						500 mm spacing						
Rut cross points		R	M	M	M	R	R	M	M	M	R	M	M	R
Depth(mm)		Plots												
10	P1	2.74	2.66	2.54	2.62	2.70	2.70	2.56	2.51	2.51	2.70	2.56	2.51	2.77
	P2	2.65	2.58	2.50	2.61	2.66	2.66	2.47	2.41	2.41	2.53	2.47	2.41	2.52
	P3	2.81	2.75	2.59	2.71	2.87	2.87	2.80	2.68	2.68	2.89	2.80	2.74	2.91
50	P1	4.03	3.91	3.69	3.76	3.99	3.99	3.81	3.67	3.67	4.03	3.81	3.67	3.99
	P2	3.98	3.90	3.74	3.81	3.97	3.97	3.73	3.61	3.61	3.82	3.73	3.61	3.79
	P3	4.18	4.05	3.96	4.03	4.23	4.23	4.03	3.97	3.97	4.14	4.03	4.05	4.19
100	P1	4.52	4.52	4.29	4.33	4.45	4.45	4.43	4.31	4.31	4.39	4.43	4.37	4.42
	P2	4.26	4.26	4.21	4.17	4.12	4.12	4.22	4.11	4.11	4.15	4.22	4.2	4.11
	P3	4.60	4.60	4.41	4.57	4.61	4.61	4.57	4.41	4.41	4.45	4.57	4.58	4.59
150	P1	-	-	-	-	-	-	-	-	-	-	-	-	-
	P2	-	-	-	-	-	-	-	-	-	-	-	-	-
	P3	-	-	-	-	-	-	-	-	-	-	-	-	-

Table A3.8

Wheel sinkage (mm) in the loose field

Treatments		50 mm	200 mm	350 mm	500 mm	Single
Plots	Rep.					
Plot 1	R1	25	30	29	30	36
	R2	30	28	29	33	34
	R3	30	28	28	28	34
	R4	25	30	31	29	30
	R5	30	-	30	30	38
Plot 2	R1	25	25	30	29	30
	R2	26	30	30	29	35
	R3	27	28	28	27	36
	R4	30	26	28	30	38
	R5	-	30	30	28	32
Plot 3	R1	25	30	30	30	33
	R2	28	28	28	28	32
	R3	25	30	25	26	33
	R4	30	31	30	28	34
	R5	29	30	25	30	30
Plot 4	R1	30	24	30	36	34
	R2	28	28	30	34	34
	R3	26	26	28	36	36
	R4	27	27	30	33	35
	R5	25	29	31	34	35
Average		27.5	28.3	29	30.4	34

Table A3.9

Wheel sinkage (mm) in the firm field

Treatments		50 mm	200 mm	350 mm	500 mm	Single
Plots	Rep.					
Plot 1	R1	14	28	32	25	35
	R2	20	21	25	15	21
	R3	19	28	22	18	30
	R4	19	17	15	28	39
	R5	25	24	-	-	23
Plot 2	R1	17	25	23	23	28
	R2	20	17	20	28	31
	R3	14	30	23	28	28
	R4	25	18	25	25	26
	R5	-	-	21	20	28
Plot 3	R1	20	14	20	20	31
	R2	23	21	25	20	30
	R3	21	20	26	28	22
	R4	15	27	17	20	29
	R5	17	18	14	26	30
Plot 4	R1	25	23	25	23	33
	R2	23	27	23	26	28
	R3	18	24	18	18	30
	R4	25	14	26	21	34
	R5	20	18	22	25	32
Average		20	21.8	22.2	23	29.4

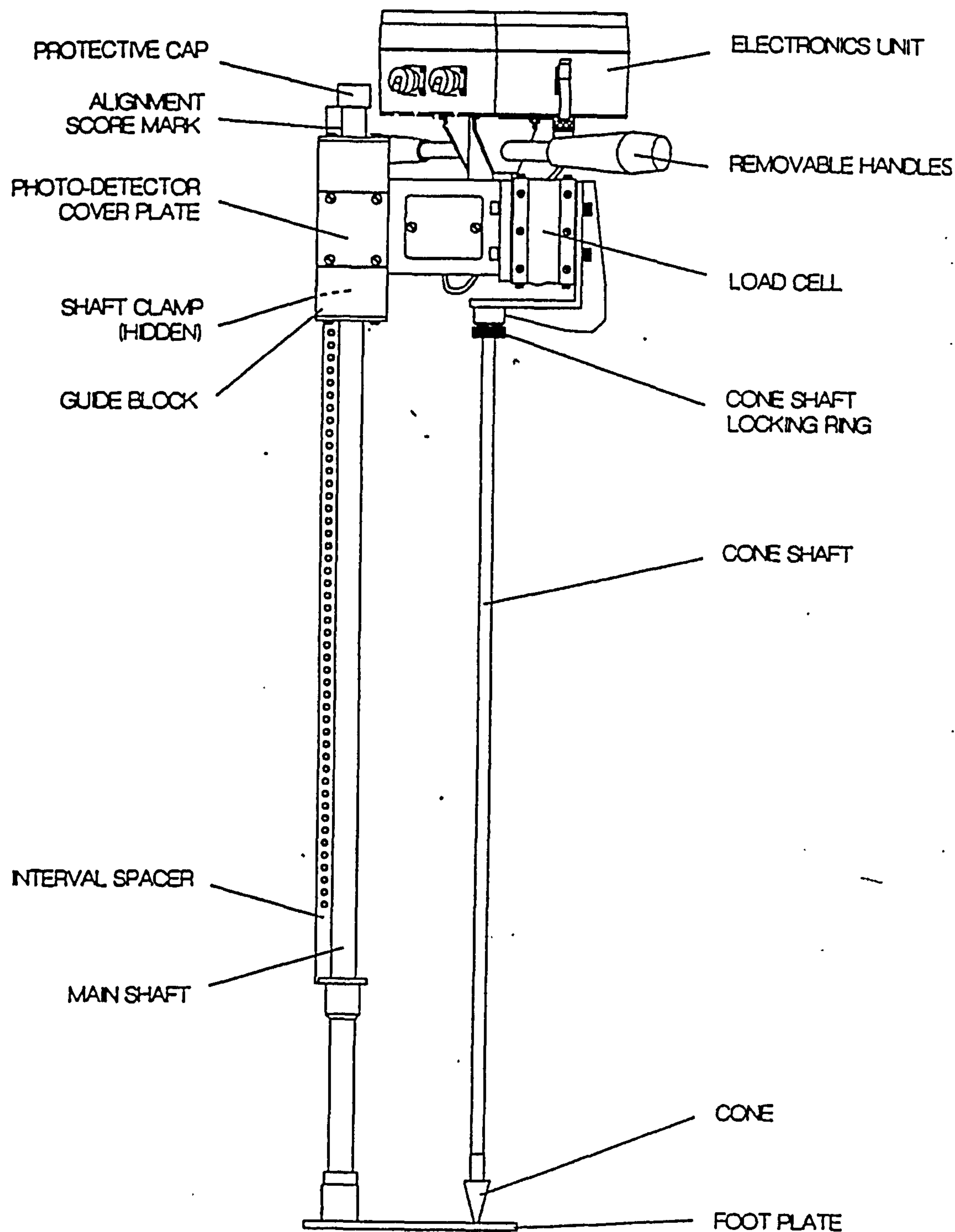


Figure A3.1. Penetrometer SP1000 general arrangements drawing

Penetrometer Specification

Weight of SP1000	Approx 7.5 kg (carrying case aprox. 15 kg) Total weight approx 22.5 kg.
Carrying Box size	1090 mm x 240 mm x 300 mm.
Battery type	6'C' Size rechargeable cells 1.2 V, 2.2 Ah.
Battery life	Fully charged: 20 hours continuous operation. Shelf life: 8 weeks. A full recharge takes 14 hours.
Temperature range	0 C to +40 C
Depth measurements	Measurements of load can be made at up to 50 depth. The depth intervals can be defined on the SP1000 or by the Computer. Maximum depth = 50 cm Minimum depth = 1 cm Interval variable There is an audible alarm if the cone is inserted faster than 50 cm/ second.
Cones	30° cones corresponding to the American Society of Agriculture Eng. Standard. 12.83 mm diameter (small) and 20.27 mm diameter (large) ones are supplied.
Force measurements	Strain gauge transducer, 0.5 kg resolution. 50 kg maximum load. There is an audible alarm if this load is exceeded.
Display	16 characters Alpha Numeric Liquid Crystal Display
Tools	A cones wear test gauge with machined holes is supplied. The cones will not pass through theses holes unless wear of cone exceeds 3 per cent. The gauge also has spanner rebates for making adjustments to certain fittings on the SP1000

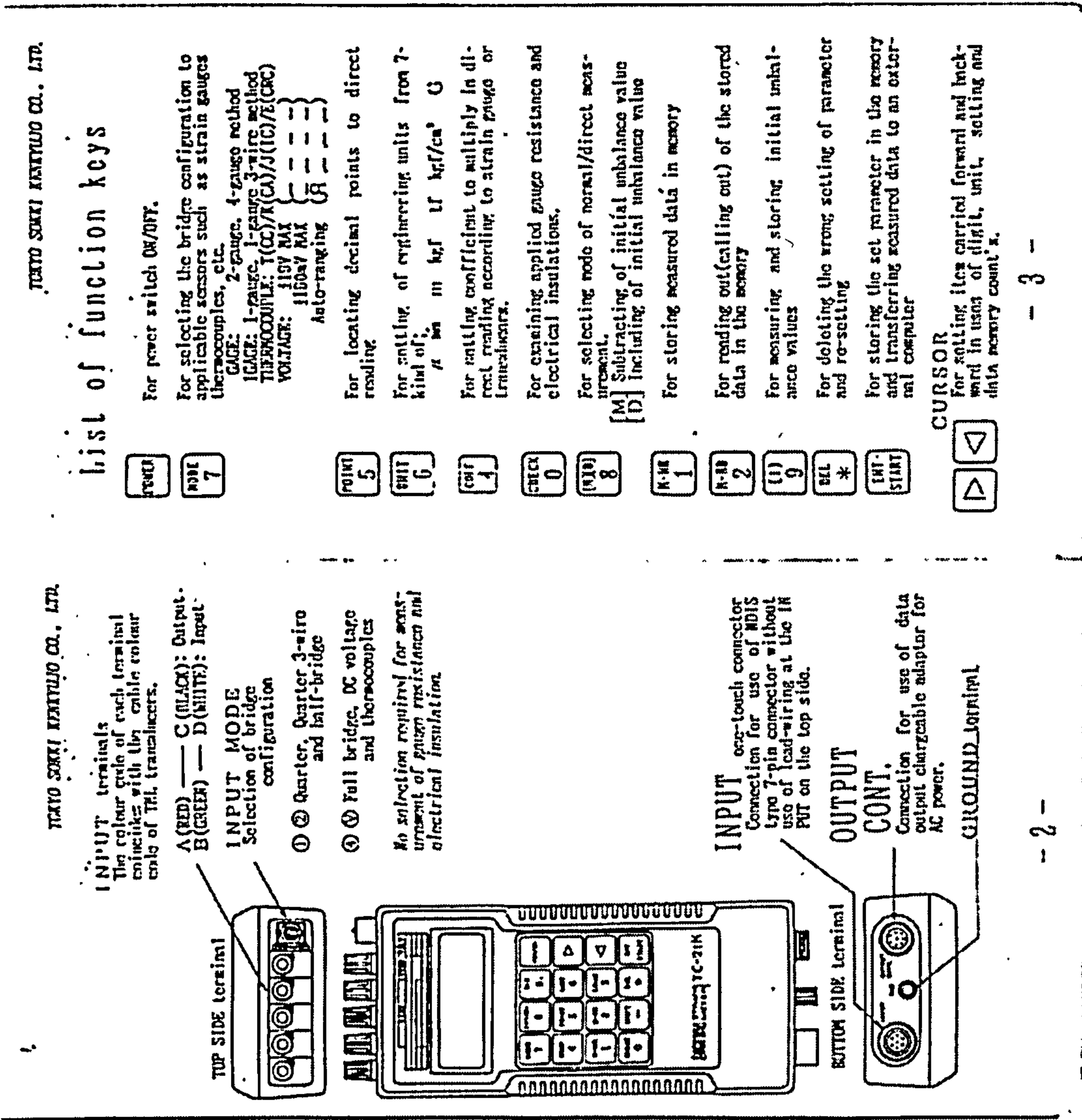
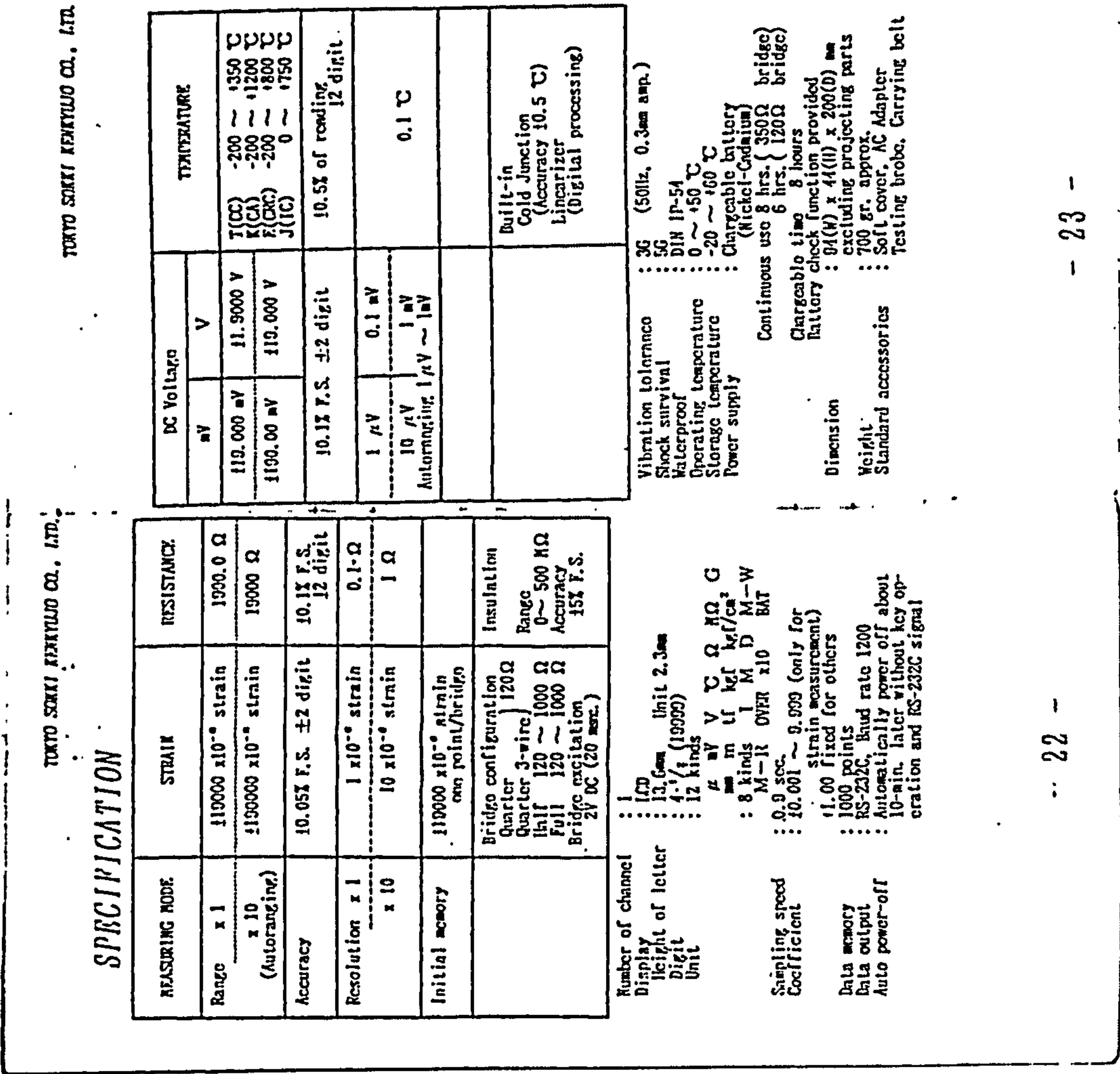


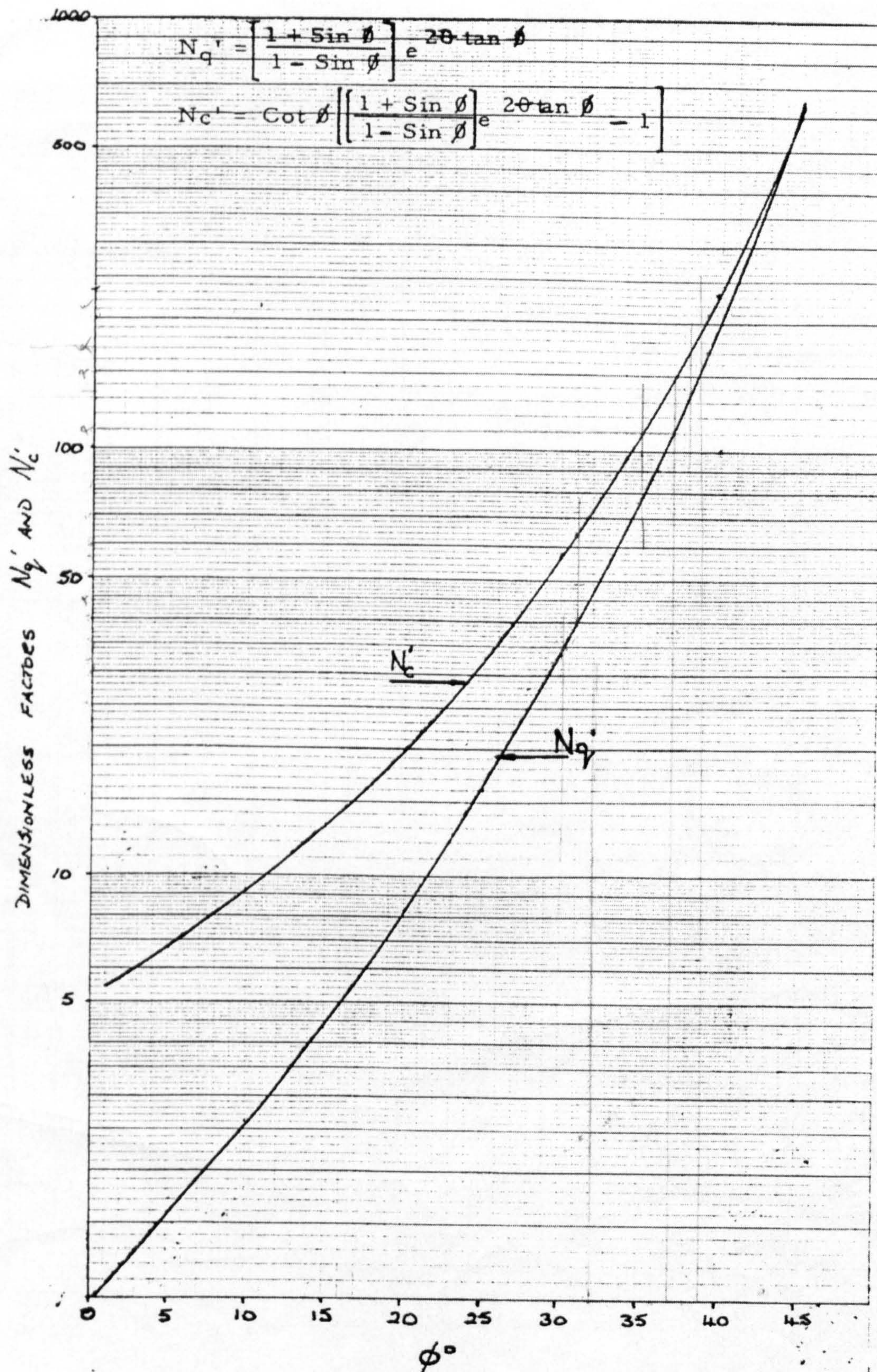
Figure A3.2. Load cell TC-21K information and operation keys



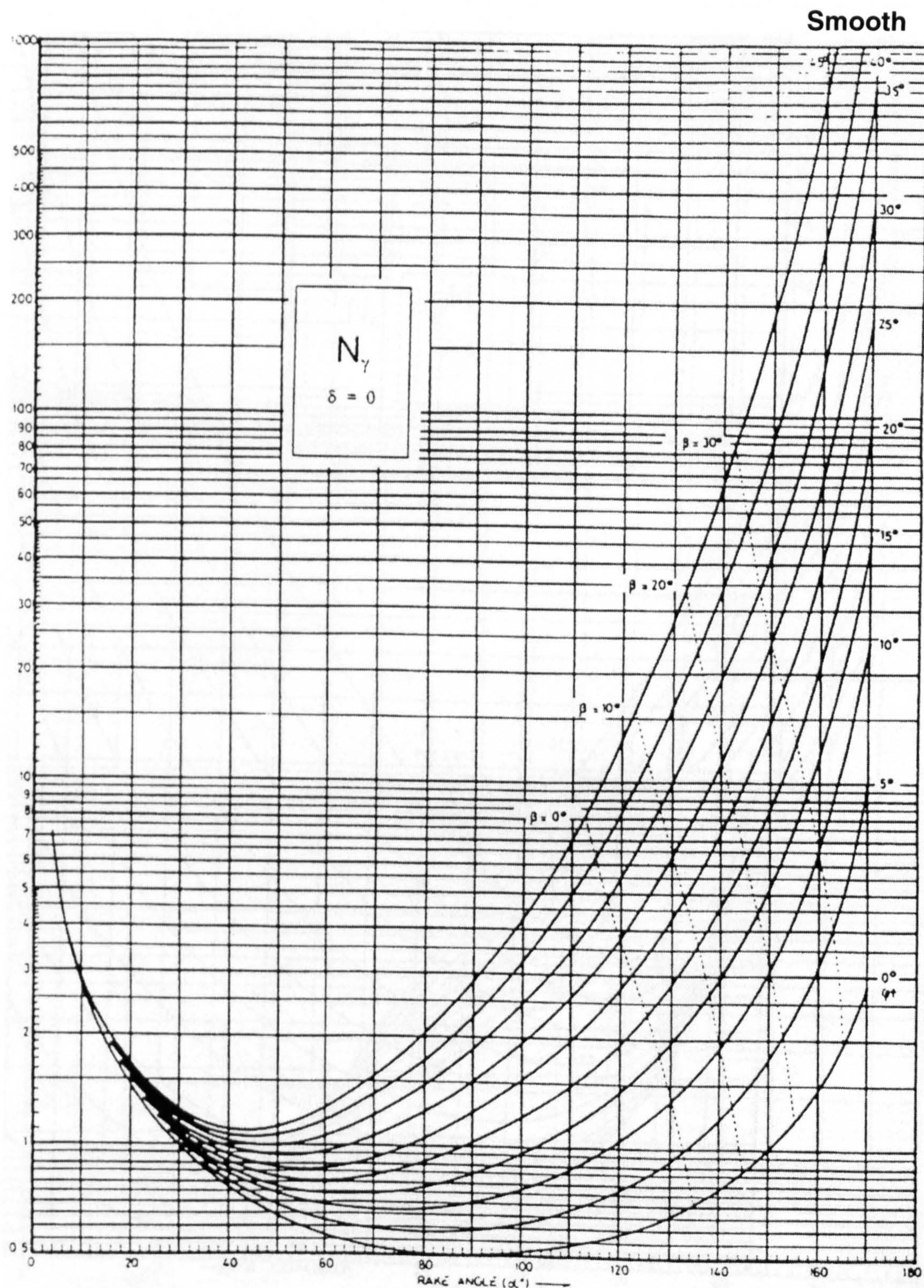
Appendix 4

***N* factor graphs**

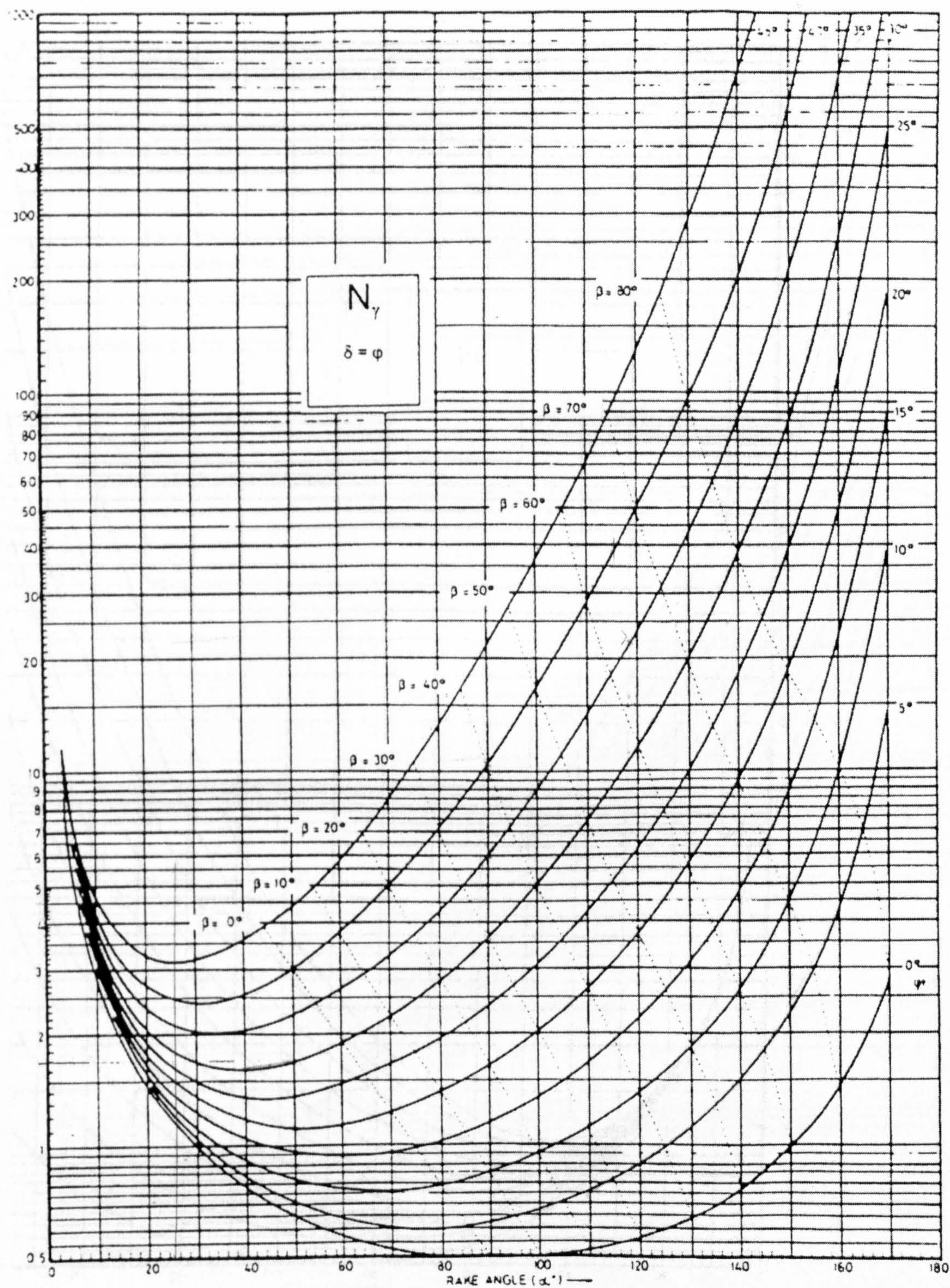
A4.1. Meyerhof graph to find N factors



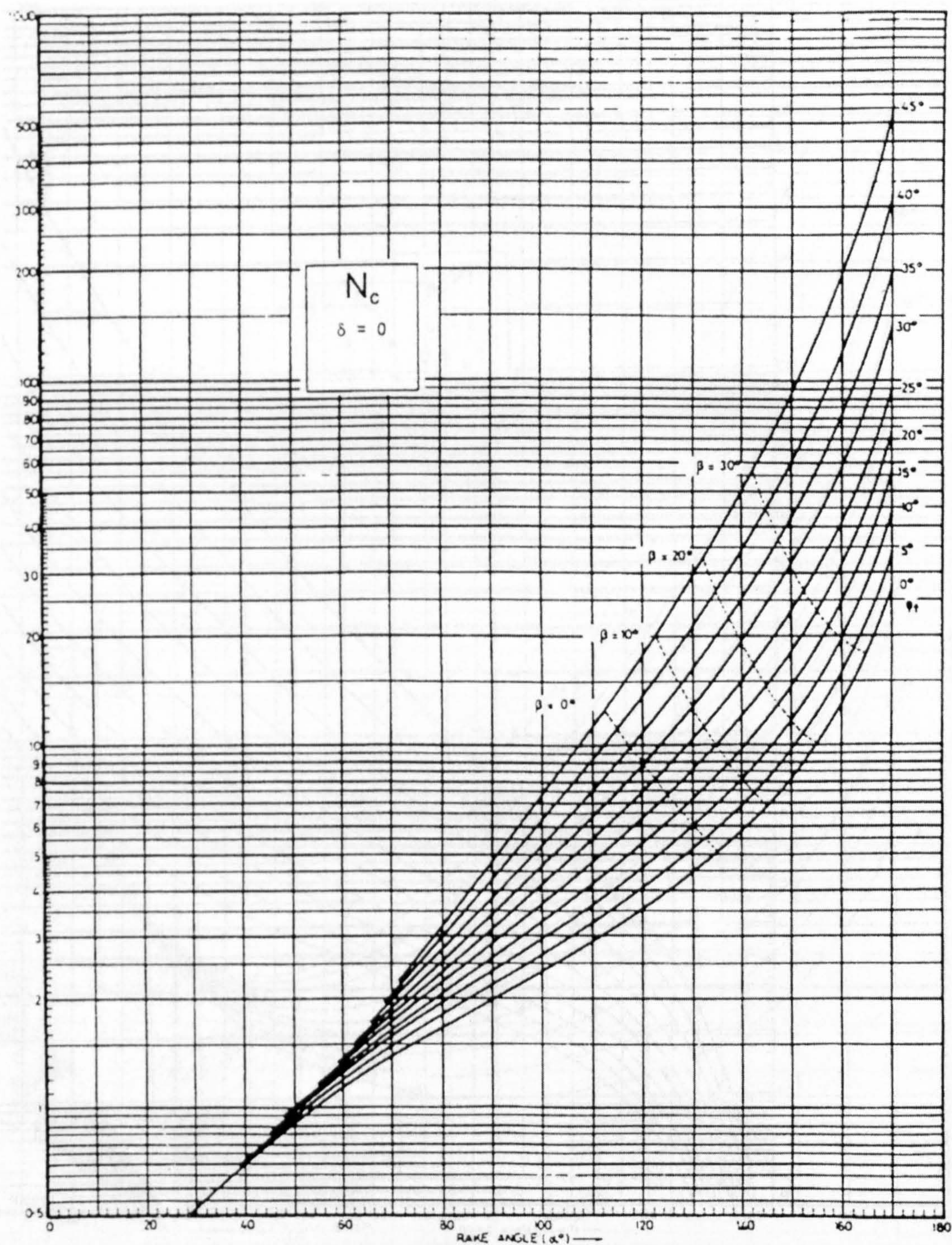
A4.2. Graphs to find N factors in General Soil Mechanics Equation



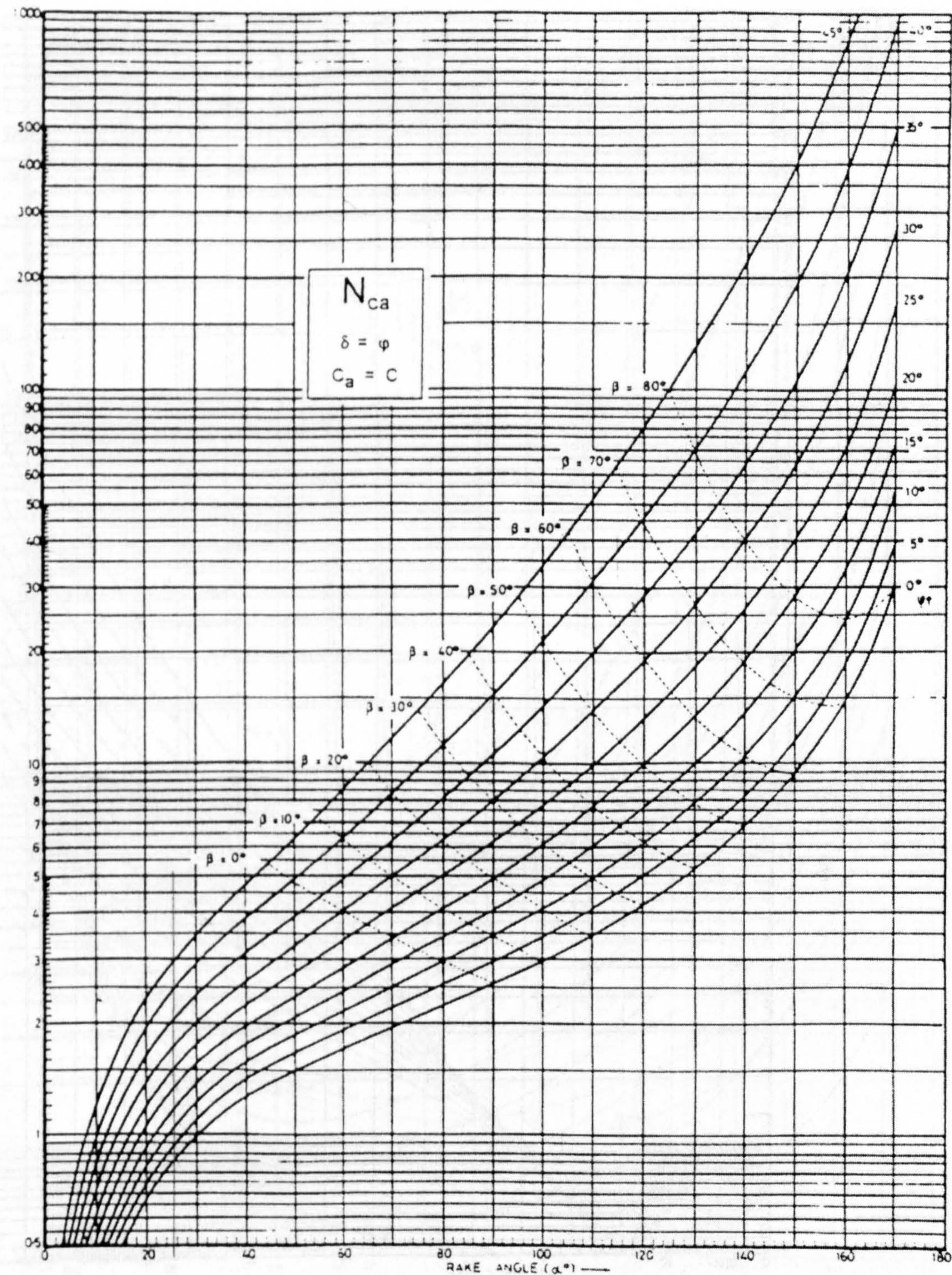
Rough



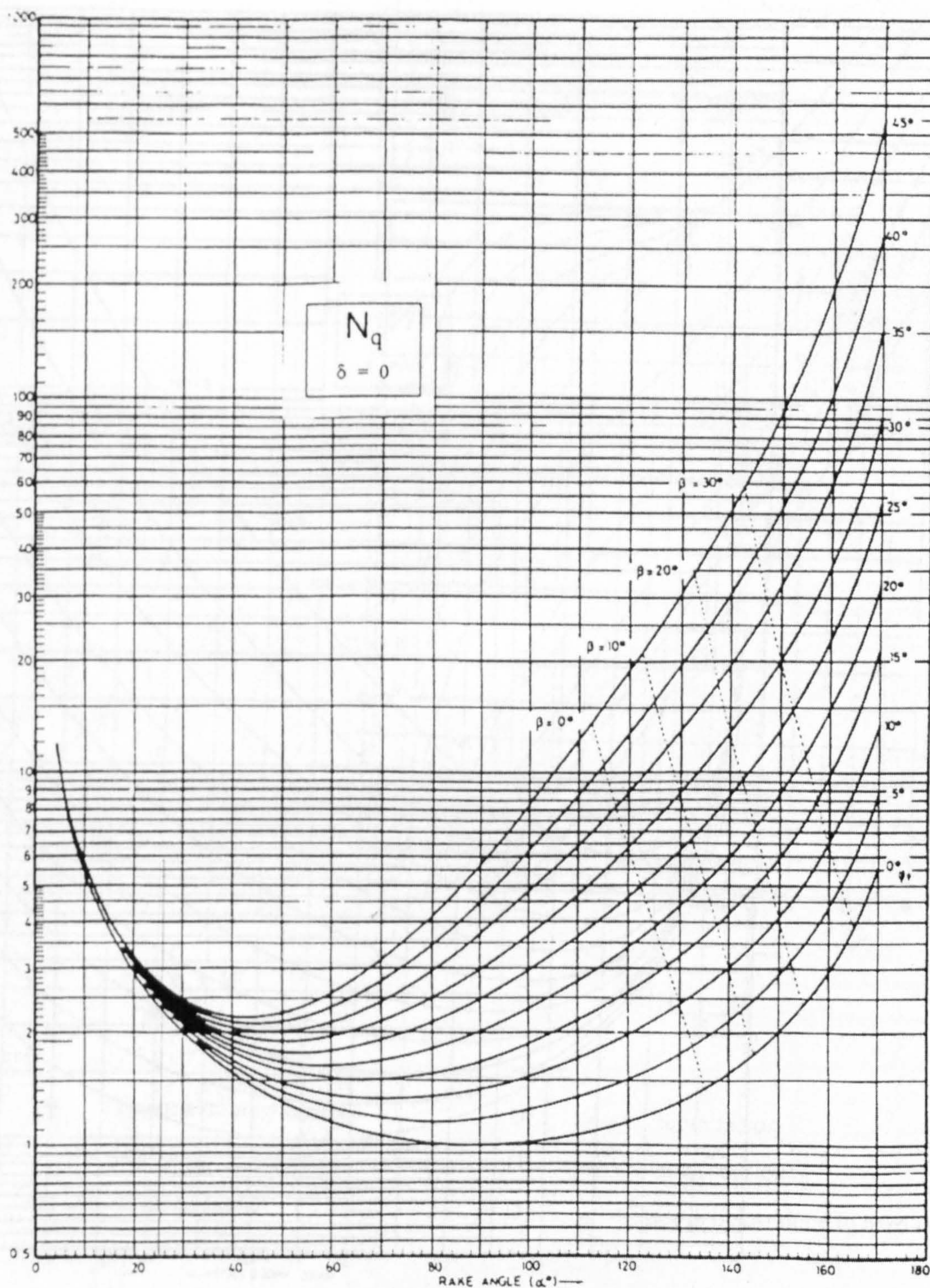
Smooth



Rough



Smooth



Rough

