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Soil Compactability

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SUMMARY.

Subsoiling and deep loosening are widely used to alleviate soil compaction but little is known about the mechanics of the compaction process. Further information is required on the process that soil goes through during compaction, along with the effect on the amount of soil compaction of various tyre configurations. Such information will allow more confident recommendations to farmers on the susceptibility of their soil to compaction.

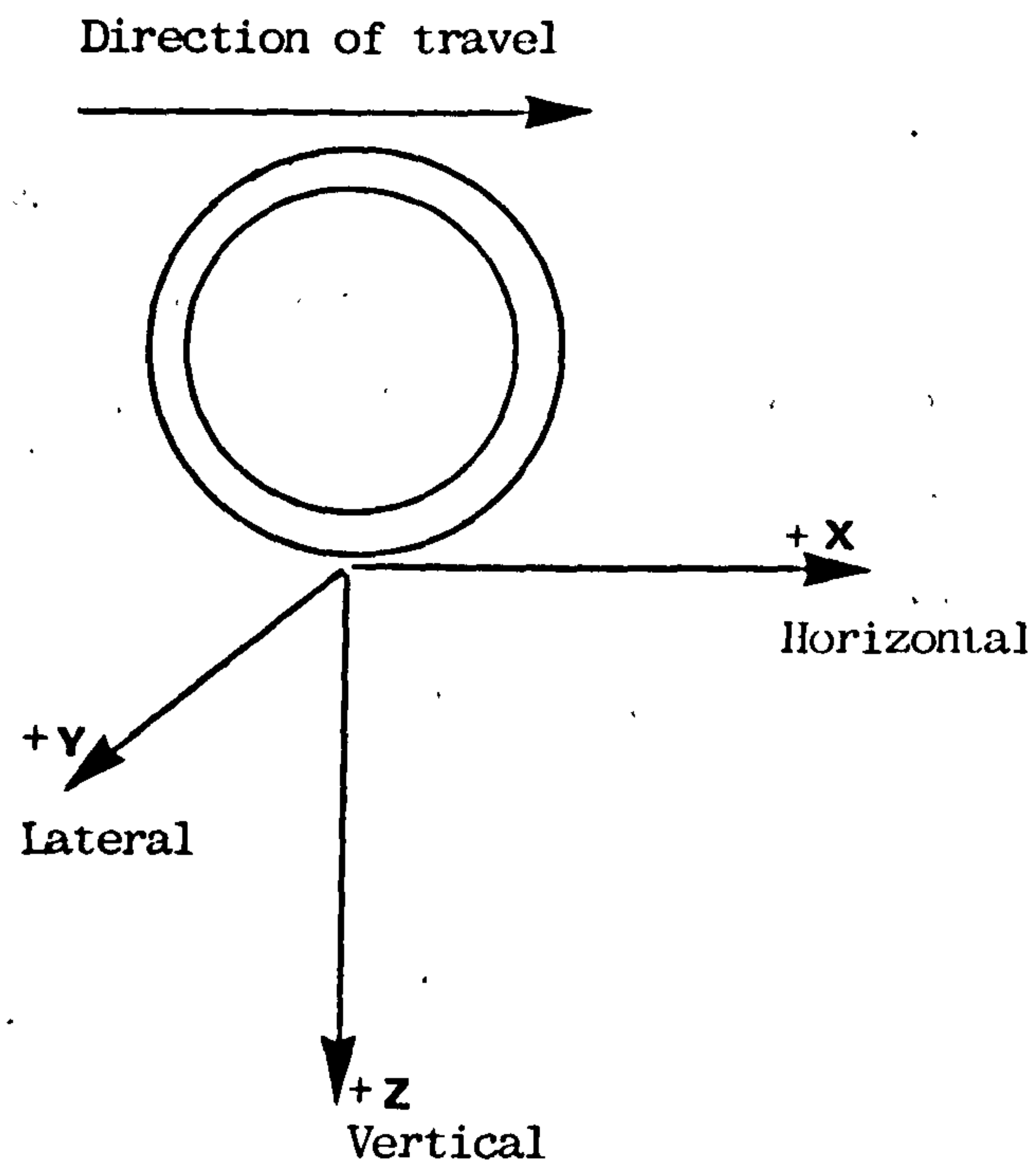
Experimental work was conducted where the soil deformations of a light textured soil were monitored throughout the whole soil mass. The deformations in the soil were caused by a loaded pneumatic tyre on the surface. In the experimental work, both the process of soil compaction and the final state of the soil following the passage of a wheel were monitored. The experiments showed that soil compaction on light textured soils is caused by a punch failure of the soil, therefore most of the compaction is confined to the area directly below the wheel.

The experimental monitoring of soil deformations was a slow and complex process, drawing firm conclusions from the work was further complicated by the interactions of the input variables, such as load and contact length. In order to monitor the effect of individual inputs on soil compaction a three dimensional mathematical model of the process was developed from Theories of Elasticity and a confined compression soil test. The model predicted the subsurface deformations in the three principle directions due to surface loads. Once the model was modified to account for the support capability of the soil it proved it

could, with reasonable accuracy, predict the deformations and hence soil compaction due to a tyre on the soil surface.

The model was used to predict the effect of various tyre configurations on soil compaction. From a number of these runs it was possible to find the sensitivity of soil to compaction due to that input. The results showed that the sensitivity of soil to compaction is not a linear relationship and significant reductions in the amount of soil compacted and the level of the compaction can be achieved by the right tyre configuration.

DEFLECTION NOTATION.



1. INTRODUCTION.

1.1. PROJECT OUTLINE.

Soil compaction is caused by forces acting on the soil. These forces may be applied by wheels, tillage tools and animal traffic or may be due to natural forces such as wetting and drying or freezing. The intended use of the soil determines the required level of soil compaction. If the soil is to be used for crop production the prevention of excessive soil compaction is desirable.

Modern systems of crop production are tending to increase the number of passes, the weight of vehicles and the inflation pressures. This is causing compaction problems to arise especially during the seedbed preparation and harvest of the crop. Experimental evidence has shown that once subsoil compaction has occurred it may persist for many years, often below the depth of subsoilers and deep freezing in winter.

In order to help understand the damage caused to soil by wheels, mathematical models of soil compaction have been developed. These models have by and large been limited to producing a general solution and have been unable to give a specific solution for an individual tyre size and inflation pressure. A soil mechanics model that would give the deformation of soil below the soil surface for an individual case would be a

significant advance on previous models and would provide quantitative data on the levels and amounts of soil compaction caused by different wheel configurations.

1.1.1. OBJECTIVE.

To develop a fundamental understanding of soil behaviour, when it is subjected to externally applied loads.

1.1.2. METHODOLOGY.

The soil compaction process was investigated by monitoring the trajectory, in each of the three principal directions (X,Y,Z), of soil below an externally applied load. Loads were applied to the soil surface by means of small pneumatic tyres, mounted in a frame in the controlled conditions of a soil tank. The design of the mounting frame of the tyre allowed a range of tyre widths and loads to be applied through the tyre to the soil surface. The trajectory of the soil particles was monitored by soil movement detectors placed in a regular grid both below and outside the width of the tyre. The rolling tyre was stopped in the centre of the monitoring region and lifted clear of the soil surface. This technique allowed the process of soil compaction to be studied by analysing the soil undisturbed in front of the tyre and fully compacted soil behind the tyre.

Following the small scale detailed experimental work further full scale tests were conducted in a large soil bin using an agricultural tractor running on smooth grassland tyres towed

along the soil surface. The soil deformations were monitored in a plane across the direction of travel of the tyre, at a range of loads, tyre pressures and soil densities.

The results from the experimental work were used to develop and verify a three dimensional model of the compaction process. The model was able to predict the movement of soil particles in each of the three principal directions below surface loads such as tyres. This three dimensional approach, although significantly increasing the complexity of the model, allowed the effects on soil compaction of tyre geometry to be investigated and could be used to produce a specific solution for a specific tyre configuration and soil condition.

Following the successful development of the model, it was used to develop an understanding of the sensitivity of soil compaction to changes in tyre geometry, pressure and load for a range of soil conditions. The model allowed situations that are difficult to obtain in the field to be investigated and the effect of various input factors on the compactability of soil was assessed. The model helped identify the major factors that influence compaction and the parameters to be changed to effect the greatest reduction in compaction.

1.2. REVIEW OF LITERATURE.

1.2.1. INTRODUCTION

Information about the soil potential deformation under tractor tyres is desirable when selecting a tyre for minimum soil compaction. Much research work has been involved in determining the stress distribution at the soil-wheel interface, see Vanden Berg and Gill (1962). A review of the literature however, reveals very little information on the deformation of soil within the soil mass due to loads on the surface. The few experimental observations of the deformations that have been conducted have been limited to two dimensions, either along the centre line or at right angles to the tyre. As experimental observation is so slow, a number of widely different theoretical approaches have been used to model the soil compaction below tyres. In a review of soil compaction by Soane et al. (1980) the main approaches to modelling were listed from Karafiath and Nowatzki (1978), some as listed below:

(a) Mohr-Coulomb theory has been used to express shear strength as a function of normal stress. This approach has been successful in studies where the soil exhibits slip lines, for compactable soil this type of solution has been unable to successfully predict the compaction.

(b) Classical compression theory based on the experimental observation of a linear relationship between void ratio and the log of the effective stress. Use of effective stress

means that the sum of the mechanical and physical stresses can be used.

Chancellor (1971), Butterfield (1979).

(c) Boussinesq-Sohne theory predicts the stress distribution within an elastic medium when subjected to surface loads. Adjustments are made to the solution to account for different contact areas, surface pressures, and soil stress-strain relationships.

Sohne (1958). /

(d) Bernstein-Bekker theory is based on empirical relationships between contact pressure and sinkage. It is possible to predict a compactive resistance and compactive work done per unit area from these relationships.

Bekker (1976).

(e) Critical state soil mechanics was developed to provide a universal theory of soil response to a wide range of stress situations. It is useful in the study of soil compactability as the stresses can be simplified to hydrostatic and deviatoric stress, the soil response is expressed in terms of specific volume changes. Although critical state mechanics was developed for saturated soils, there is now evidence for its application to unsaturated agricultural soils.

Blackwell (1979), Smith (1984)

Some of the above approaches to the problem can be divided into two basic methods for modelling soil deformation under wheels:-

(a) Empirical models: A simplified expression of the major factors affecting the compression process is developed from a large quantity of field data, the regression is then used to predict further situations.

Freitag (1965), Eriksson et al. (1974).

(b) Soil mechanics models: A combination of soil mechanics principles and numerical techniques, such as Finite Element Analysis, Yong et al. (1978) or Theories of Elasticity. Sohne (1953) developed equations that could predict the stress within the body of a soil mass when subjected to surface loads. The deflection of a soil element to the stress condition could be predicted by the use of the soil's stress-strain relationship.

Empirical models can, in the right circumstances provide an adequate solution to the soil compaction problem. They do however suffer from the major drawback of needing large amounts of data to be collected to provide an accurate solution. The time-consuming nature of the data collection makes this method of prediction unsuitable. Soil mechanics models, although significantly more complex than the above methods, can provide a means of modelling the complexity of soil compaction and can

help in the understanding of the soil compaction process. The following review of literature will concentrate on the models of soil compaction based on soil mechanics principles. The two major numerical methods used in soil compaction research are Theories of Elasticity and Finite Element Methods.

1.2.2. FINITE ELEMENT METHODS.

Perumpral et al. (1971) used Finite Element Analysis to predict the deformation of soil below the centre line of a tyre. The model took account of the non-linear stress-strain characteristics of soil. The basic concept of Finite Elements is that soil is an idealized continuum of a finite number of small elements, figure (1.1), connected together by a number of nodal points.

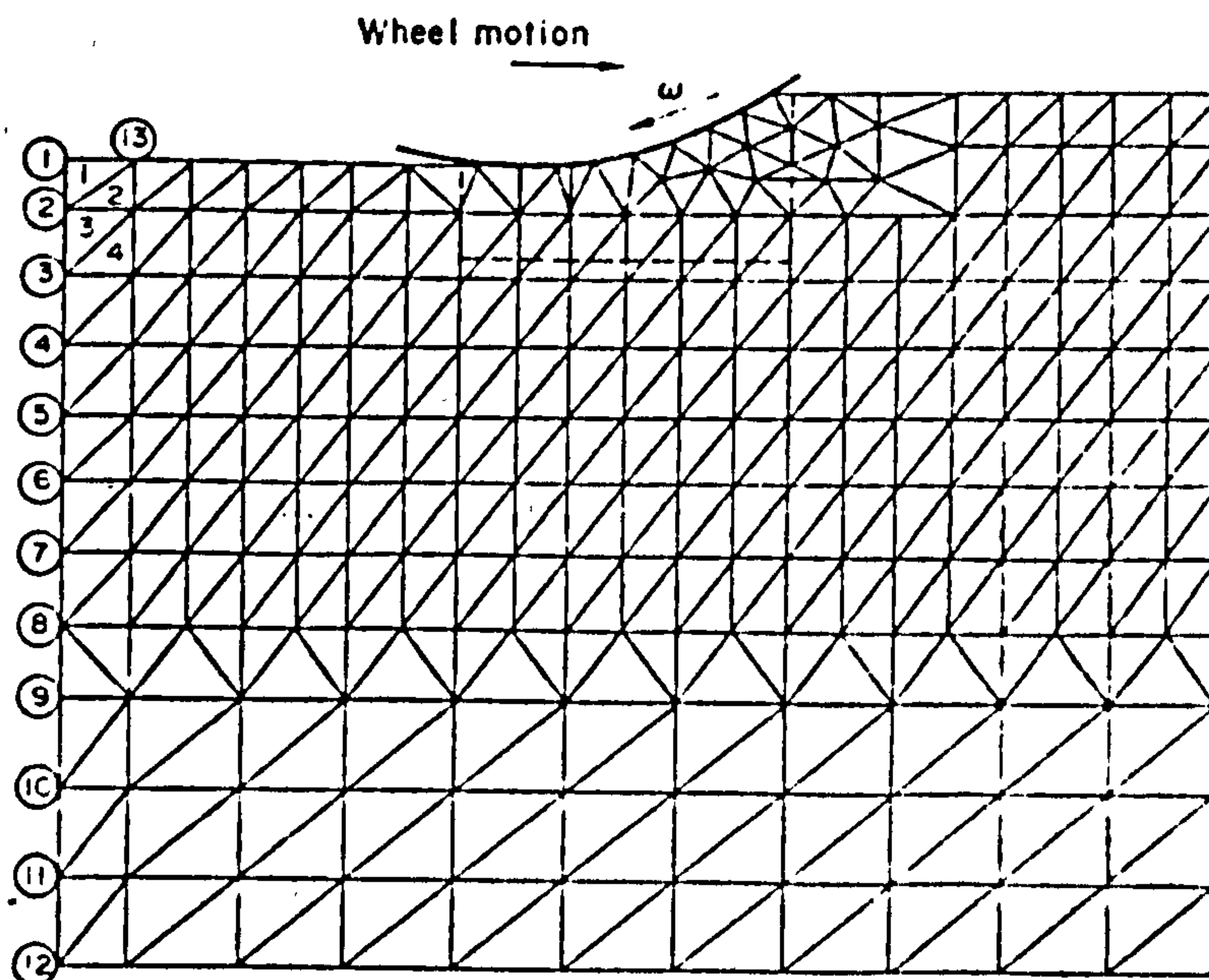


Figure 1.1. Finite elements.

The behaviour of the whole soil mass is predicted by

approximating the behaviour of these small soil elements expressed in the form of equilibrium equations in terms of the unknown deflections. In this study a rigid wheel was modelled as a circular area using radial and tangential stresses taken from the work of Onafeko and Reece (1967). The model developed predicted the deflection along the centre line of the tyre but no attempt was made to compare the solution with any experimental results. Other experimentors have extended the above method to take account of the elastic recovery of soil as the load is removed, see Chung and Lee (1975). Further improvements to the solution were made by Yong et al. (1978) to take account of the effect of a pneumatic tyre on the soil surface. Finite Elements have also been used to predict the performance and effect of crawler tracks, see Karafiath (1984) and Wong (1984). The method allows the complex non-linear properties of soil to be modelled and the effect of them on the performance of the vehicle assessed.

1.2.3. SOIL ELASTICITY METHODS.

Much of the early work on the use of Elasticity to predict the stresses in a soil and hence the compaction was conducted by Sohne (1953). He developed a method of calculating the pressure distribution in a soil using equations developed by Boussinesq (1885). The equations are only strictly valid for a soil that is isotropic and obeys Hookes law, but making these assumptions good agreement between measured and predicted has been found.

In the vertical point method, Sohne (1953), figure (1.2), it is assumed the tyre can be simplified to a single point load resting on the surface of a semi-infinite soil mass.

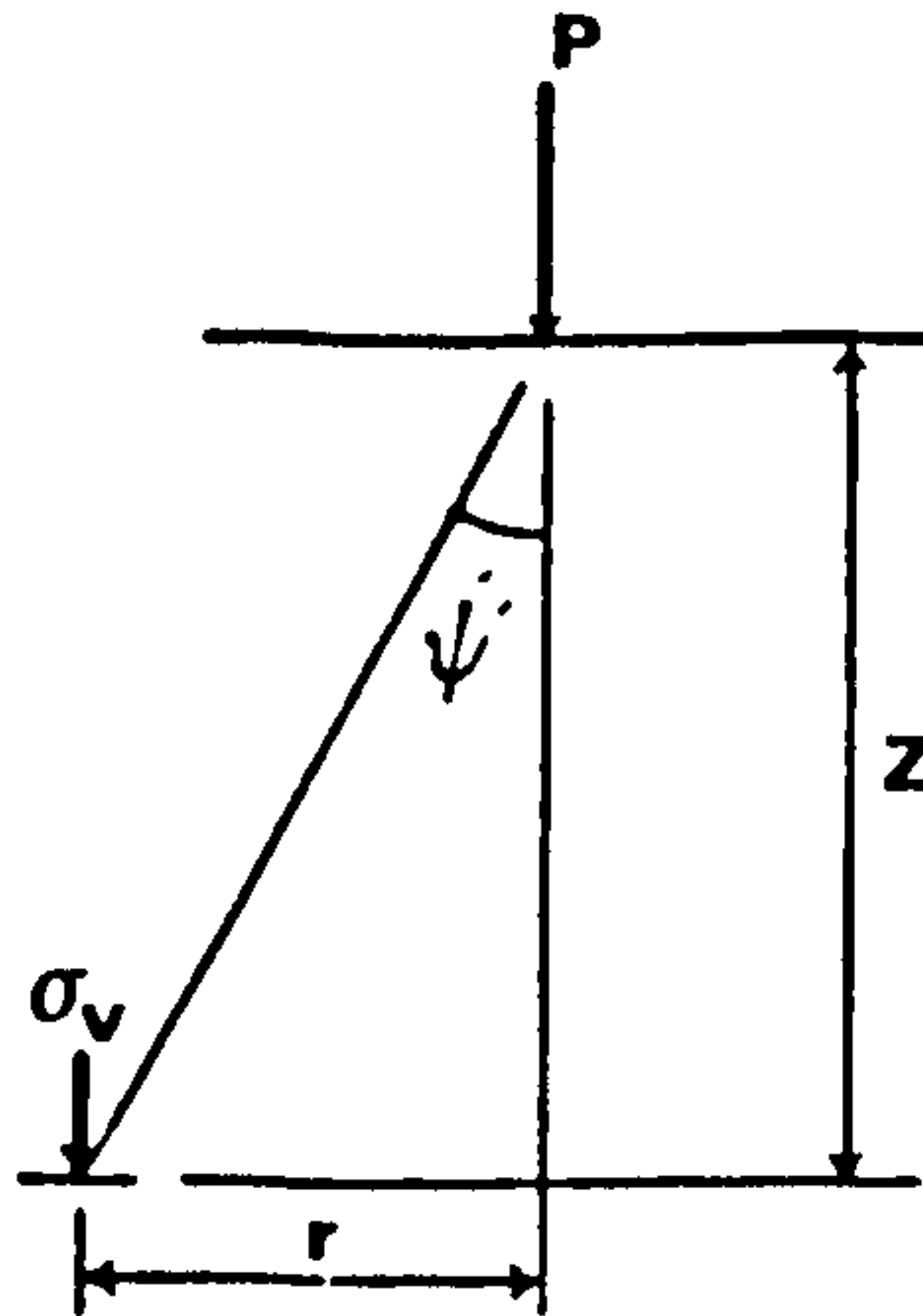


Figure 1.2. Vertical point method.

The vertical stress at any point in the soil is given by:-

$$\sigma_v = \frac{3P}{2\pi z^2} \left[\frac{1}{1 + \left(\frac{r}{z}\right)^2} \right]^{3/2} \quad \text{OR} \quad \sigma_v = \frac{3P}{2\pi z^2} \cos^3 \psi$$

This very simple solution suffers from several drawbacks:

- i) As the radial distance of the solution decreases the value of stress tends towards infinity.
- ii) No account is taken of the size of the contact area.
- iii) No account is taken of the effect of soil strength on the stress distribution.

Bowen (1975) developed a correction factor to try to eliminate the infinity at the soil surface, these factors increased from zero at the soil surface to unity at a depth equal to half the width of the tyre.

Due to the assumption of elastic soil behaviour, the vertical point method predicts the same stress distribution for all soils. It is known, however, that soil strength influences the stress distribution. To account for this, the above formula was:

modified using a concentration factor (ν) developed by Frohlich (1934), the modified formula taking the form:

$$\sigma_v = \frac{\nu P}{2\pi z^2} \cos^{\nu-2} \theta.$$

The concentration factor increases as soil becomes softer. The reason for calling it a concentration factor can be seen in figure (1.3), which shows isobars of constant stress and Frohlich's values for the concentration factor.

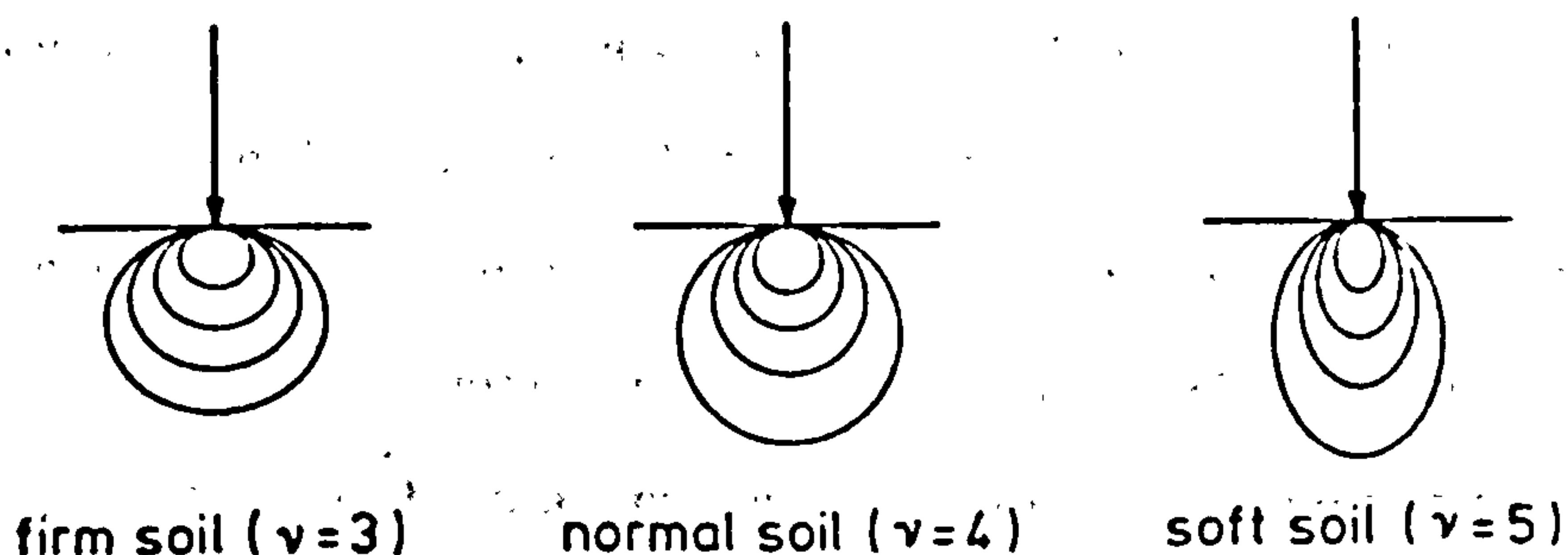


Figure 1.3. Isobars using three concentration factors.

It is clear that the stresses are more concentrated under the load and extend to greater depth in the soil as the concentration factor increases. For models predicting the stresses using concentration factors selection of the appropriate factor influences the accuracy of the predictions. Work has continued on concentration factors with the arbitrary whole number values of Frohlich being replaced by continuously variable factors, see Ram (1984). Ram showed that the concentration factor increased with depth and reported that for a sandy soil the concentration factor increased from 3.28 to 5.84. Research continues on using concentration factors in

conjunction with Elastic equations, though concentration factors have no fundamental base in Elasticity.

A further refinement to the point load method was to include some measure of width of the contact patch, Sohne (1953). To do this the contact between tyre and soil was described by an evenly loaded infinitely long strip, the width of the strip being equal to the section width of the tyre. The tyre contact patch have also been modelled as circular and elliptical areas equal to the contact area of the tyre, see Carpenter and Fausey (1983) and Kline and Perumpral (1984). The contact area supports a uniformly distributed stress equal to the mean normal stress at the tyre-soil interface. A more advanced method of calculation is a summation procedure developed by Sohne (1953), figure (1.4), which is a numerical procedure of summing a large number of point loads, this yields a specific solution depending on the tyre size, inflation pressure, load and soil type.

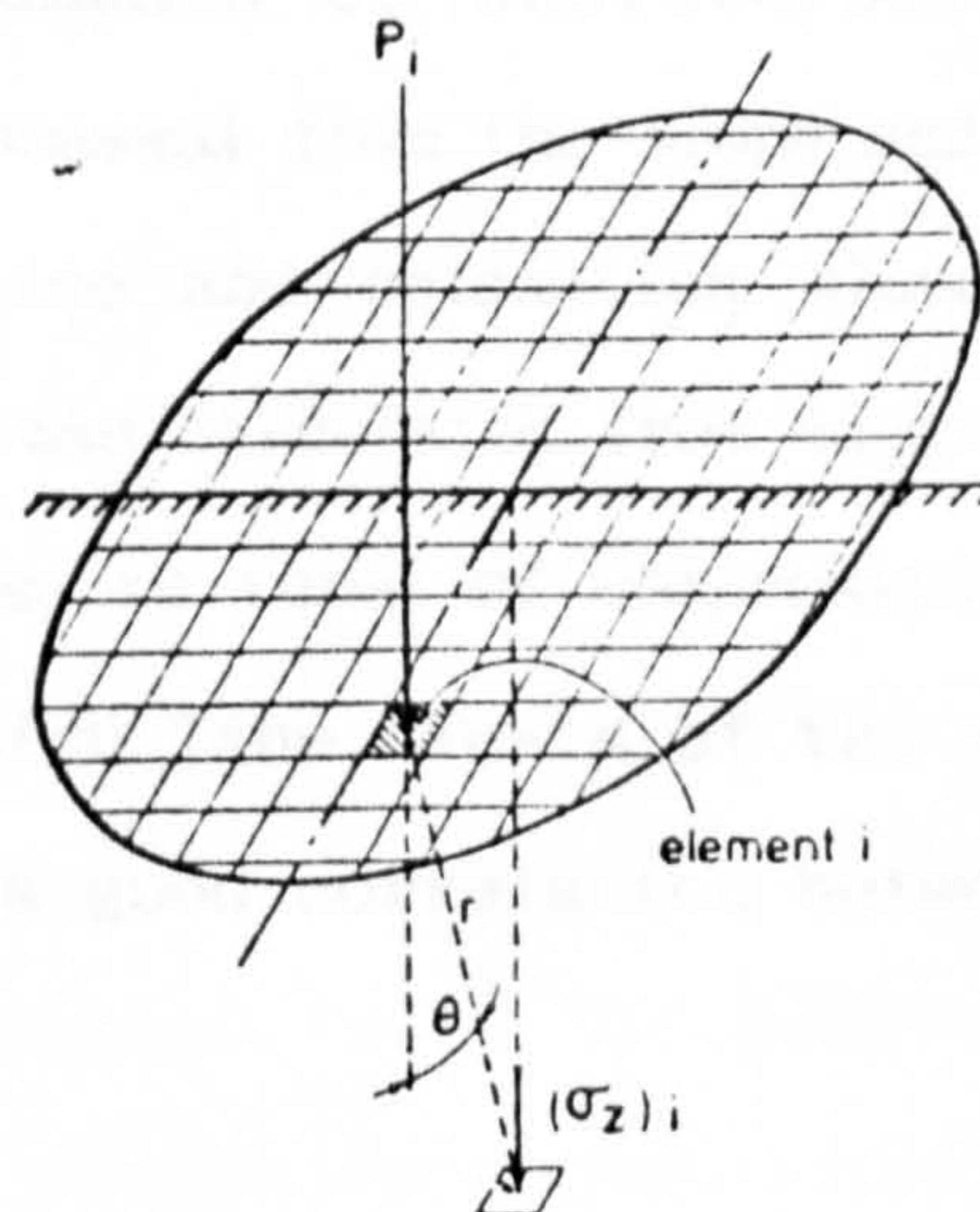


Figure 1.4. Sohne's summation procedure.

The Bousinesq equations have also been used to predict the stress below tracks, Fujii et al. (1984). It was found that the predicted values were smaller than the measured values, the discrepancy was thought to be due to load transfer between track shoes.

From the stress in the soil the volumetric strain can be calculated using logarithmic relationships such as:

$$\text{Pore Space} = -A \cdot \log(\text{stress}) + B \quad \text{Sohne (1953)}$$

$$\text{Bulk Density} = C \cdot \log(\text{stress}) + K \quad \text{Bertilsson (1971)}$$

Where A, B, C and K are soil constants. Bailey et al. (1985), using the same form of equation found that by using six coefficients they could predict the bulk density of soil after a known stress had been applied and removed.

Blackwell (1979) and Smith (1984), developed models on the basis of Critical State Soil Mechanics and Elasticity. Measurements of soil compactability were found from in-situ and laboratory measurements of undisturbed soil samples. Compactability was assessed from the slope and intercept of the virgin compression line and relaxation slopes. The predicted stress of an element was calculated from equations developed by Sohne and the response in terms of compression calculated from the virgin compression line. Tests of the model in a field situation revealed a good correlation between measured and predicted values.

1.3. DISCUSSION.

Some of the models of soil compaction discussed here have given

a two dimensional solution, either the compaction for a line along the centre line of the tyre or at right angles to the direction of travel. The solutions of these models are general cases and are not able to predict the effect to a specific tyre configuration. Improvements in the prediction of soil compaction have been achieved by working in three dimensions thus allowing the contact of the tyre to have finite values of length, width, contact pressure and load distribution which allows individual tyre configurations to be modelled. However the extra flexibility of this form of model means a significant increase in the complexity. Three dimensional models can predict the deformations in the horizontal and lateral directions and allow not only vertical but horizontal and lateral loads to be applied in complex distributions on the soil surface. The solutions of such models show the depth and width of soil compaction over the whole volume of soil disturbed.

It is possible to use either of the two major mathematical methods, Finite Element Methods and Elastic Theory, as the base of a model. Much of the Finite Element work conducted in compaction research has been done using commercial software packages which limits the flexibility of the model. Elastic Theory provides a simple route for improvement and it is possible to not only predict the stress induced in a soil but by using two material properties, Young's Modulus and Poisson's Ratio, it is possible to predict the strain and deflection.

Equations are available that will give the X,Y and Z deflections at any point in a material due to a load on the surface.

1.4. DETAILED OBJECTIVES.

The project falls into the following three parts:

- 1) Determination of the actual deflections in the soil under a wide range of loading and soil conditions.
- 2) Development of a three dimensional mathematical model based on Elasticity Theory to predict the deflections.
- 3) Validation of the Theory and use of the model to identify the major factors influencing the deflections and hence compaction and determine the sensitivity of compaction to changes in these factors.

2. EXPERIMENTAL INVESTIGATION INTO SOIL DEFORMATION BELOW TYRES.

2.1. INTRODUCTION.

It is possible to monitor the effect of surface loads by assessing either the stress or the strain induced in the soil at depth. Both of these methods are very slow due to the necessary insertion of sensors. Some major problems exist with stress sensors because of the importance of getting good contact between the soil and the measuring device. The device should also be able to monitor the three perpendicular stresses, this is further complicated by the change in orientation of the device as the soil compacts. This tends to make stress detectors quite large and expensive. Strain detectors can also be large and complex but they can be very cheap and adaptable. A detector can be as simple as a marker, the strain being calculated by its change in position. If the markers are placed in a regular grid pattern the volume change and hence the compaction of the elemental cube can be calculated. The main drawback of the system is the time-consuming nature of placing and measuring the individual markers. This has meant that only a small amount of experimental data on the deflection of soil particles below tyres is available, with little information on the extent to which the deflections extend outside the contact area of the tyre. In order to verify a mathematical model of the compaction process it is important to conduct detailed experimental work into the deflection of the soil both at the soil-tyre interface and to a depth in the soil greater than the disturbance extends.

The monitoring of soil deformations was conducted in the controlled environment of a soil tank. Preliminary studies to find the mode and extent of soil failure were conducted in a small tank with small wheels, about quarter scale. These tests monitored the process the soil goes through during compaction and the final compacted state after the passage of a wheel. Further investigations were conducted using a full size tractor in a larger scale soil tank to provide data on the effect of scale and for the verification of the mathematical model of the process. These investigations were conducted using a light textured sandy loam soil. To keep the analysis of the problem as simple as possible, the wheels used were pneumatic tyres with very little tread pattern and towed across the surface so as to induce as little shear in the soil at the surface as possible.

2.2. EXPERIMENTAL TECHNIQUE AND APPARATUS.

2.2.1. SOIL DEFORMATION MONITORING.

The accurate measurement of strain throughout a soil body is very time-consuming. A technique was required that was precise and able to cover, in three dimensions, a large volume of soil. The device should not cause the soil to fail in a different manner due to its presence. Several devices and techniques have been used by other experimenters:-

Gliemeroth (1953), dug a trench parallel to the centre line of

a tyre and exposed the soil in a small area. The movement of the soil was filmed using a camera. His apparatus and results are shown in figure (2.1).

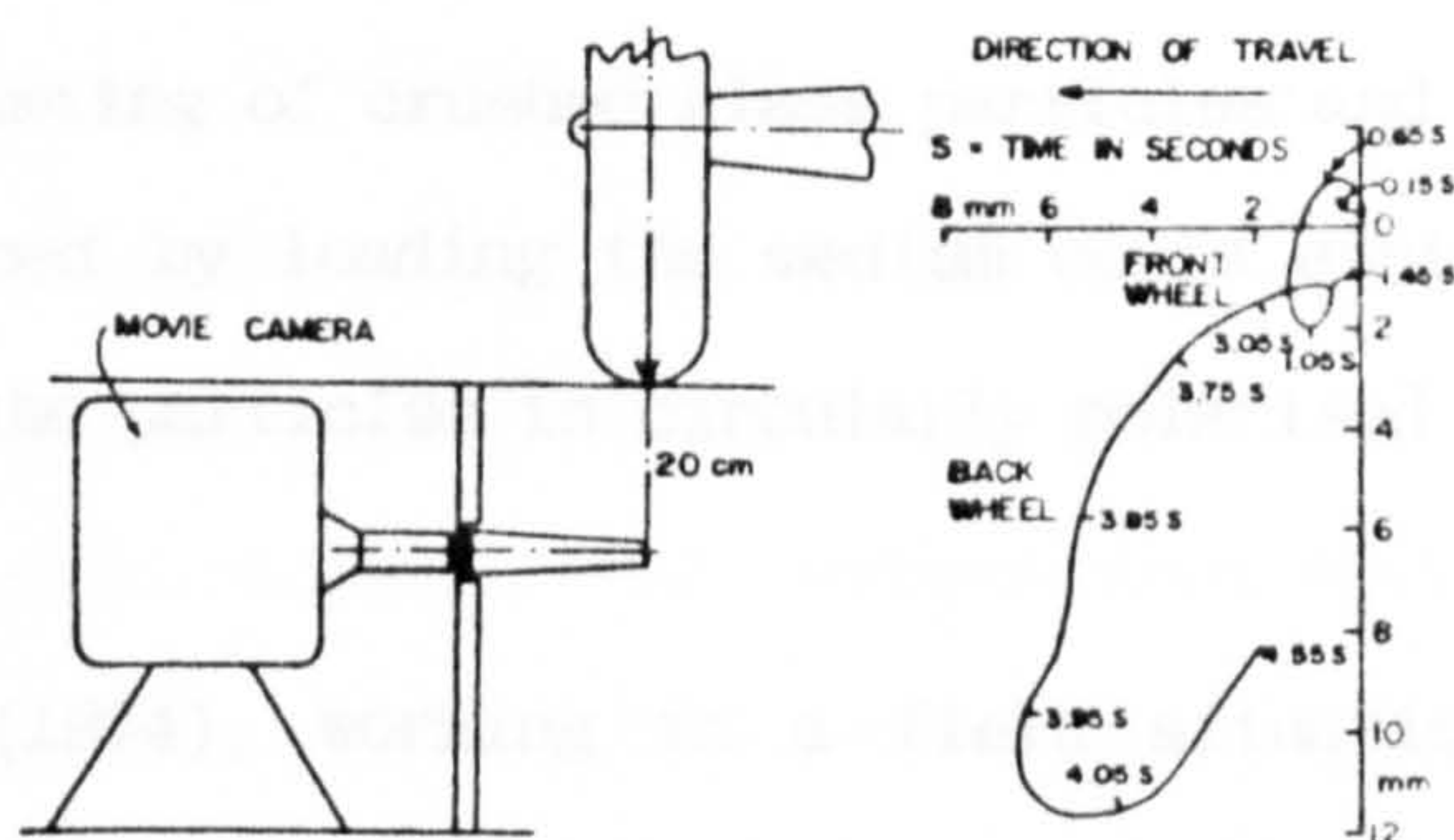


Figure 2.1 Gliemerths equipment and results.

This type of approach is useful for the dynamic monitoring of a single point, but cannot be extended to cover a larger area of soil.

Roscoe et al. (1963), described a method of determining the incremental strain throughout a soil volume when deformed under conditions of plane strain, ie. 2 dimensional strain. The strains were calculated from the displacement of lead shot placed in a grid pattern in the soil. The displacements were measured by placing an X-ray source in front of the soil and X-ray sensitive film behind the soil. The movement of the shot produces shadows on the film, which when corrected for the distance from the X-ray source, give a good measure of the strain. This approach is limited to working in 2 dimensions as the overlapping X-ray shadows of several planes of beads at

once would be impossible to analyse.

Drescher (1976) adopted the approach of substituting another material for the soil, he used an optically sensitive granular medium consisting of crushed glass particles and oil. The plane strain induced by loading the medium could easily be observed by viewing the particles in circularly polarised light.

Danfors (1974), working in a field situation, used large elevation markers buried in the soil and measured their deflection in relation to a datum at the surface. These markers were quite large and had to be placed well away from each other so as not to distort the failure pattern.

Nichols and Randolph (1925) used foil strip markers, others have used coloured sand, gypsum and coal dust. These markers were placed in lines or grid patterns depending on the type of failure to be observed. This type of monitoring gives a visual display of the movement, but accurate measurements of the displacement of individual points are difficult to make.

Gill (1968), measured soil displacement by embedding small beads in the soil in a regular grid pattern using a template. After placement of the beads their position was marked with a coloured pen on a sheet of transparent plastic laid over the top. After the soil had been deformed the process was repeated again and marked on the sheet with a different colour.

Most investigations of strain have been carried out in small areas or 2 dimensions. The distribution over larger areas has not been well investigated because of the difficulty in finding a suitable technique. The technique used in this study was an expansion, into three dimensions, of the method used by Spoor and Fry (1983). A large number of markers were buried in the soil in a regular grid pattern. The markers used were small plastic beads about 5mm in diameter, these were large enough to be easily detectable yet not so large as to cause a change in the soil failure pattern. The beads were buried in layers, in a regular grid pattern, starting at the centre line of the tyre to a point 5 times as wide as the width of the tyre and down to a depth of 5 times the width of the tyre. Beads were only placed over half the area that may be disturbed by the tyre to keep to a minimum the number of beads used. This was possible because of the symmetrical failure of the soil about the centre line of the tyre. If the start and final position of the individual beads is known the deformation and strain induced in the soil at that point can be found.

The soil tank to be used for the small scale study was 0.47m wide by 1.5m long by 0.3m deep. To speed up the monitoring of the movement of the beads, a frame was constructed that ran on two rails on the top of the soil tank, figure (2.2).

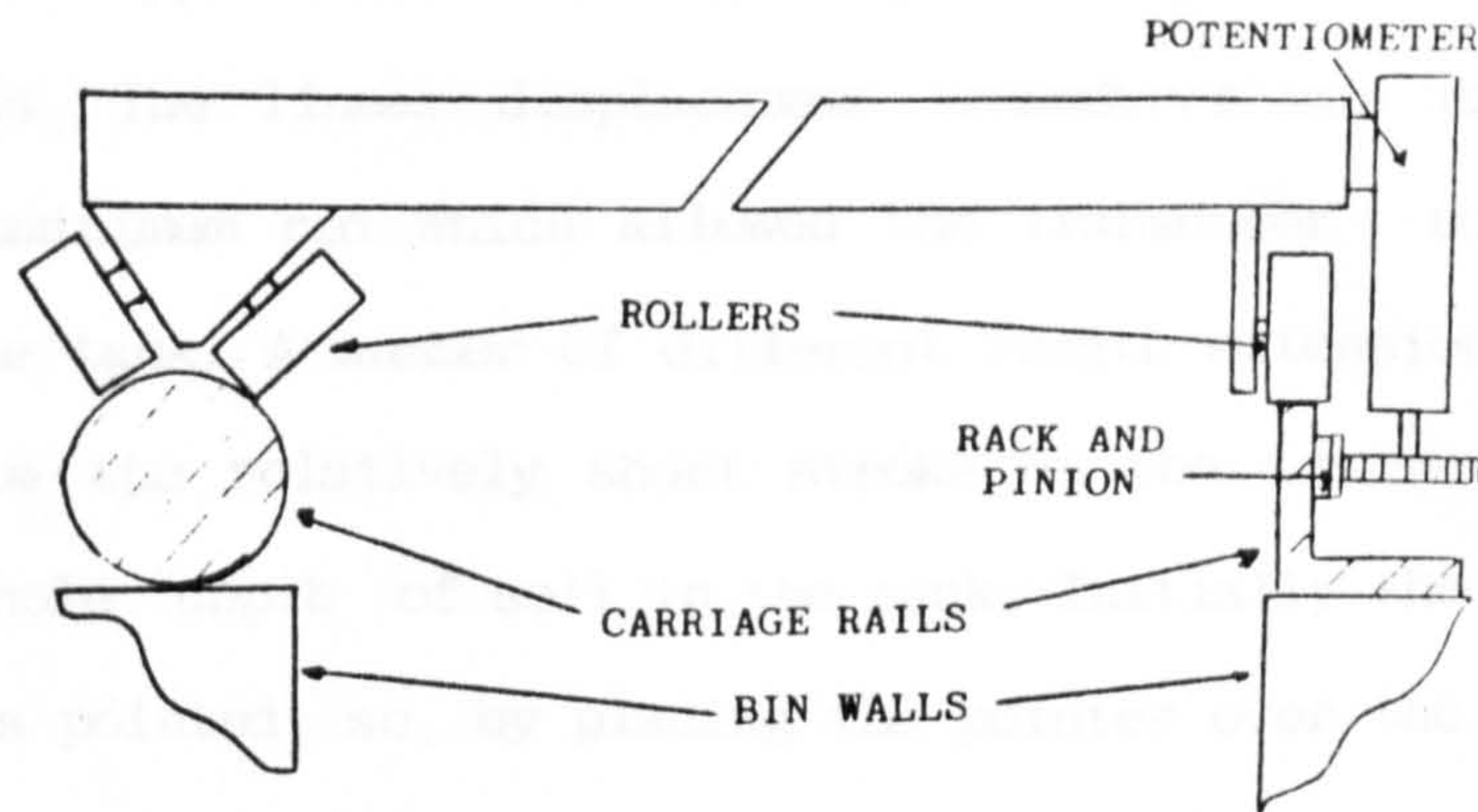


Figure 2.2 Lower measuring carriage support frame.

The two rails, one round, the other angular, ran the whole length of the tank, the circular rail acted as a self-centering device for the rollers that supported the frame. Fixed to the right angled rail was a rack gear, that ran the whole length of the bin, the pinion was mounted on the frame itself. The drive from the pinion was connected directly to a linear 10 turn potentiometer, the size of this gear wheel was chosen so as to allow approximately 8 turns of the potentiometer to cover the whole length of the tank. The potentiometer was energised with a small voltage, so that as the frame was moved along the tank the output of the potentiometer changed in direct relation to its position. The two sides of this lower frame were in turn held together by a round and angular rail at right angles to the lower pair. The upper set of rails was a smaller version of the lower and used to measure the distance across the tank. The gear size was again selected so as to allow approximately 8 turns to cover the whole width of the tank. A linear displacement transducer was

mounted on the upper frame for measuring the vertical deflection of the beads. The linear displacement transducer was extended using an aluminum rod which allowed the transducer to probe down into the tank. A number of different length extensions were made to allow the relatively short stroke of the transducer to cover the whole depth of soil in the tank. Initially the end of the probe was pointed, so, by placing the pointer over the top of the bead the X, Y and Z co-ordinates from the reference point in the bin could be found. Tests were conducted with the pointer where a single bead was measured repeatedly, this produced a variation in the X and Y co-ordinates of 1 to 2 mm, the Z co-ordinate was within 1/2mm. This variation was due to the difficulty in exactly placing the pointer over the top of the bead. By hollowing out the end of the extension to fit exactly over a bead, it was found the position of the bead could be measured to 1/2 mm precision in all three directions. The outputs of the three position transducers, an electric voltage between 0 and 2 volts, was fed into a scanning datalogger. The logger was operated by a hand held trigger, this was fired once the frame had been manually placed over the bead to be measured. Once fired the 3 transducer voltages were punched onto paper tape. When the run was completed the paper tape could be read into a main frame computer and converted from a voltage into a distance from the origin using the calibration coefficient.

2.2.2. SOIL PREPARATION.

For accurate experimental work it is essential that the initial

soil density is constant throughout the soil and the lower layers of soil are dense enough to support the upper layers of soil without deformation. The soil used for all the experiments was kept at 10% moisture content (dry basis) for ease of handling. To prepare the soil in the tank it was first levelled with a scraper and firmed down with a wooden block. The soil was then rolled with a 0.3 m dia. roller which had the same width as the soil tank. The roller weighed 30 kg, but by the addition of 20 kg weights and variations in the number of passes over the soil, the initial density of the soil could be varied. The initial gentle pressing of the soil with the wooden block stopped large soil movements for the first pass of the roller. Once the soil was at the required density for the test, a plastic template was placed on top and accurately positioned using guides located in the side of the tank. The template was accurately drilled with holes in a regular grid pattern, at 25mm spacing, the holes being just large enough to allow a bead to be pushed through. Each bead was then pushed through the template into the soil to a depth so that the top of the bead was level with the top of the soil. This technique stopped the beads from being displaced during the placing of the soil for the next layer. The measuring frame was set to zero at an origin mark in the end of the bin, then the X,Y,Z positions of each bead relative to the origin logged. The next layer of soil was then placed in the tank and levelled off at a depth so that when compressed to the required density would give the correct depth of soil (25mm). The bead placement process was then repeated. It was found that at soil densities below 1.2g/ml, the

weight of the upper layers of soil would compress the layers below and the logged positions of the beads would change. This problem was overcome by not using soil densities below 1.2g/ml. After a test had been conducted the soil layers were removed with a brush to expose the beads and their new position logged.

2.2.3. WHEEL LOAD TROLLEY DESIGN.

A load trolley for the tyre was designed so a constant load could be applied to the tyre no matter what the deflection of the soil. This trolley was fixed to a headstock that could be powered along the bin at various speeds. The system used is shown in figure (2.3).

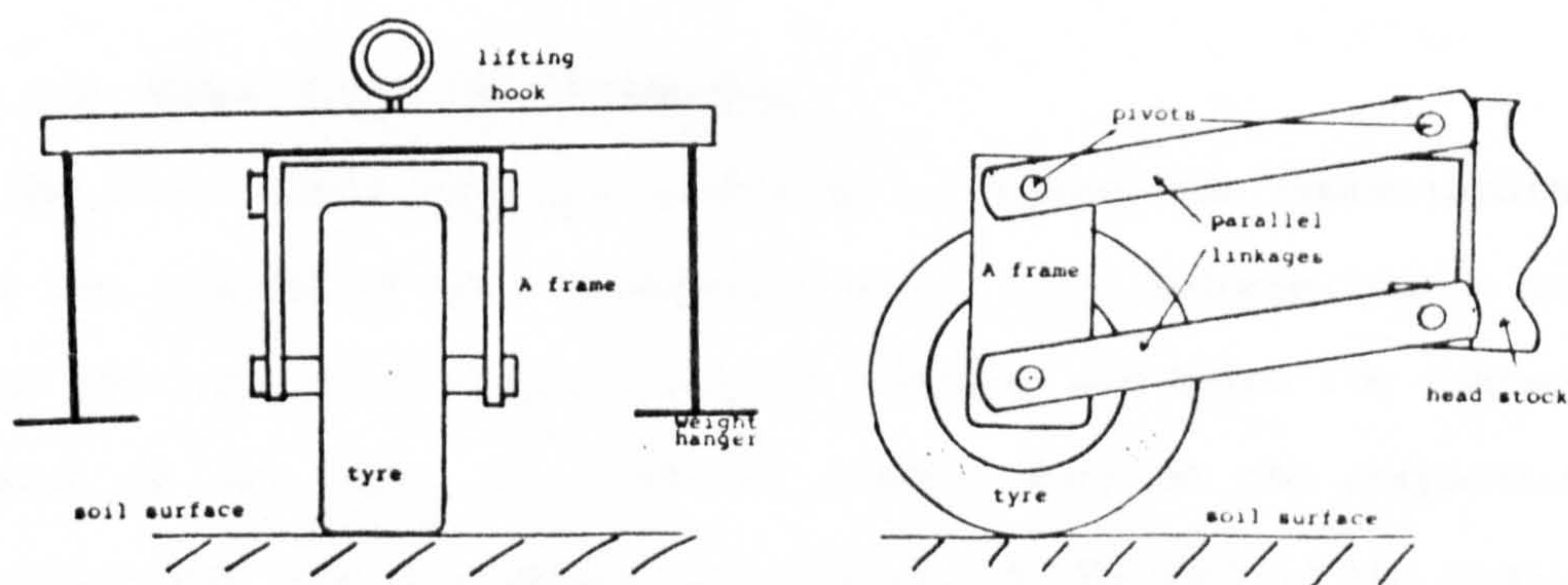


Figure 2.3. Load trolley design.

The two tyre widths to be used fitted a common axle in the frame. The load was applied to the tyre by the addition of 20 kg. weights to both sides of the trolley.

2.3. EXPERIMENTAL INVESTIGATIONS.

2.3.1. INTRODUCTION.

The experimental work was conducted as two investigations:

1) Small scale work using 0.40 m diameter tyres with widths of 100 and 50 mm. These investigations were conducted to monitor the mode and process of soil failure below tyres.

2) Full scale work using a 1.1 m diameter tyre with a width of 275 mm. These investigations were conducted to verify the findings of the small scale work and provide data for the verification of the mathematical model.

2.3.2. SMALL SCALE INVESTIGATIONS.

The small scale work was conducted to improve the understanding of the process of soil compaction and to give information on how far the soil deformations extended sideways and below the contact patch of the tyre. In order to conduct work on the compaction process the tyre was stopped and lifted off the soil in the middle of the measurement area. This left beads in front of the wheel that had not been disturbed, beads below the wheel that were going through the process of compacting and beads that were behind the wheel that had been fully compacted and were in their final position. This method of monitoring allowed the process and the final condition of the beads to be observed.

The work was conducted over a range of conditions of inflation pressure, initial soil density and contact width. Some of the conditions were difficult to monitor, eg at a very low inflation pressure and high soil densities the soil deflections were too small to be measured. Both tyres used had very low ply ratings of 2 and carried a constant load of 180 kg.

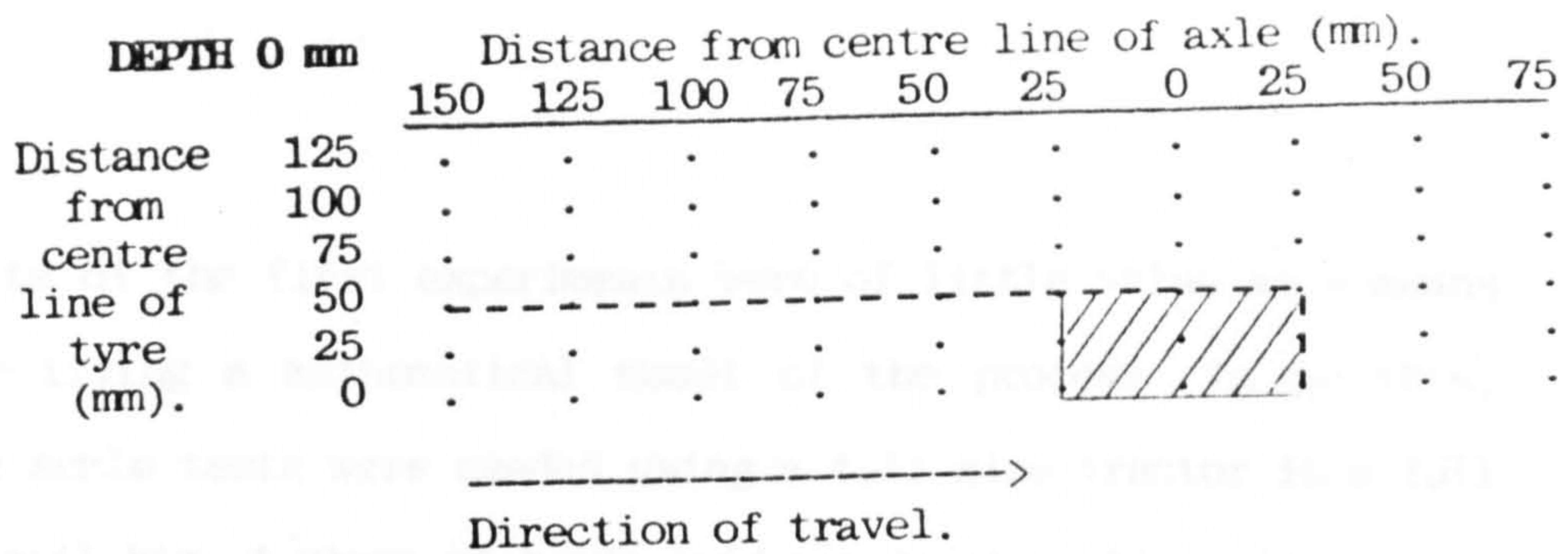
The following runs were conducted:-

Run number.	Inflation pressure. kN/m ²	Initial soil density. g/ml	Tyre width. mm
1	345	1.2	100
2	345	1.3	100
3	207	1.2	100
4	207	1.3	100
5	207	1.2	50

The forward speed of the wheel was kept at a constant 20 mm/s in order to reduce the effect of inertia on the deflections.

2.3.3. RESULTS.

The results of the experimental work are given in Appendix (2.1). The method of identifying the position of a bead with respect to the tyre is shown in figure (2.4), where the bead at 0 0 is on the centre line of the tyre at the point where the centre of the axle was stopped and lifted off the soil surface.



The dotted line shows the path of the tyre and the shaded area shows the position of the tyre when stopped.

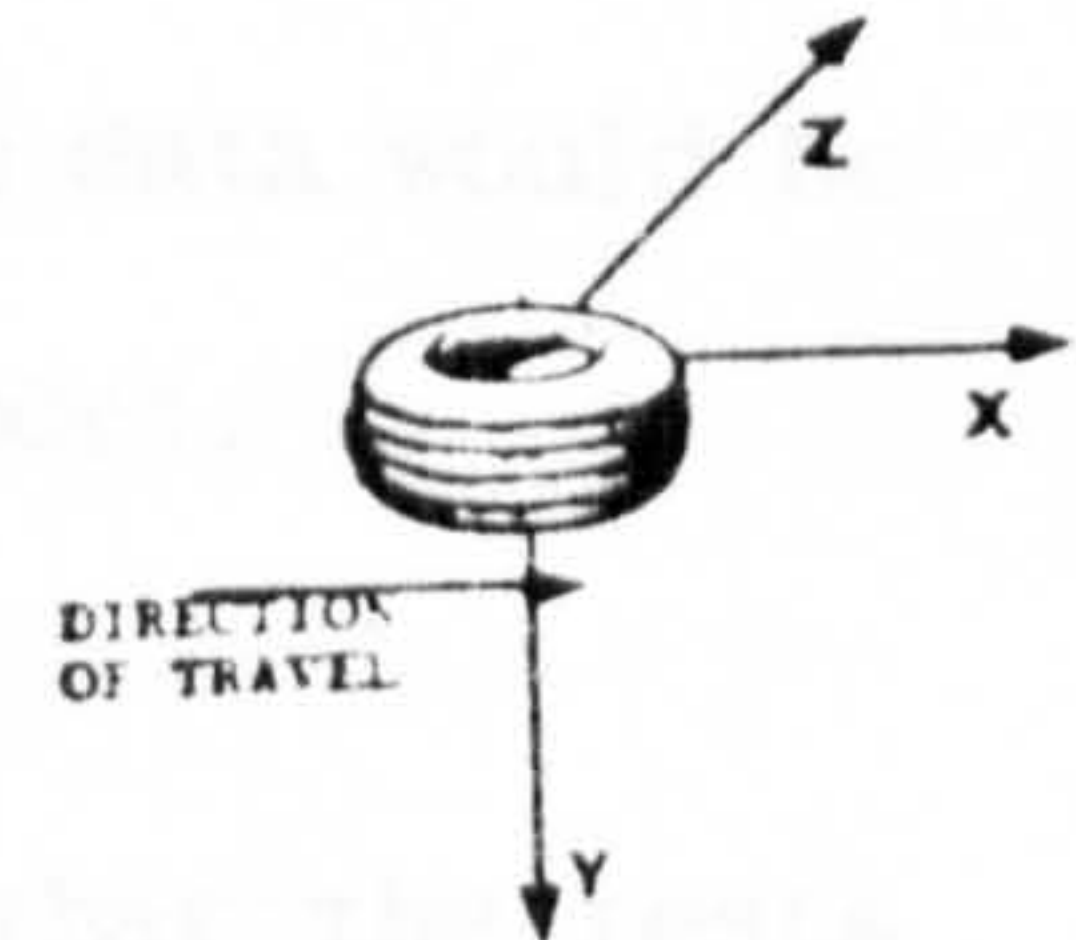


Figure 2.4 Small scale bead identification system.

On the figure the direction of positive deflection is shown by the direction of the arrow heads. The results of the investigation are given as the deflections of each point, in the 3 mutually perpendicular directions, of each layer in plan view. The results presented only cover a small part of the actual area of soil monitored. The grid size used was 25 mm for a grid of 30 beads long by 10 beads wide by 10 beads deep. Also shown in the results are the percentage volume changes of the elemental cubes, calculated from the deflection of the corners of the cubes, a positive volume change implies an increase in volume ie dilation. From the % volume change it is possible to find the actual soil density. It is difficult, however to see the pattern of soil compaction using the density values so the results are left as % volume changes. All the results are rounded to the nearest mm.

2.3.4. FULL SCALE DEFORMATION MEASUREMENT.

The inaccuracy caused by working on a small scale meant that the

results of the first experiments were of little value as a means of verifying a mathematical model of the process. To do this, large scale tests were needed using a full size tractor in a full size soil bin. A plane of beads laid across at right angles to the direction of travel of the wheel would provide data on the final state of the soil after the passage of a tyre. This data would be sufficient for the purpose of verification of the model.

The type of tractor used, a Leyland Mini, meant that the tests would have to be carried out in a larger soil bin, approximately 15m long by 1.8m wide with a soil depth of 0.5m. The tests were carried out using only one wheel of the tractor, this wheel ran in the soil bin whilst the other ran on an elevated runway beside the bin, figure (2.5).

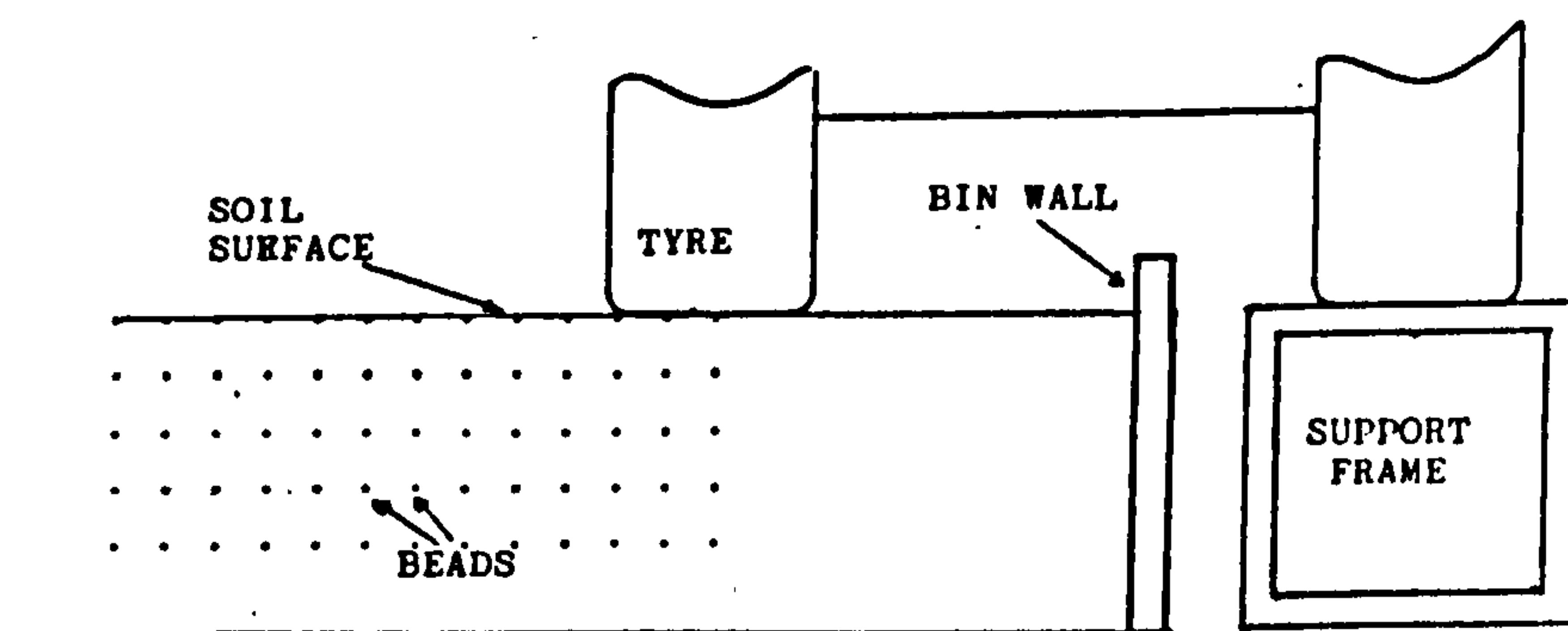


Figure 2.5 Full scale tractor test arrangement.

The front axle of the tractor was modified so that it was supported by only one wheel, running outside the bin. To reduce

the shearing induced in the soil by the tyre, the tractor was winched along the tank. The load on the axle and the inflation pressure in the tyre could be altered to give a range of experimental conditions. The displacement beads were placed in the bin at 50mm. spacing; to reduce the number of beads, only half the disturbed soil width was covered. To obtain more precise results 5 complete planes of beads were placed at 50mm spacing in the direction of travel, the deflection of these were averaged to give a more accurate result. The same bead measuring device, described previously, was used, except it was turned through 90°. In these tests the long axis covered the bin width and the shorter axis covered the distance along the bin. Extra extensions were also made for the displacement transducer to allow it to go to the deeper depths of the larger bin. The investigations included 3 variables, (a) initial soil density, (b) wheel load, (c) inflation pressure. The levels of these three experimental variables were selected to cover as wide a range of field conditions as possible. The levels are given below:-

(a) Soil density	1.4-1.5-1.6 g/ml.
Wheel load	9 kN.
Pressure	173 kN/m ² .
(b) Wheel loads	7-9-11 kN.
Soil density	1.3 g/ml.
Pressure	173 kN/m ² .
(c) Pressures	69-173-276 kN/m ² .
Soil density	1.4 g/ml.
Wheel load	7 kN.
(a,b,c) Wheel width	275 mm.

2.3.5. RESULTS.

The results of the experiments are given in Appendix 2.2. The results given are the averaged deflection of the five sets of beads. The four tables given for each situation give the three principal deflections of each of the 50mm grid points and the % volume change of their associated cubes. The results are given as a vertical plane of deformations using the identification system shown in figure (2.6). All the results are given rounded to the nearest whole number.

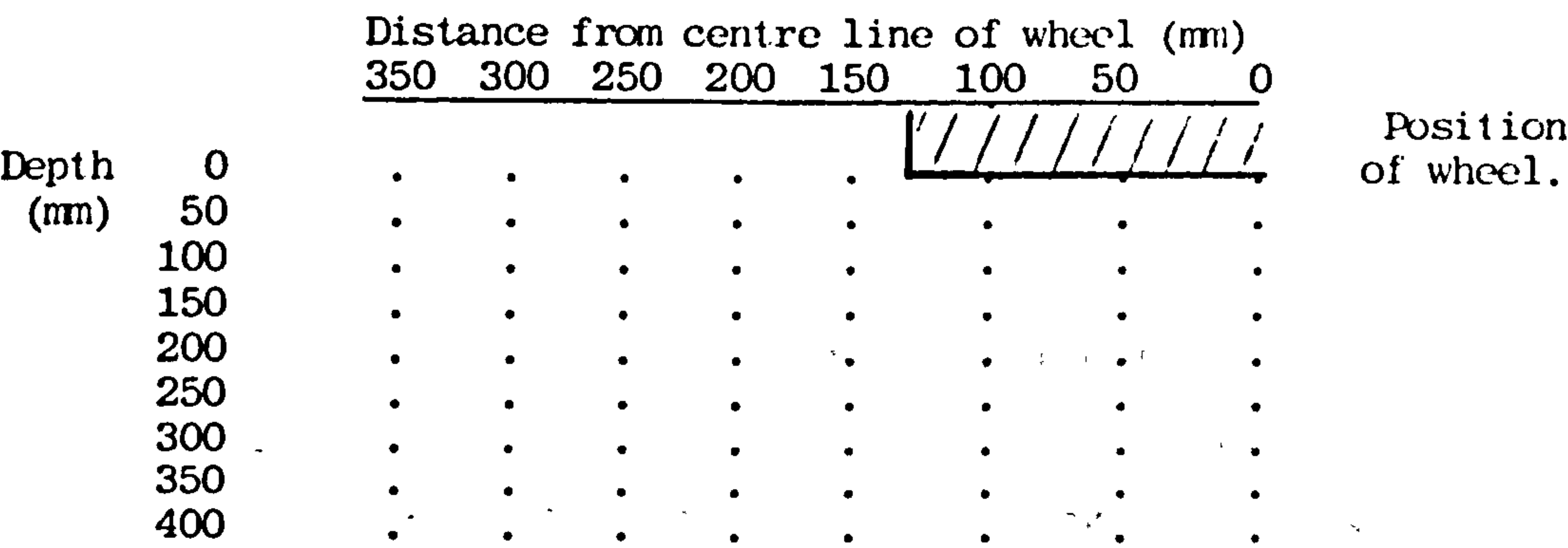


Figure 2.6. Full scale bead identification system.

2.4. DISCUSSION OF RESULTS.

Nine runs were conducted with five replications within each run. The runs were conducted by holding two of the variables at one level and monitoring the effect varying the third, a full set of treatment combinations was not conducted due to the time-consuming nature of the work. A sample set of results are shown in figure (2.7 a to d), these are the results of a full scale test with a wheel load of 11 kN and an inflation pressure of

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
Depth (mm)	0	0	-1	-4	-7	-8	20	41	42
	50	0	0	0	0	4	18	39	41
	100	0	0	0	0	3	13	29	30
	150	0	0	0	0	3	9	20	20
	200	0	0	0	0	2	6	15	14
	250	0	0	0	0	0	4	9	10
	300	0	0	0	0	0	2	4	4
	350	0	0	0	0	0	0	1	1
	400	0	0	0	0	0	0	0	0

Figure 2.7 a. Vertical

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
Depth (mm)	0	0	0	0	-1	-3	-4	0	0
	50	0	0	0	0	-2	-2	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

Figure 2.7 b. Lateral

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
Depth (mm)	0	0	0	0	3	9	27	38	38
	50	0	0	0	0	5	12	25	25
	100	0	0	0	0	4	7	14	14
	150	0	0	0	0	0	4	8	8
	200	0	0	0	0	0	0	3	5
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

Figure 2.7 c. Horizontal

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
Depth (mm)	25	+1	+5	+10	+14	+9	+2	3
	75	0	0	0	3	6	13	21
	125	0	0	0	0	4	13	19
	175	0	0	0	1	4	8	11
	225	0	0	0	2	4	8	10
	275	0	0	0	0	4	7	11
	325	0	0	0	0	2	5	6

Figure 2.7 d. Volume change

Figure 2.7 Sample deflection results.

173 kN/m². The results show that there was very little lateral movement of soil, figure 2.7 b, the lateral movement that did occur was in a direction away from the centreline of the tyre and in the surface layers of soil. A large lateral movement of soil was usually associated with some surface heave at the edge of the tyre, figure 2.7 a. The horizontal deformations in the direction of travel were large, these deformations being due to the rolling action of the tyre and would be responsible for generating the rolling resistance of the wheel. The deformations were mainly a surface phenomenon diminishing as the depth increased and not reaching as deep as the vertical deflections, figure 2.7 c. The magnitude of the horizontal deflections were related to the magnitude of the vertical deflections, as the vertical deflections decreased so did the horizontal deflections. The vertical deflections were usually the largest of the movements, figure 2.7 a, occurring mainly in the area directly below the contact patch of the tyre. The bulk of the deformations were downward, therefore compressive, but on the soil surface there was some heave due to the lack of surcharge. These results show that the mode of soil failure below tyres on soft compactable soil is a punch failure, where the vertical deflections are the most significant in causing the compaction of the soil. The volume changes were a little erratic because the total volume error was the sum of the errors of the individual corners that made up the cube, this could amount to an error of 12%. This size of the possible error makes it difficult to draw any firm conclusions from the results. However the results do show that the maximum volume change and

hence density does occur at a depth in the soil and not at the soil surface. Comparison between the two scales of experiments shows that there was no change in the type of soil failure due to the change in scale of the work.

The results of the small scale work detail the process by which soil compacts. Most of the compression occurs in the front half of the wheel, as shown by Table 2.A. Appendix 2.1, where the vertical deflections had reached approximately 80% of their maximum value as the centre line of the axle passes. The full scale results show the following trends:

i) Reductions in the level of deformations can be achieved by increasing soil density (Tables 9,10,11. Appendix 2.2). An increase in the soil's initial density also reduces the depth to which the deformations extend and reduce the magnitude of the volume change, although the magnitude of the final soil density ($\text{Initial density} \times (1 + (\% \text{vol. ch.}) / 100)$) were all fairly constant for each of the initial densities.

Initial Density.	1.4	1.5	1.6
Max. % Vol. Ch.	16	5	5
Final Density.	1.64	1.57	1.68

ii) Increases in the tyre inflation pressure significantly increase the level of the deformations and the magnitude of the maximum volume change, (tables 12,13,14. Appendix 2.2).

iii) Reducing the load from 11 to 9 kN (tables 6,7. Appendix 2.2) had little effect on either the level of the deformation or the

magnitude of the volume change but a further reduction to 7 kN (table 8) reduced the magnitude of the maximum vertical deflection from 42 to 33 mm and the maximum volume change from 20 to 15%. Although the surface deformation did not reduce with a load reduction from 11 to 9 kN the depth to which the deformation extended did reduce by 50 mm.

3. THE DEVELOPMENT OF THE SOIL DISPLACEMENT MODEL.

3.1. OUTLINE.

The mathematical model was based on Elasticity Theory. Equations from Elastic Theory can predict the deformation of any point in a semi-infinite material due to point loads on the surface. By numerically summing a number of point loads over a finite area the solution could be found for a uniform load which approximated to a tyre on the soil surface. To increase the flexibility of the model the equations were modified so the solution was independent of load and soil strength. These equations were then used to find the partial solution to a uniform load over a small square area. The solution was found for a three dimensional grid of points and called the basic data matrix. The size and shape of the contact area could be varied by placing the appropriate number of basic areas along side each other and summing. By multiplying the solution by the soil strength characteristics the deflection could be found. The soil strength was found from tests using a confined compression cylinder which induced in the test sample the type of failure found below a wheel. To produce a solution for a specific tyre and soil condition the model required the following inputs:

- a) Contact Length.
- b) Contact Width.
- c) Contact Pressure.

d) Young's Modulus of the Soil.

e) Poisson's ratio of the Soil.

The solution produced by the model was the deformation of each of the grid points in the three principal directions, from the deflections it was also possible to calculate the volume change of the cubes and hence the compaction.

3.2. ASSUMPTIONS

i) The soil was assumed to be homogeneous, so that the smallest element cut from the body possessed the same material properties as the whole. So long as the size of the body of soil as a whole is large in relation to the crystalline structure the assumption of homogeneity can be used with great accuracy.

ii) The soil was assumed to be isotropic, ie its properties are the same in all directions. If the orientation of the structure within the soil is random it will be isotropic.

iii) The soil was assumed to be perfectly Plastic. In Elasticity the material should be perfectly elastic so if certain limits are not exceeded the deformation of the soil disappears when the stress is removed and the material returns to its original form. This is most certainly not true for the compactable soils to be used in this study, therefore the model assumed that the soil was perfectly plastic. Once the maximum deflection of a point in the soil had been reached it was frozen at that level of deformation with no elastic recovery.

iv) The stress-strain characteristics of the soil were assumed to be linear. They were represented by a Young's Modulus and Poisson's ratio. It is possible to use non-linear characteristics in two dimensional Elasticity but due to the extra complexity of three dimensional Elasticity only a linear model was used in this case.

3.2.1. NOTATION.

D	Constrained Modulus. kN/m^2
E	Young's Modulus. kN/m^2
G	Shear Modulus. kN/m^2
μ	Poisson's ratio.
X	Horizontal, in the direction of travel.
Y	Lateral, across the direction of travel.
Z	Vertical.
R	Resultant.
u	Horizontal deflection.
v	Lateral deflection.
w	Vertical deflection.
u'	Partial solution to horizontal deflection.
v'	Partial solution to lateral deflection.
w'	Partial solution to vertical deflection.
P	Point load. kN
c	Depth of point load.

3.2.2. MODEL DEVELOPMENT.

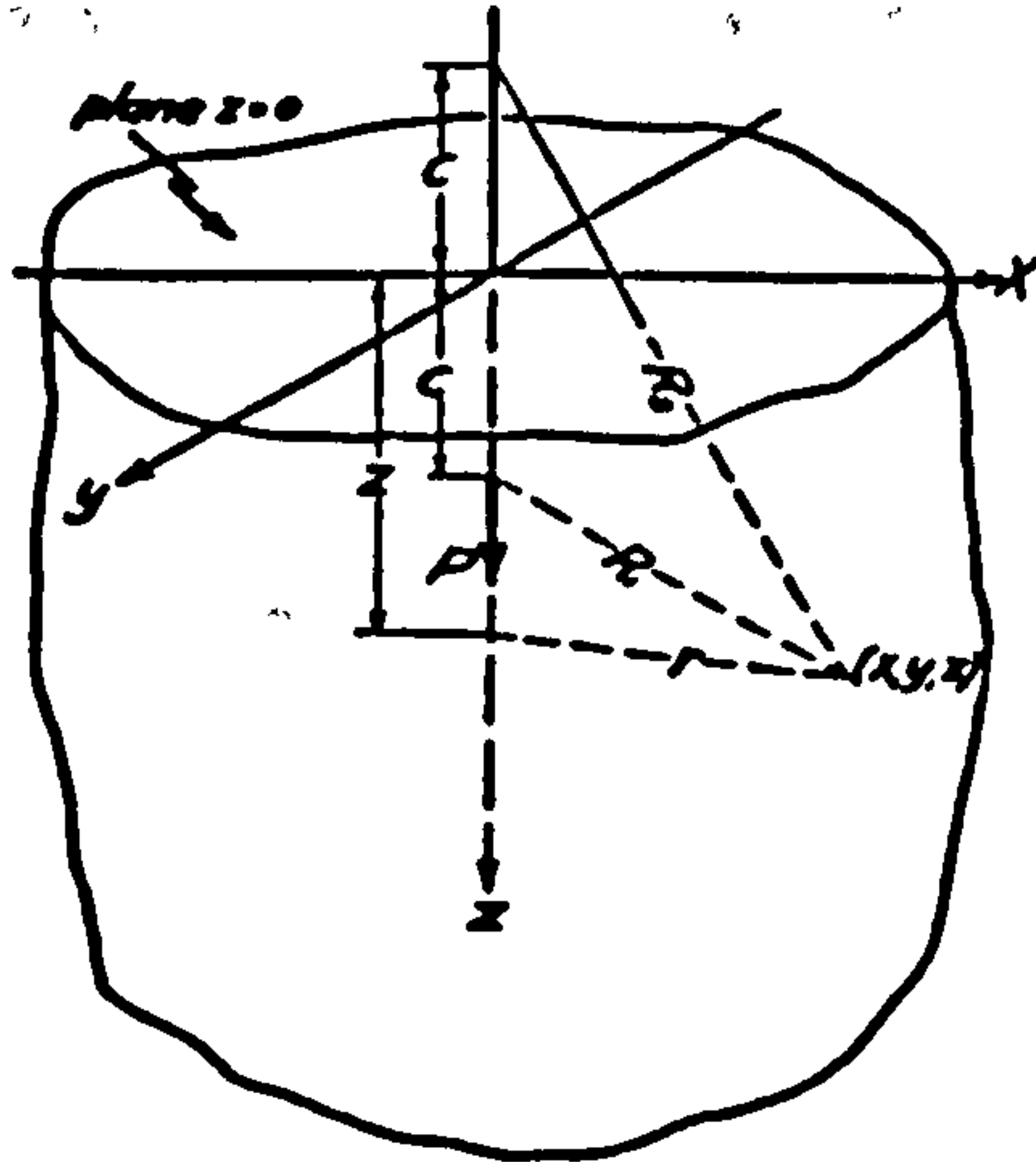
If soil were elastic, homogeneous and isotropic there would be no difficulty in predicting the trajectory of soil particles that would take place as a direct result of a surface load. For such a simple case there are formulas from the Theories of Elasticity that give not only the relationship between surface load and stress within the soil, but also the relationship between load and displacement. In an actual soil it is very difficult to predict the magnitude of these displacements as soil is not only non-homogeneous but non-isotropic. Despite these complications Elasticity Theory can play a key role in displacement prediction. The results from the theories can provide an understanding of the displacement phenomenon and an approximate method for predicting displacements and hence compaction. Several methods, based on Elasticity Theory, are available to predict stress distribution below surface loads, Sohne (1953), Blackwell (1979). These models calculate the stress in the soil from which it is possible, if the stress-strain relationship of the soil is known, to predict the deflection or strain. By using two material constants Elasticity Theory also allows the direct calculation of deflection. The two constants are Modulus of Elasticity or Young's Modulus and Poisson's ratio. A three dimensional model was used as it allowed the effect of changes in the area of contact to be monitored as well as giving a solution that showed the whole volume of soil compacted across the width and length of the contact area. Three dimensional Elasticity Theory is

significantly more complex than its two dimensional counterpart. Due to the extra complexity of the solution the model was based on a simplified linear stress-strain relationship. The simplest approximation for the distribution of the load over the contact area was a uniformly distributed load over a rectangular area, this approximated to a tyre running on the soil surface. The equations for this case can be calculated by the double integration of a point load within the limits of the area. Unfortunately this solution was not available in the literature and was too complex an undertaking to be within the scope of this study. A close approximation to the required solution could however be obtained by numerically integrating a point load over a small square area. By using a summing procedure similar to the one used by Sohne, the solution for a larger and more complex area can be found. The solution for a uniform load over a square area will therefore be used as the basic building block of the model, this calculated solution was called the basic data matrix.

3.2.3. CALCULATION OF THE BASIC DATA MATRIX.

The equations needed for the basic data matrix were the solution to a point load on the surface of a semi-infinite mass. To simplify the calculations they should be in rectangular co-ordinates. Even these simple equations were not readily available, but they could be developed from basic equations given by Mindlin (1936), for a point load at a depth 'c' in the interior of a media, equations 3.1 to 3.5.

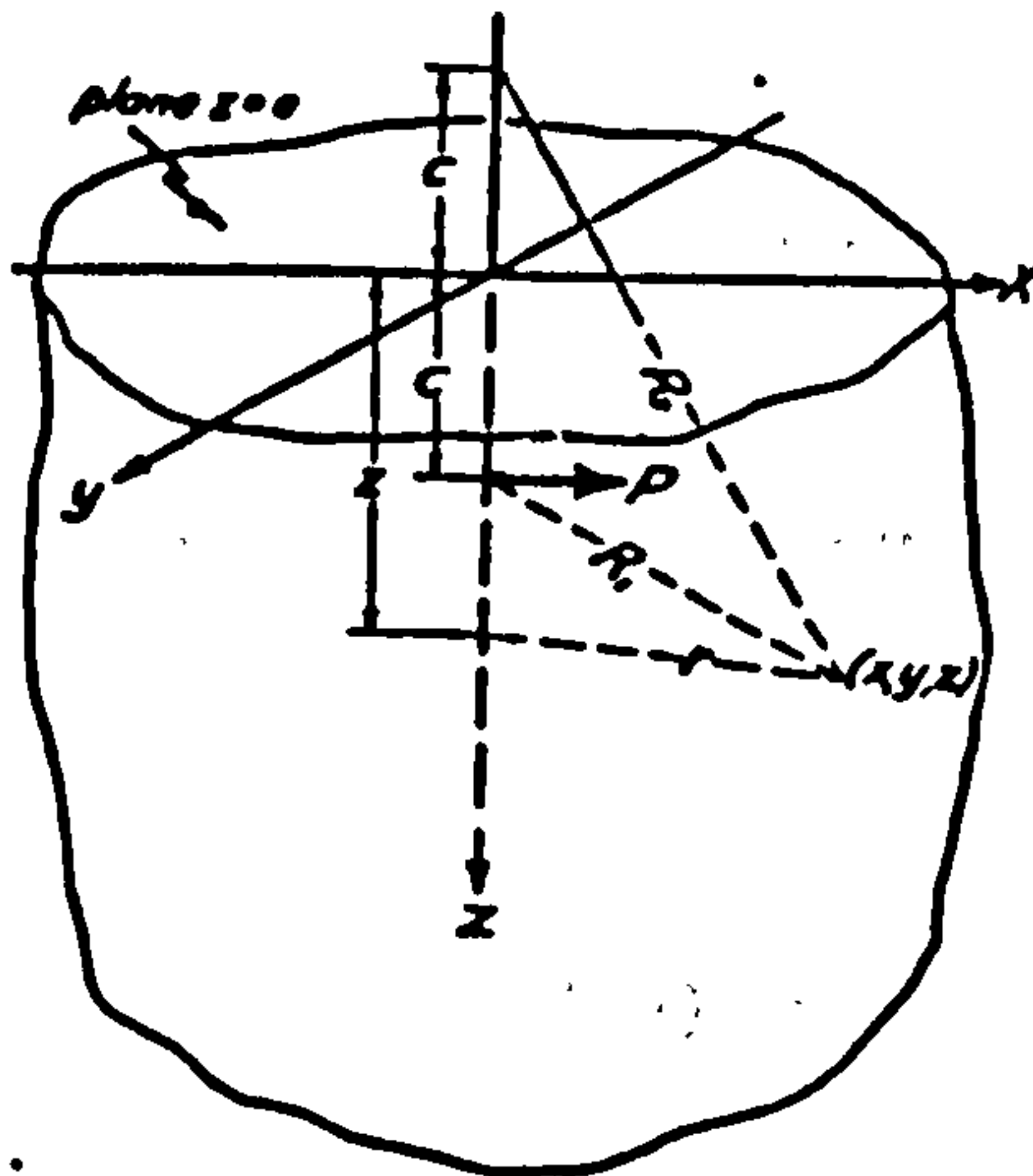
For a vertical load at a depth c below the soil surface.



$$u = v = \frac{Pr}{16\pi G(1-\mu)} \left[\frac{z-c}{R_1^3} + \frac{(3-4\mu)(z-c)}{R_2^3} - \frac{4(1-\mu)(1-2\mu)}{R_2(R_2+z+c)} + \frac{6cz(z+c)}{R_2^4} \right] \quad 3.1$$

$$w = \frac{P}{16\pi G(1-\mu)} \left[\frac{3-4\mu}{R_1} + \frac{8(1-\mu)^2 - (3-4\mu)}{R_2} + \frac{(z-c)^2}{R_1^3} + \frac{(3-4\mu)(z+c)^2 - 2cz}{R_2^3} + \frac{6cz(z+c)^2}{R_2^4} \right] \quad 3.2$$

For a horizontal load at a depth c below the soil surface.



$$u = \frac{P}{16\pi G(1-\mu)} \left[\frac{3-4\mu}{R_1} + \frac{1}{R_2} + \frac{x^2}{R_1^3} + \frac{(3-4\mu)x^2}{R_2^3} + \frac{2cz}{R_2^3} \left(1 - \frac{3x^2}{R_2^2} \right) + \frac{4(1-\mu)(1-2\mu)}{R_2+z+c} \left(1 - \frac{x^2}{R_2(R_2+z+c)} \right) \right] \quad 3.3$$

$$v = \frac{Pxy}{16\pi G(1-\mu)} \left[\frac{1}{R_1^3} + \frac{3-4\mu}{R_2^3} - \frac{6cz}{R_2^4} - \frac{4(1-\mu)(1-2\mu)}{R_2(R_2+z+c)^2} \right] \quad 3.4$$

$$w = \frac{Px}{16\pi G(1-\mu)} \left[\frac{z-c}{R_1^3} + \frac{(3-4\mu)(z-c)}{R_2^3} - \frac{6cz(z+c)}{R_2^4} + \frac{4(1-\mu)(1-2\mu)}{R_2(R_2+z+c)} \right] \quad 3.5$$

These equations give the deflections due to a vertical and horizontal load. For the vertical load only the horizontal deflection (u) is given as the lateral deflection (v) has the same magnitude as u but in a different direction. By rotating the horizontal solution through 90° , the solution for a lateral load was found.

To calculate the solution for a point load on the soil surface the following simplifications were made to Mindlin's solution.

$$c = 0$$

$$R_1 = R_2 = R$$

Giving equations 3.6 to 3.10.

For a vertical load at the soil surface.

$$u = v = \frac{Pr}{\pi 16 G(1-\mu)} \left\{ \frac{4(1-\mu)Z}{R^3} - \frac{4(1-\mu)(1-2\mu)}{R(R+Z)} \right\} \quad 3.6$$

$$w = \frac{P}{\pi 16 G(1-\mu)} \left\{ \frac{8(1-\mu)^2}{R} + \frac{4(1-\mu)Z^2}{R^3} \right\} \quad 3.7$$

For a horizontal load at the soil surface.

$$u = \frac{P}{\pi 16 G(1-\mu)} \left\{ \frac{4(1-\mu)}{R} + \frac{4(1-\mu)X^2}{R^3} + \frac{4(1-\mu)(1-2\mu)}{R+Z} \left[1 - \frac{X^2}{R(R+Z)} \right] \right\} \quad 3.8$$

$$v = \frac{P XY}{\pi 16 G(1-\mu)} \left\{ \frac{4(1-\mu)}{R^3} - \frac{4(1-\mu)(1-2\mu)}{R(R+Z)^2} \right\} \quad 3.9$$

$$w = \frac{PX}{\pi 16 G(1-\mu)} \left\{ \frac{4(1-\mu)Z}{R^3} + \frac{4(1-\mu)(1-2\mu)}{R(R+Z)} \right\} \quad 3.10$$

Where:

$$R = (X^2 + Y^2 + Z^2)^{\frac{1}{2}}$$

$$r = (X^2 + Y^2)^{\frac{1}{2}}$$

These equations can be further simplified by substituting in:

$$G = \frac{E}{2(1+\mu)}$$

Equations 3.6 to 3.10 simplify to the following:

For a vertical load at the soil surface.

$$v = u = \frac{Pr(1+\mu)}{2\pi E} \left(\frac{Z}{R^3} - \frac{(1-2\mu)}{R(R+Z)} \right) \quad 3.11$$

$$w = \frac{P(1+\mu)}{2\pi E} \left(\frac{Z^2}{R^3} + \frac{2(1-\mu)}{R} \right) \quad 3.12$$

For a horizontal load at the soil surface.

$$u = \frac{P(1+\mu)}{2\pi E} \left(\frac{1}{R} + \frac{X^2}{R^3} + \frac{(1-2\mu)}{R+Z} \left(1 - \frac{X^2}{R(R+Z)} \right) \right) \quad 3.13$$

$$v = \frac{PXY(1+\mu)}{2\pi E} \left(\frac{1}{R^3} - \frac{(1-2\mu)}{R(R+Z)^2} \right) \quad 3.14$$

$$w = \frac{PX(1+\mu)}{2\pi E} \left(\frac{Z}{R^3} + \frac{1-2\mu}{R(R+Z)} \right) \quad 3.15$$

To increase the flexibility of the model the equations were further simplified by taking out P/E as a common factor, hence the solution derived was independent of load (P) and soil strength (E), equations 3.16 to 3.20.

For a vertical load at the soil surface.

$$v' = u' = \frac{r(1+\mu)}{2\pi} \left(\frac{Z}{R^3} - \frac{(1-2\mu)}{R(R+Z)} \right) \quad 3.16$$

$$w' = \frac{(1+\mu)}{2\pi} \left(\frac{Z^2}{R^3} + \frac{2(1-\mu)}{R} \right) \quad 3.17$$

For a horizontal load at the soil surface.

$$u' = \frac{(1+\mu)}{2\pi} \left(\frac{1}{R} + \frac{X^2}{R^3} + \frac{(1-2\mu)}{R+Z} \left(1 - \frac{X^2}{R(R+Z)} \right) \right) \quad 3.18$$

$$v' = \frac{XY(1+\mu)}{2\pi} \left(\frac{1}{R^3} - \frac{(1-2\mu)}{R(R+Z)^2} \right) \quad 3.19$$

$$w' = \frac{X(1+\mu)}{2\pi} \left(\frac{Z}{R^3} + \frac{(1-2\mu)}{R(R+Z)} \right) \quad 3.20$$

By numerically summing a large number of small point loads the solution would be a close approximation to a uniform load, the number of loads used was a compromise between computational speed and solution accuracy. In this case a grid of 64 point loads was used in an 8 by 8 matrix over a contact area of 25mm by 25mm. The solution to this loading was found at discrete points in a three dimensional grid, with solutions found at the same grid spacing, 25mm, as the dimensions of the square area. This spacing of the solution points simplified the summation procedure used later, as when two basic square areas were placed next to each other the points of solution lay one on top of the other and could easily be summed.

One problem that had to be avoided with this form of numerical integration was to attempt to find the solution at a point directly below the point of application of a load. At this point the resultant R would be zero, hence if a value of zero is substituted for R in equation 3.12 no matter what the value of P or E, the vertical deflection (w) would be equal to infinity. This was overcome by never putting a point load directly over

the point of solution, this is shown in figure (3.1).

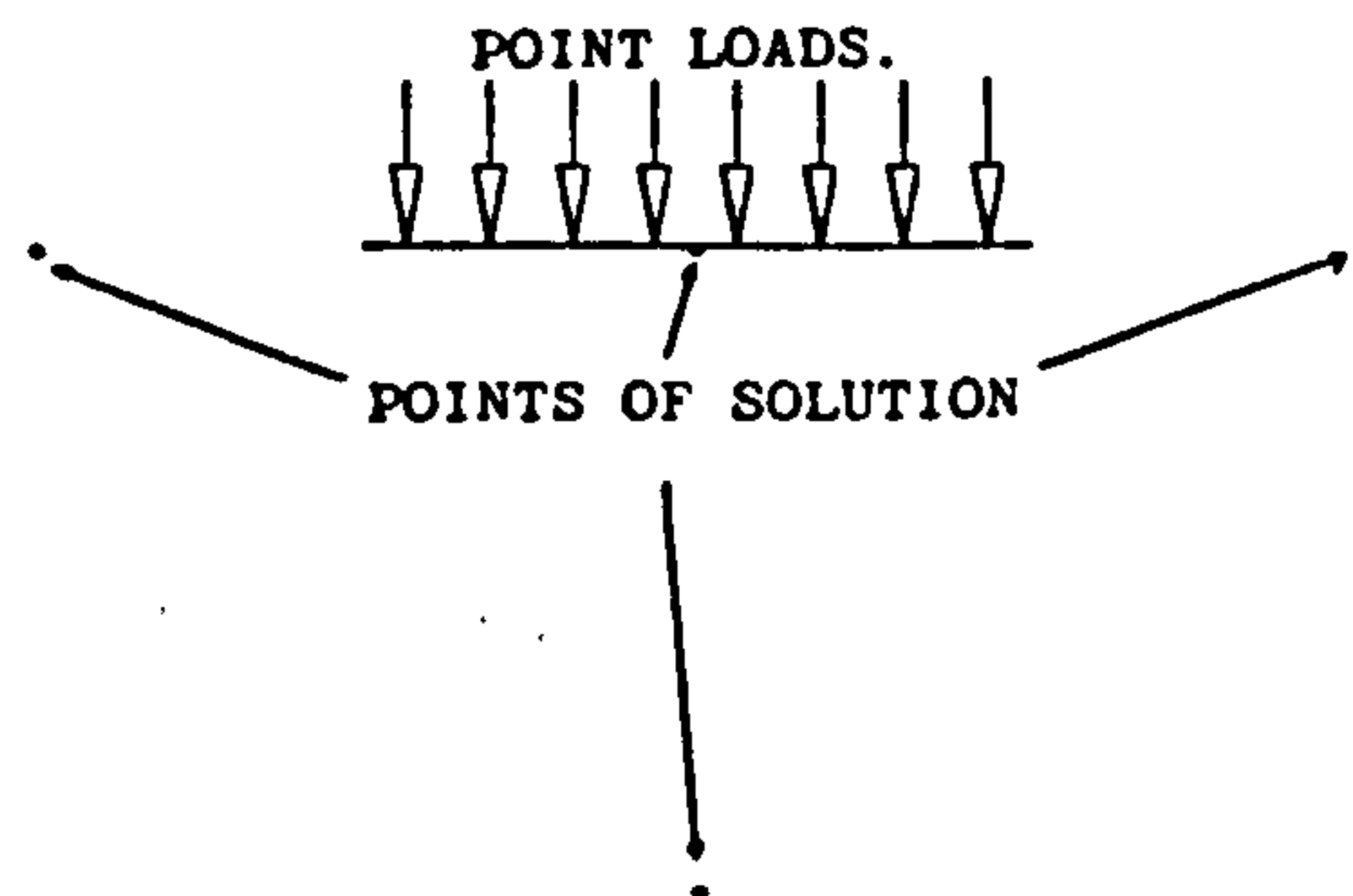


Figure 3.1. Surface point load distribution.

The basic 3 dimensional data matrix was a grid of solutions 61 points wide by 61 points long by 31 points deep. The number of points in the matrix could be significantly reduced as the solutions were all symmetrical about the X and Y axes. The data could therefore be reduced to a 31 by 31 by 31 grid covering only one quadrant, as shown in figure(3.2).

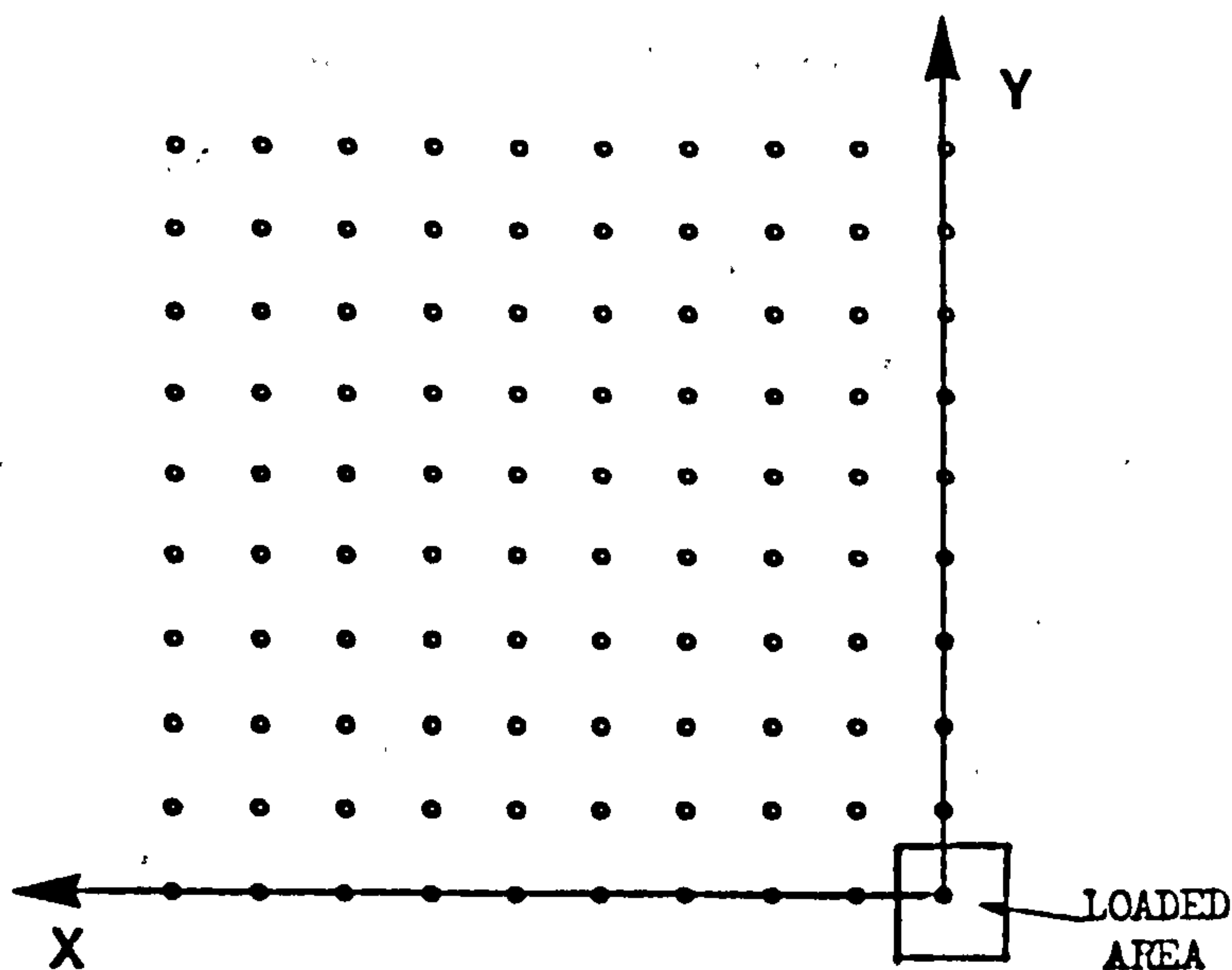


Figure 3.2. Solution quadrant.

9 basic data matrices were developed for the three directions

of deflection and the three directions of surface load. These solutions were stored on a computer as large 3 dimensional arrays.

The computer programme developed to produce the basic data matrices is given in Appendix 3.1.

3.3. SUMMATION PROCEDURE.

The nine individual basic data matrices were the partial solution to a uniformly distributed load over a small square area. By multiplying the solutions by P/E the actual deflection was found. To increase the area or change the shape of the area of solution several matrices have to be added together in a simple summing procedure. Firstly, the stored data matrix was expanded out from the one quadrant of solution to the full four quadrants. This was done by reflecting the data around the principle axes, ensuring that the sign was correct. The summing procedure was greatly simplified by selecting the points of solution at the same spacing as the size of the input area. By placing two areas next to each other, all the points of solution lay on top of each other and the effect of these two areas could be found by adding up the two partial solutions at the point of interest.

The value obtained from the nine summing operations is not the actual deflection in that direction. The actual deflection can be found in two ways, by multiplying the values after the

summation by P/E to give the solution for an even pressure distribution over the whole surface or by multiplying the individual matrices by an individual value of P/E prior to summing. The latter accounts for uneven pressure distributions (P) across the contact patch of the tyre. This procedure was repeated for each loading direction and direction of deflection. The solutions to the model are given as the deflections in the three principle directions of each grid point at a spacing of 25 mm.

The computer programme developed to sum the basic data matrices is given in Appendix 3.2.

3.4. VERIFICATION OF CALCULATION PROCEDURE.

Following the completion of the development of the mathematical model it was important to find some method of checking that the model produced was accurate and gave the correct solution according to Elasticity Theory. No published solutions were available for a uniformly distributed load over a square area, the closest solution found in the literature was for a uniform load over a circular area, this solution was published by Ahlvin and Ulery (1956). From the tables it was possible to find the vertical and horizontal deflections due to a uniform vertical load on the soil surface. No published work was found that covered deformations associated with horizontal/lateral loads. As the input area was circular the solution was given at multiples of the radius of

the circle, (0,0.2,0.4,0.6,0.8,1,1.5,2) in a plane along a radius of the contact area, figure (3.3)

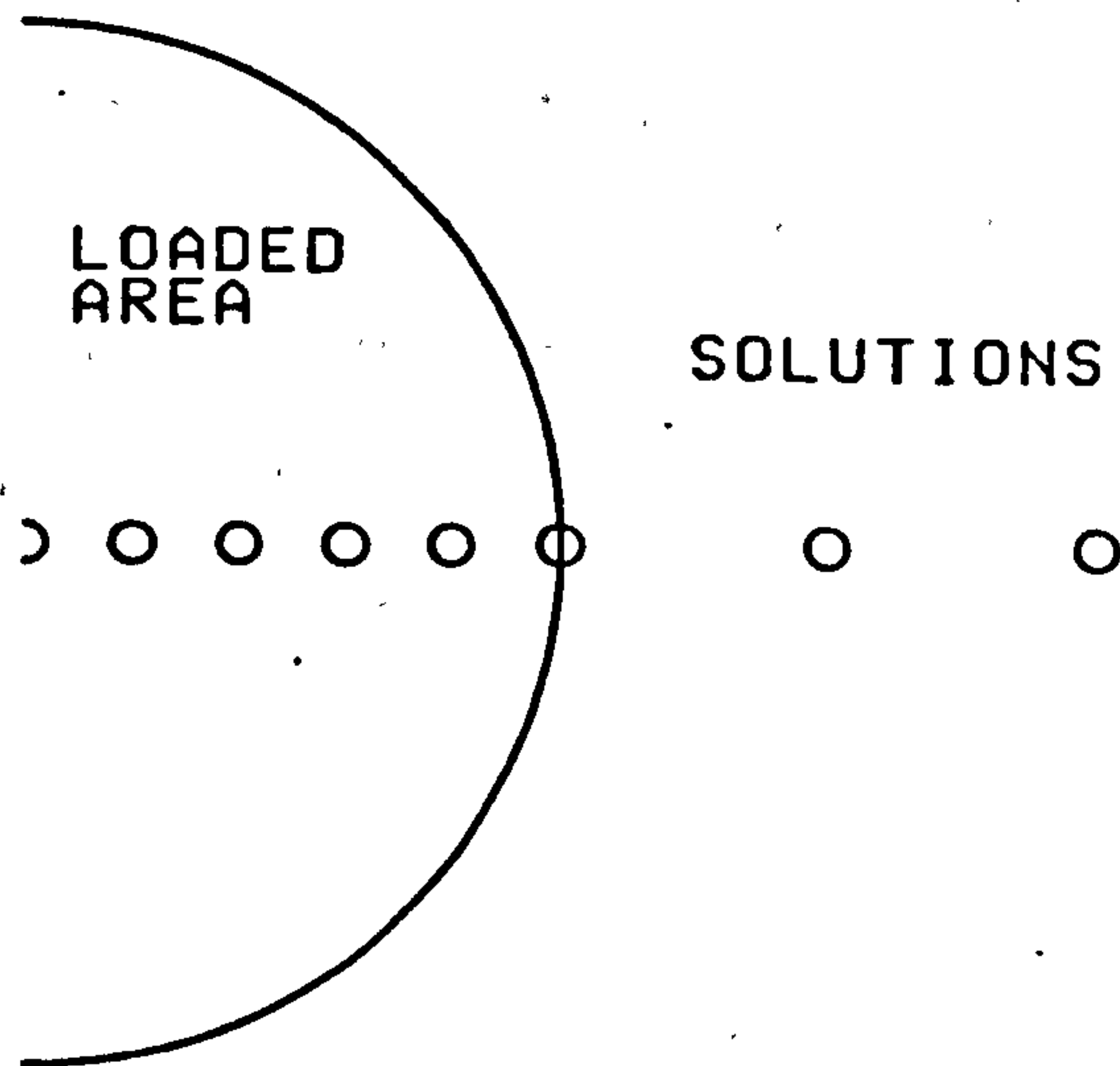


Figure 3.3. Points of solution from tables.

Two methods could be used to represent the square area of the model by a circle, either use the same area and have different diameters, figure (3.4a) or use a circle diameter the same as the square dimensions and a correction factor for the smaller load carried, figure (3.4b).

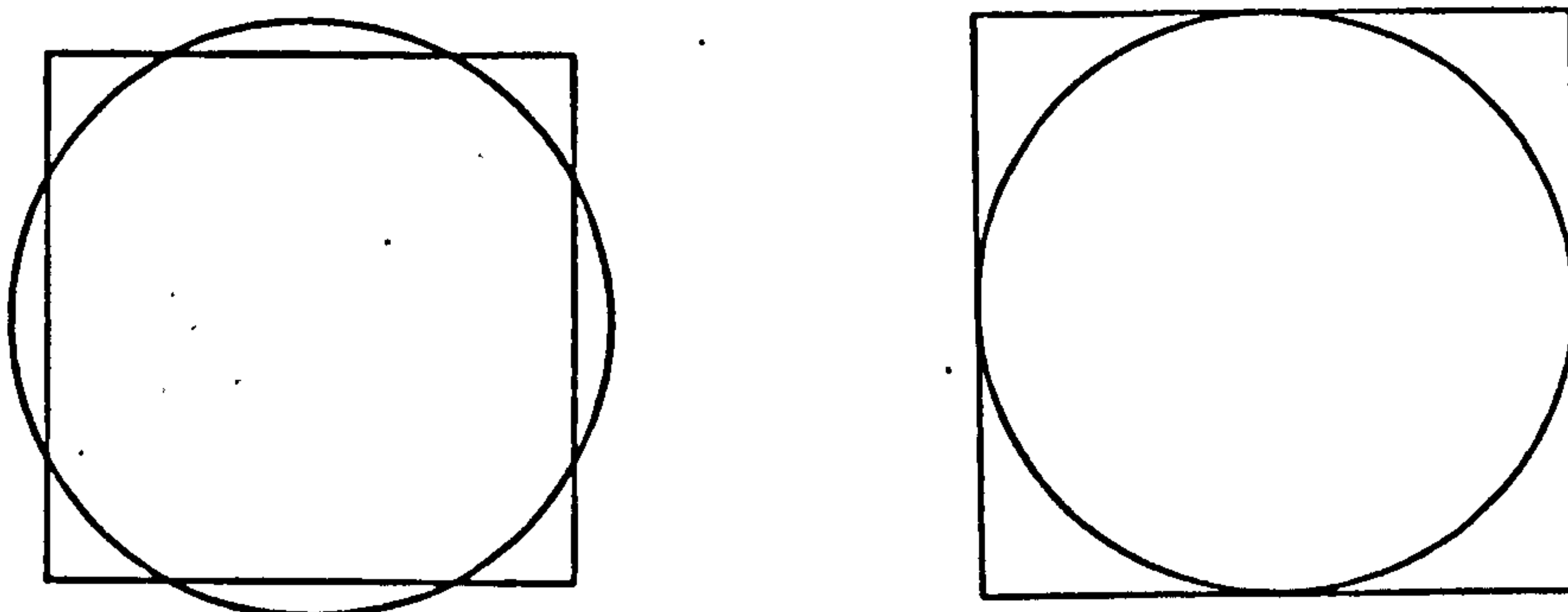


Figure 3.4a b. Two methods of representing loaded area.

The second method was used as there is a sharp change in the

level of the deflections at the boundary of the loaded area. The size of the square contact area used was 0.25m by 0.25m and a circle radius of 0.125m. This gave a square area of 0.0625m² and a circle area of 0.04908 m². The pressure on the circle was increased by a factor of 1.273 making the load on both shapes the same. The comparison of the calculated and tabulated vertical deflections of Ahlvin and Ulery (1956) at 0.25m spacing is shown in table 3.1

		DISTANCE FROM CENTRE OF CONTACT AREA (mm).									
DEPTH (mm)		0	25	50	75	100	125	187	250		
											
0	MODEL	287	285	279	268	251	222	170	94		
	TABLES	298	294	285	269	242	189	140	77		
12.5	MODEL	272	270	264	253	235	207	170	94		
	TABLES	258	258	248	232	206	170	137	76		
25	MODEL	253	251	245	234	217	193	166	94		
	TABLES	251	248	238	223	198	168	139	76		
37.5	MODEL	233	231	225	215	200	181	159	94		
	TABLES	226	222	215	200	180	156	134	76		
50	MODEL	214	212	207	197	185	169	151	94		
	TABLES	203	200	193	183	165	147	128	76		
62.5	MODEL	196	194	189	181	171	158	145	94		
	TABLES	182	184	174	164	151	136	122	76		
75	MODEL	179	178	173	167	158	147	136	93		
	TABLES	163	160	156	149	139	127	115	70		
125	MODEL	129	128	126	123	119	114	108	84		
	TABLES	112	111	107	105	102	89	70	70		
187.5	MODEL	93	92	92	90	88	86	84	71		
	TABLES	79	79	78	76	75	72	70	59		

Table 3.1. Comparison of model and tabulated values.

The correlation between the two values was good, any small

difference between the two sets of values being attributed to the change in the shape of the contact area and not due to errors in the calculations. The same level of correlation was found for the horizontal/lateral deflections. Hence it could be assumed that the mathematics of the model were correct and it would accurately give the deflections predicted from the Theories of Elasticity.

3.5. INPUTS TO THE MODEL.

3.5.1. INTRODUCTION.

The model required two groups of inputs to be able to fully describe an individual situation. One group was the soil parameters, expressed as an Elastic Modulus (E) and a Poisson's ratio (μ). The other input group described the contact patch on the soil surface, ie length, width, load and a function to describe the distribution of the load over the area.

3.5.2. EVALUATION OF SOIL PARAMETERS.

If a point in a loaded soil is considered, the state of stress and strain are linked together by a stress-strain relationship which can be very complicated. The type of test conducted will effect the mode of soil failure and therefore the stress-strain characteristics. It was important to find a soil test that produced the same mode of soil failure in the test sample as was found below the tyre in the experimental work. A common method of experimentally evaluating the stress-strain characteristics of soil is to use a tri-axial test. The type of soil failure

induced by tri-axial loading is in general a shear failure. The deflection measurements below tyres have shown that the type of soil failure was a punch or compressive failure rather than a shear failure. The stress-strain relationship developed from a tri-axial test will not therefore represent the failure below wheels. This is a conclusion also reached by several other experimenters, Koolen (1974), Eriksson et al. (1974). Both found that an odometer or confined compression test gave the most realistic stress-strain relationships for a compacting soil. In a confined compression test a sample of soil is held in a rigid cylinder and load is applied to the top of the sample by means of a piston, figure (3.5).

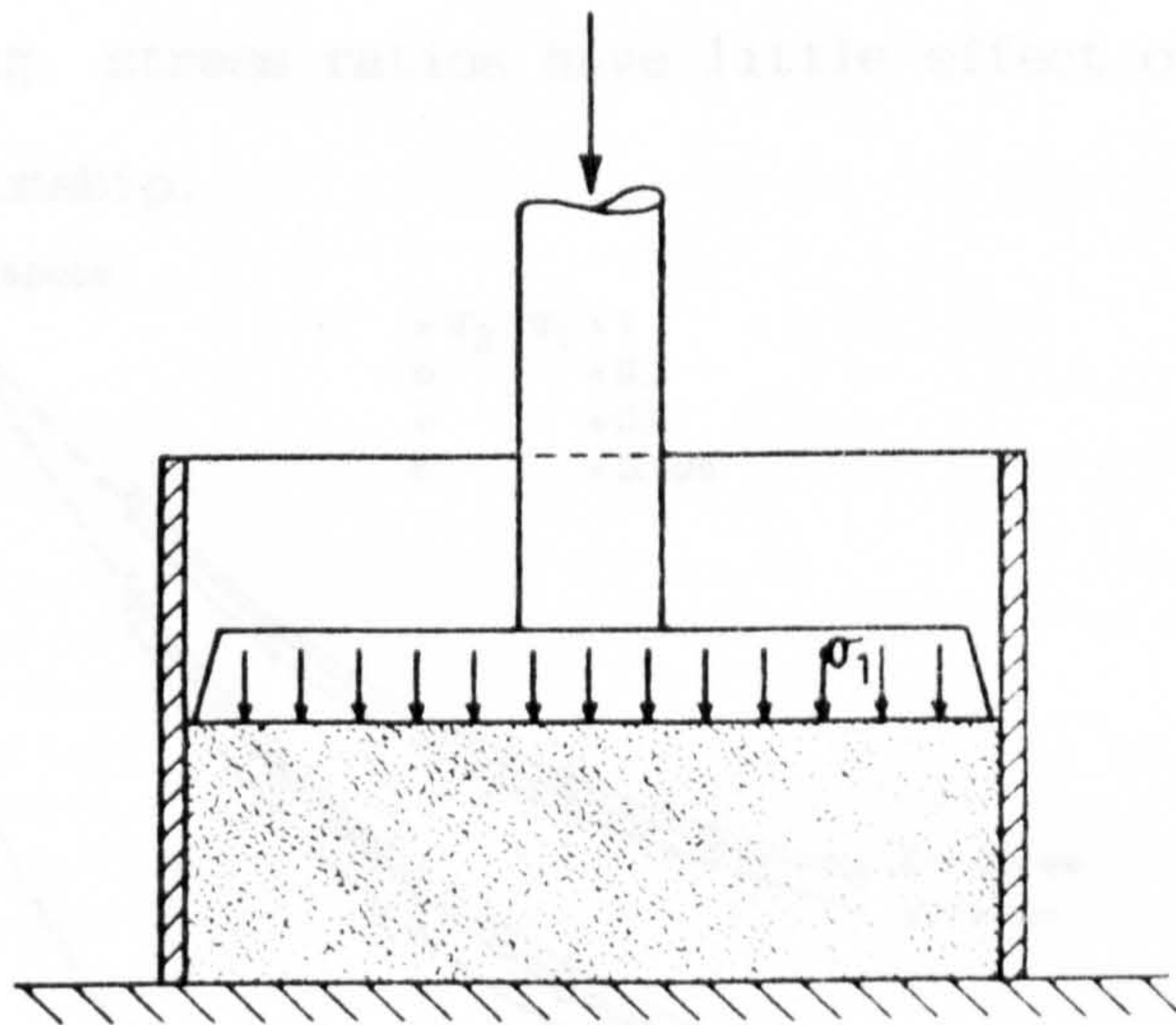


Figure 3.5. Confined compression apparatus.

The rigid sides of the cylinder stop any sideways movement of soil so the soil can only compress with no shear failure; a similar type of failure to that observed below a tyre. Representations of the two stress strain curves are shown in figure (3.6) where in confined compression, the soil strength

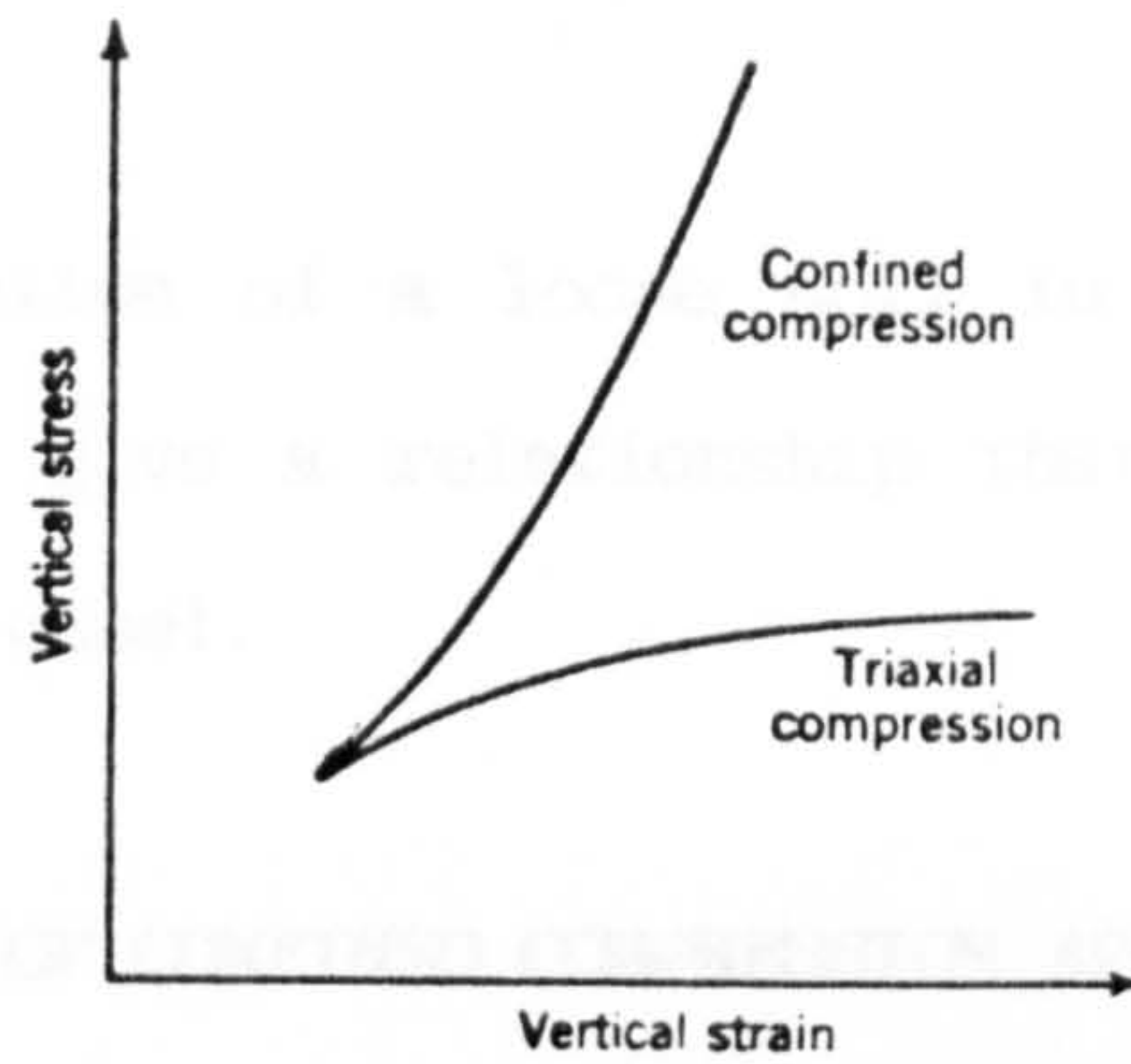


Figure 3.6. Comparison of stress-strain relationships

During a confined compression test the confining pressures can become quite large, but experimental evidence has shown that the effect on the stress-strain relationship is quite small. The results of Bailey and Vanden Berg (1968) and Dunlap and Webber (1971), are shown in figure (3.7), where the different vertical to confining stress ratios have little effect on the stress-strain relationship.

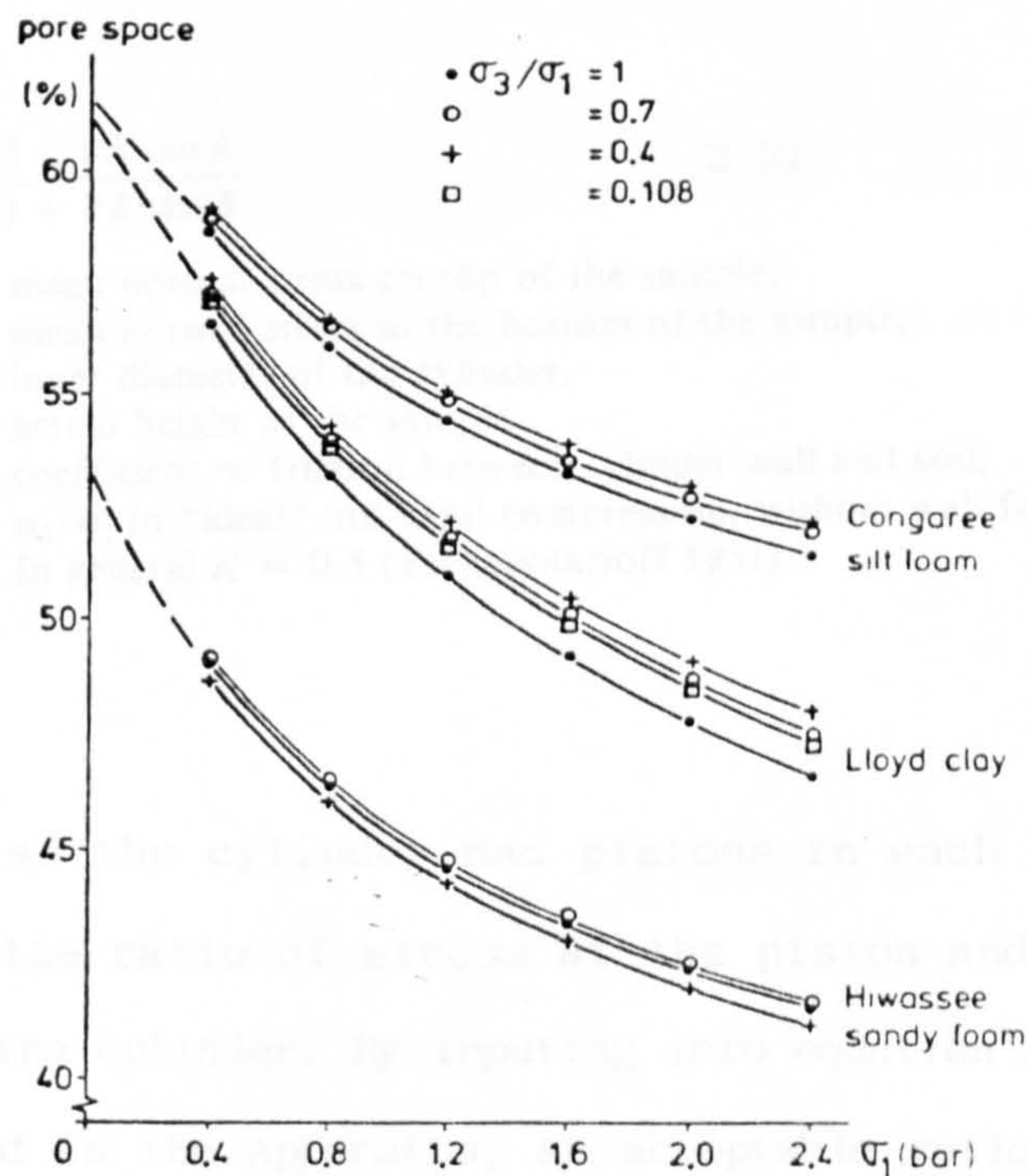


Figure 3.7. Soil stress-strain relationships.

Hence compaction of a loose soil in a confined cylinder is sufficient to give a relationship that relates to the stress state below a wheel.

3.5.3. DESIGN OF CONFINED COMPRESSION APPARATUS

Confined compression is not a commonly used soil test and no apparatus was generally available to conduct the test, therefore some simple apparatus was constructed. The apparatus consisted of a brass tube, plate (3.1), 50 mm diameter and 90 mm long with two aluminium pistons which fitted into the brass tube. The aspect ratio (length/diameter) of the cylinder was calculated from equations given by Koolen and Kuipers (1983), equation 3.21, so the stress at the top of the soil sample when placed in the cylinder was the same as stress at the bottom.

$$\frac{\sigma_b}{\sigma_t} = \frac{(D/h) - 2K \tan \delta}{(D/h) + 2K \tan \delta} \quad 3.21$$

where: σ_t = mean normal stress on top of the sample,
 σ_b = mean normal stress at the bottom of the sample,
 D = inner diameter of the cylinder,
 h = actual height of the sample,
 $\tan \delta$ = coefficient of friction between cylinder wall and soil,
 K = σ_3/σ_1 in "ideal" uni-axial compression, without wall friction.
 In general $K = 0.5$ (Tschebotarioff 1951).

In this case as the cylinder had pistons in each end the equation gave the ratio of stress at the piston and at the centre line of the cylinder. By inputting into equation 3.21 the sample size used in the apparatus, an acceptable ratio of 0.7 was obtained, this value would rise towards unity as the sample



Plate 3.1. Confined compression cylinder and pistons.

compressed and the sample height (h) decreased.

On the outside of the cylinder were bonded two pairs of strain gauges placed around the circumference at the centre of the tube, figure (3.8).

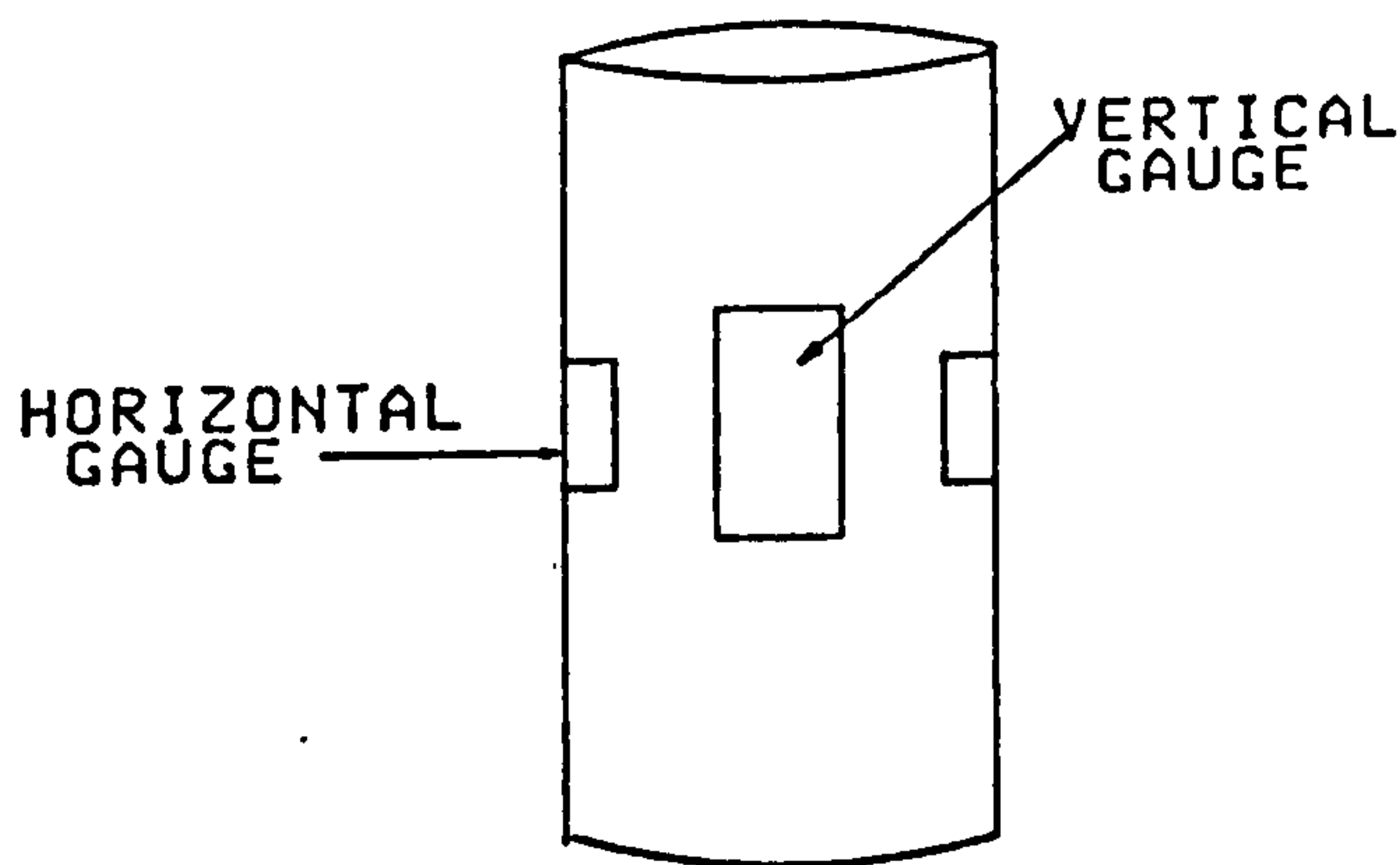


Figure 3.8. Strain gauge location on cylinder.

The two pairs of gauges were the two active arms of two wheatstone bridges. The pair of gauges orientated along the vertical axis of the cylinder were designed to monitor the longitudinal stress in the cylinder wall. The hoop stress induced in the cylinder by the compressing soil was monitored using the pair of gauges orientated along the circumference of the cylinder. The other two arms of the bridges were mounted on a reference plate, made of brass, which ensured that the outputs were temperature compensating. The longitudinal stress was calibrated by applying a vertical load to the cylinder. The hoop stress was more complex to calibrate, but was done using water pressure in the cylinder, the pressure was contained in

the cylinder using the apparatus shown in plate (3.2).

The soil in the cylinder was loaded using a tri-axial machine in an open frame, the tri-axial machine was used only to apply strain at a constant rate to the sample. Prior to using the apparatus for testing soil it was used to verify the design criteria of Koolen. Tests were conducted where a soil sample was compressed using both sets of gauges together, and the ratio of the longitudinal to the hoop stress in the walls of the brass cylinder was monitored, the results of the test are shown in figure (3.9).

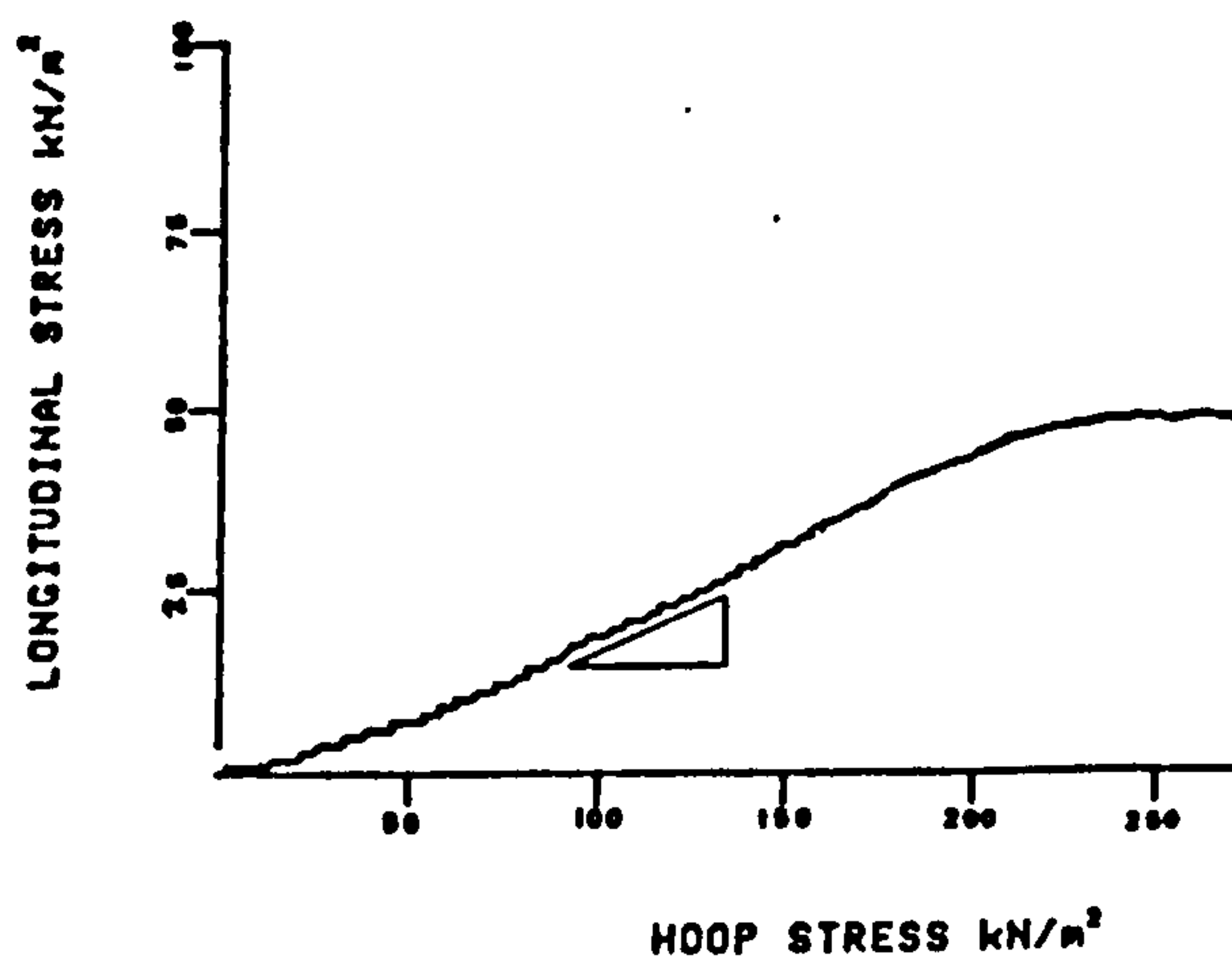


Figure 3.9. Variation of hoop stress with vertical stress.

If the friction between the soil and the cylinder walls was small, the value of Poisson's ratio from the slope of the line should be close to the value of Poisson's ratio for brass. This was because most of the longitudinal stress in the cylinder

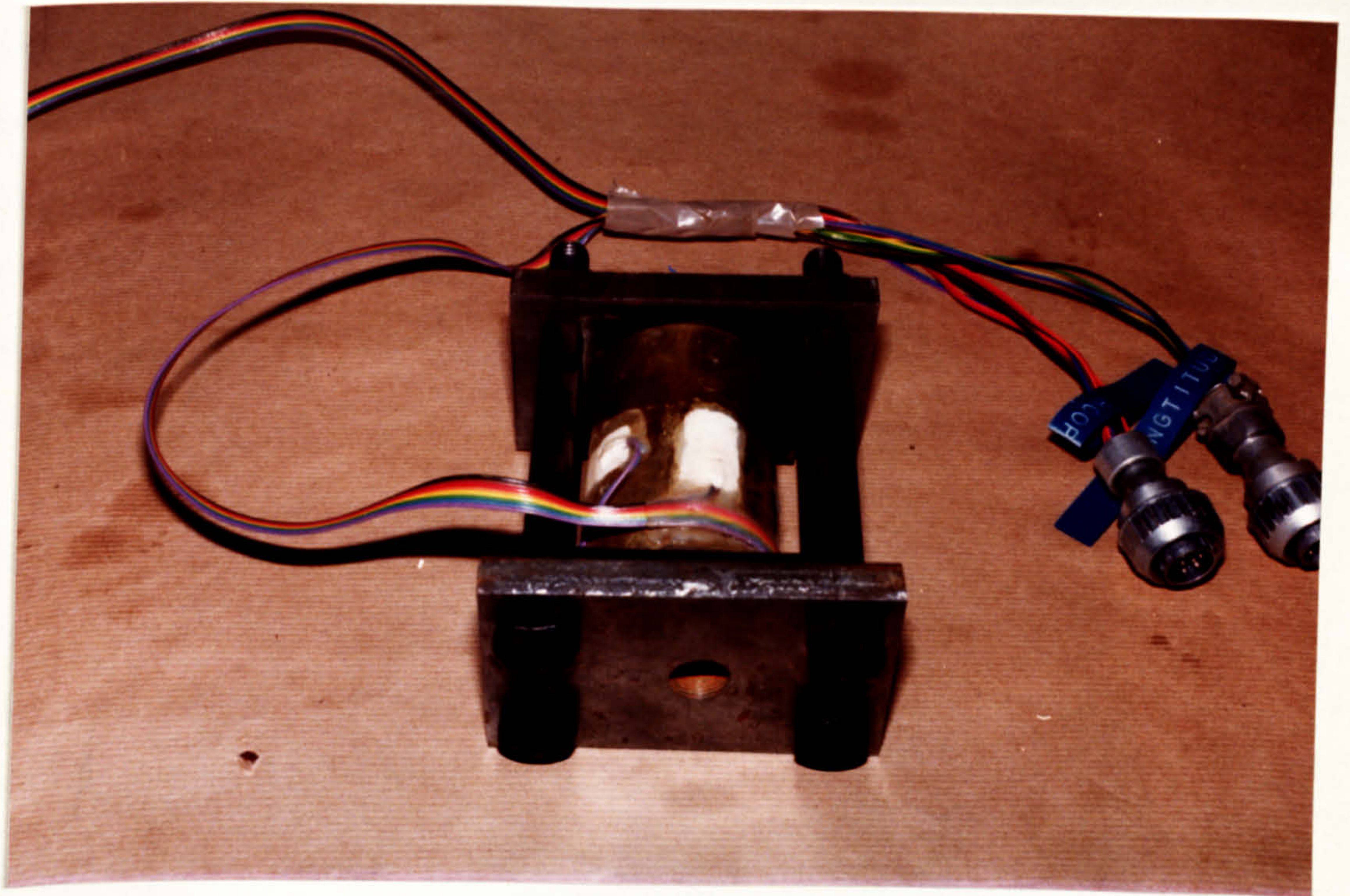


Plate 3.2. Hoop stress calibration apparatus.

should be generated by the hoop stress induced in the walls by the soil as it was compressed. The figure shows that the ratio was linear except at high levels of hoop stress where the wall friction started to have a significant effect on the ratio. A common value of the ratio for brass is 0.33, the slope of the line gives a value of 0.23. This showed that the wall friction between the soil and the brass during the compression was not too large and would not distort the results of future tests using this apparatus, as long as the level of compressive load were kept below 600 kN/m².

3.5.4. MEASUREMENT OF YOUNG'S MODULUS

Experiments were conducted using the confined compression apparatus, described previously, to find the stress-strain relationship of the soil for a range of conditions. Tests were conducted to see if one value of Young's Modulus could describe a wide range of conditions or if individual tests were needed. The Young's Modulus of a material is defined as the ratio between stress and strain. During a confined compression test the load, measured by a ring dynamometer on the loading apparatus and the axial strain, measured by a displacement transducer, could be plotted and hence a plot of stress against strain could be drawn. A typical relationship is shown in figure (3.10), where the slope of the line and hence the strength of the soil increases as the applied pressure increases. As the soil was constrained and only allowed to compress vertically, the axial strain represents the volumetric

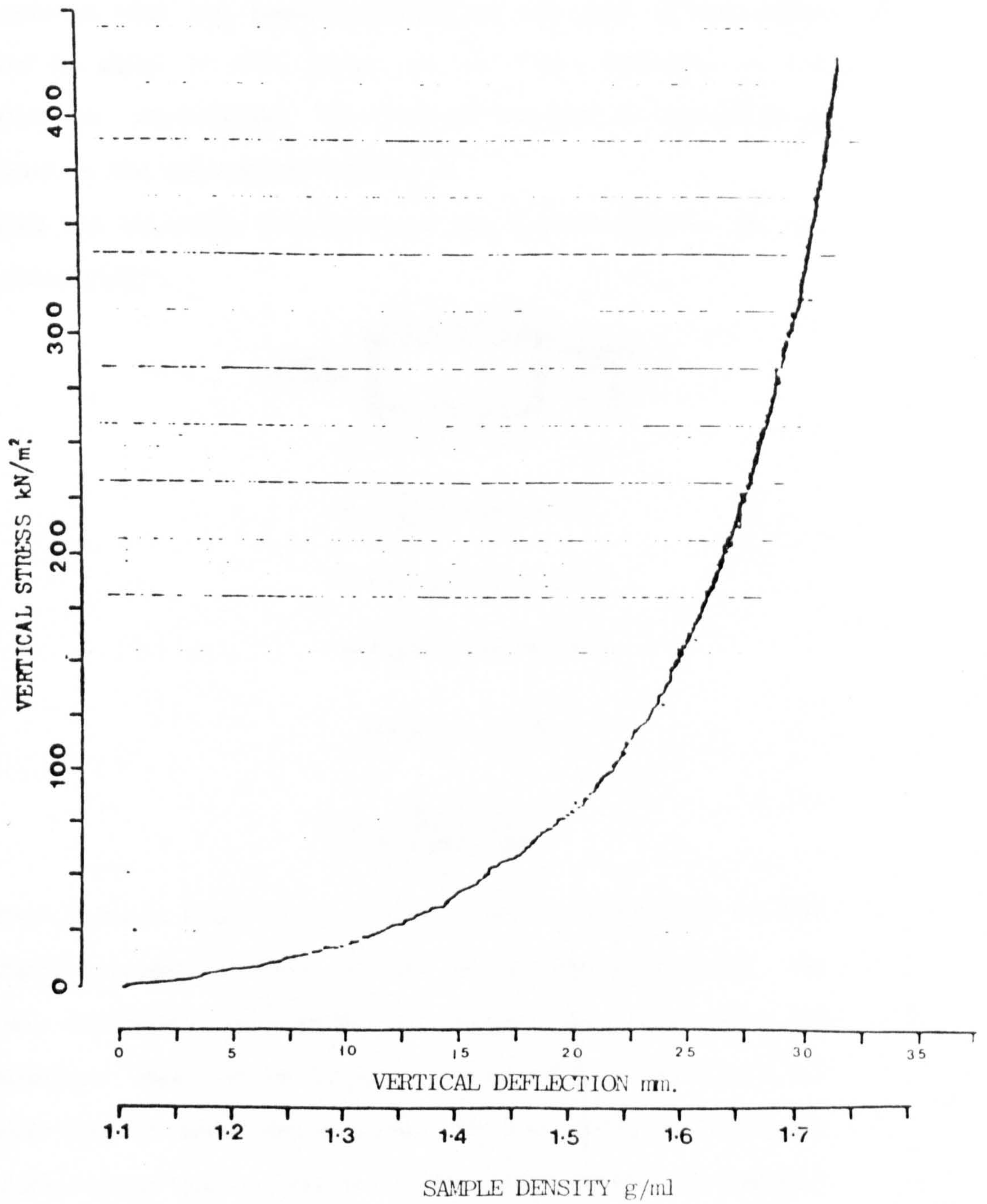
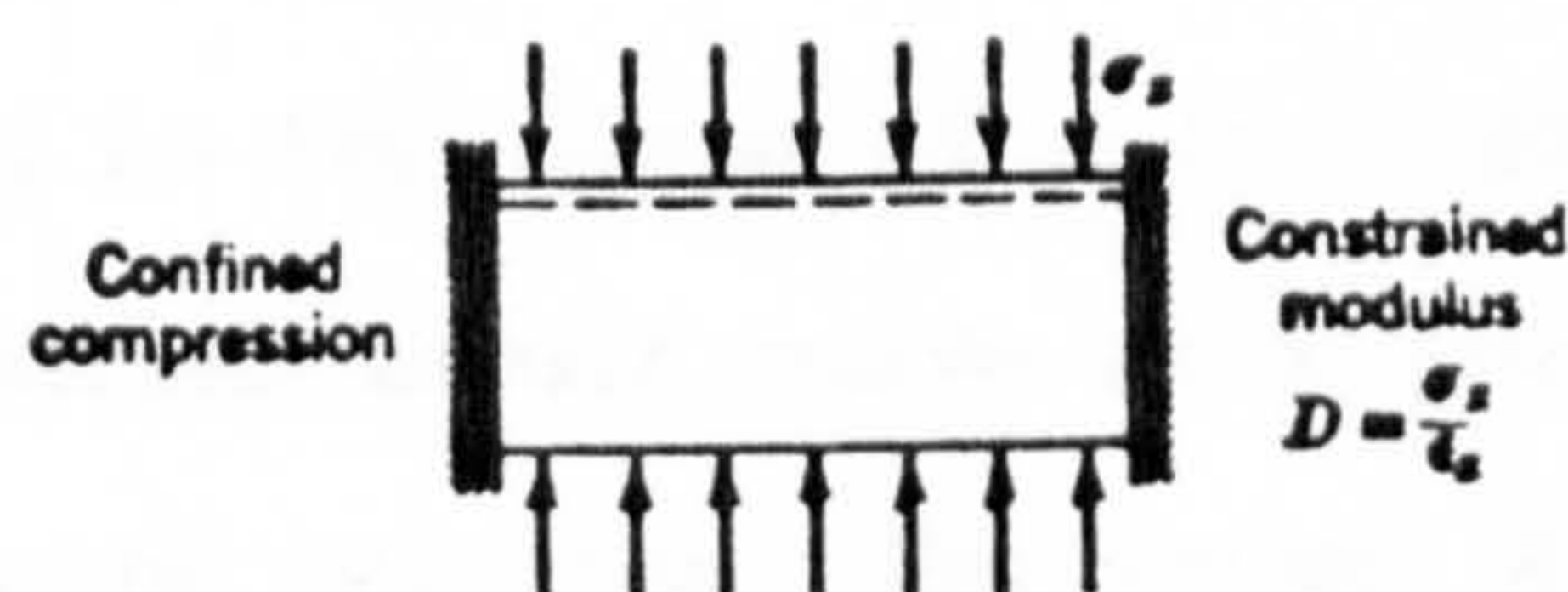


Figure 3.10. Stress-strain characteristics in confined compression.

strain of the sample, hence if the sample's initial dimensions and weight are known, the lower axis of the graph can be modified to be the sample bulk density. If this were an unconfined test the Young's Modulus of the soil at any point would be equal to the slope of the line. However, as the sample is constrained, the slope of the plot at any point is defined as the constrained modulus D.

Using the following relationships the Young's Modulus, E, can be calculated:-



$$\epsilon_x = \frac{1}{E} [\sigma_x - \mu(\sigma_v + \sigma_z)]$$

$$\epsilon_v = \frac{1}{E} [\sigma_v - \mu(\sigma_x + \sigma_z)]$$

$$\epsilon_z = \frac{1}{E} [\sigma_z - \mu(\sigma_x + \sigma_v)]$$

$$\text{setting } \epsilon_x = \epsilon_z = 0.$$

$$D = \frac{E(1 - \mu)}{(1 + \mu)(1 - 2\mu)}$$

Hence Young's Modulus is proportional to the slope of the confined compression curve. For use in the prediction model, the actual nonlinear stress-strain curves of a soil must be linearised. When using Young's Modulus it is important to specify how the value was obtained. The two most common methods of linearising such a line is to determine either the Tangent Modulus or the Secant Modulus, figure (3.11).

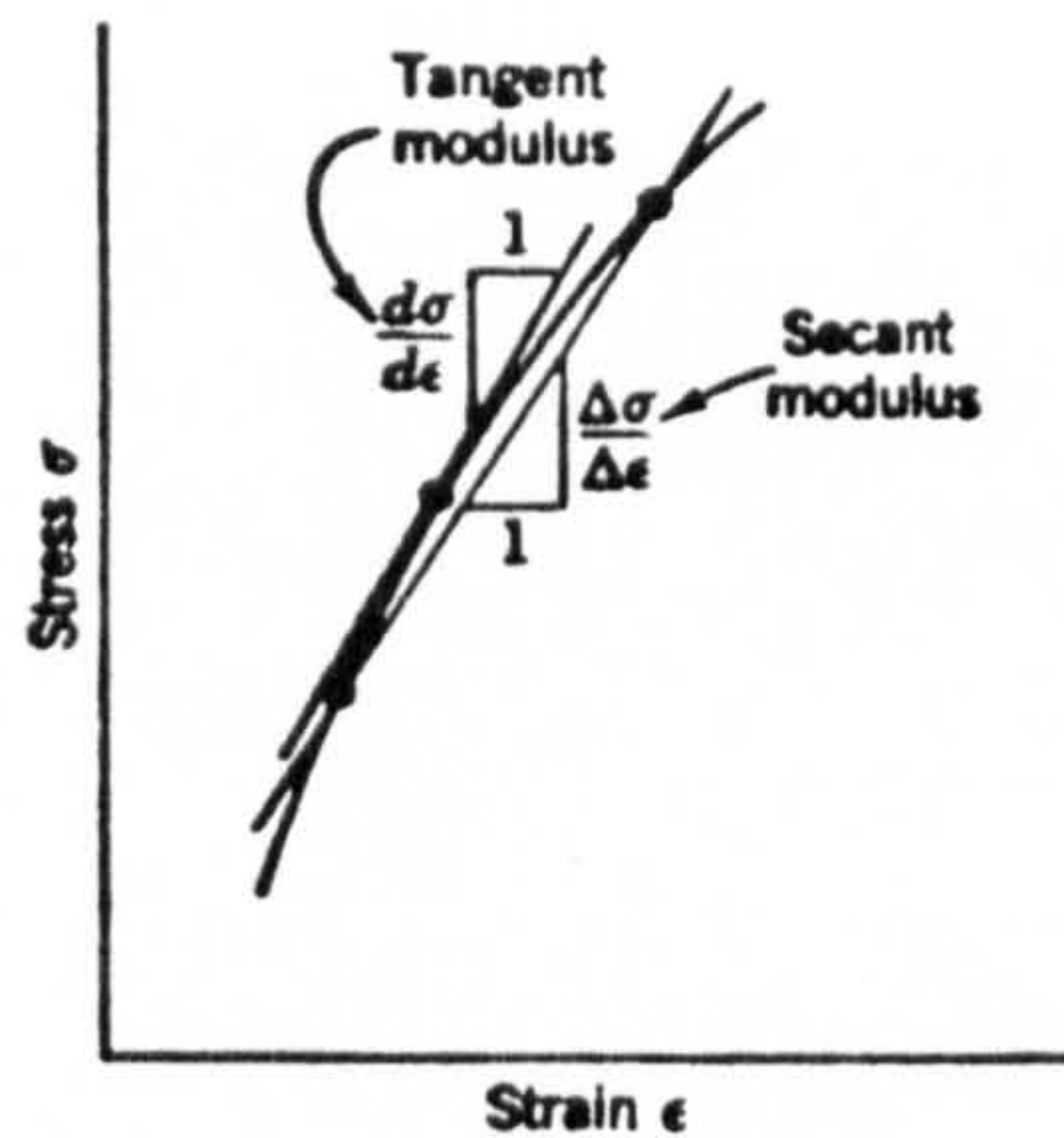


Figure 3.11 Definition of Tangent and Secant Modulus.

The Tangent Modulus is the slope of a straight line drawn tangentially to the stress-strain curve at a point. The value will vary with the point selected. The Secant Modulus is the slope of a straight line connecting two separate points on the curve. The value will vary with the location of the two points. If the stress increment is small, the Tangent Modulus is usually used, in this study the stress increments will be large and hence the Secant Modulus will be used. The two points on the curve chosen to represent the loading situation will be the initial density of the soil and the contact pressure of the wheel, figure (3.12). If for instance a tyre with a contact pressure of 200 kN/m² was operating on a soil with an initial density of 1.2 g/ml the line drawn on the figure, (A to B) was used to calculate the Young's Modulus. These two values were chosen as they represent the full range of possible conditions that might be present in the soil. The initial density represents the original soil condition and the contact pressure represents the maximum stress that was applied to the soil.

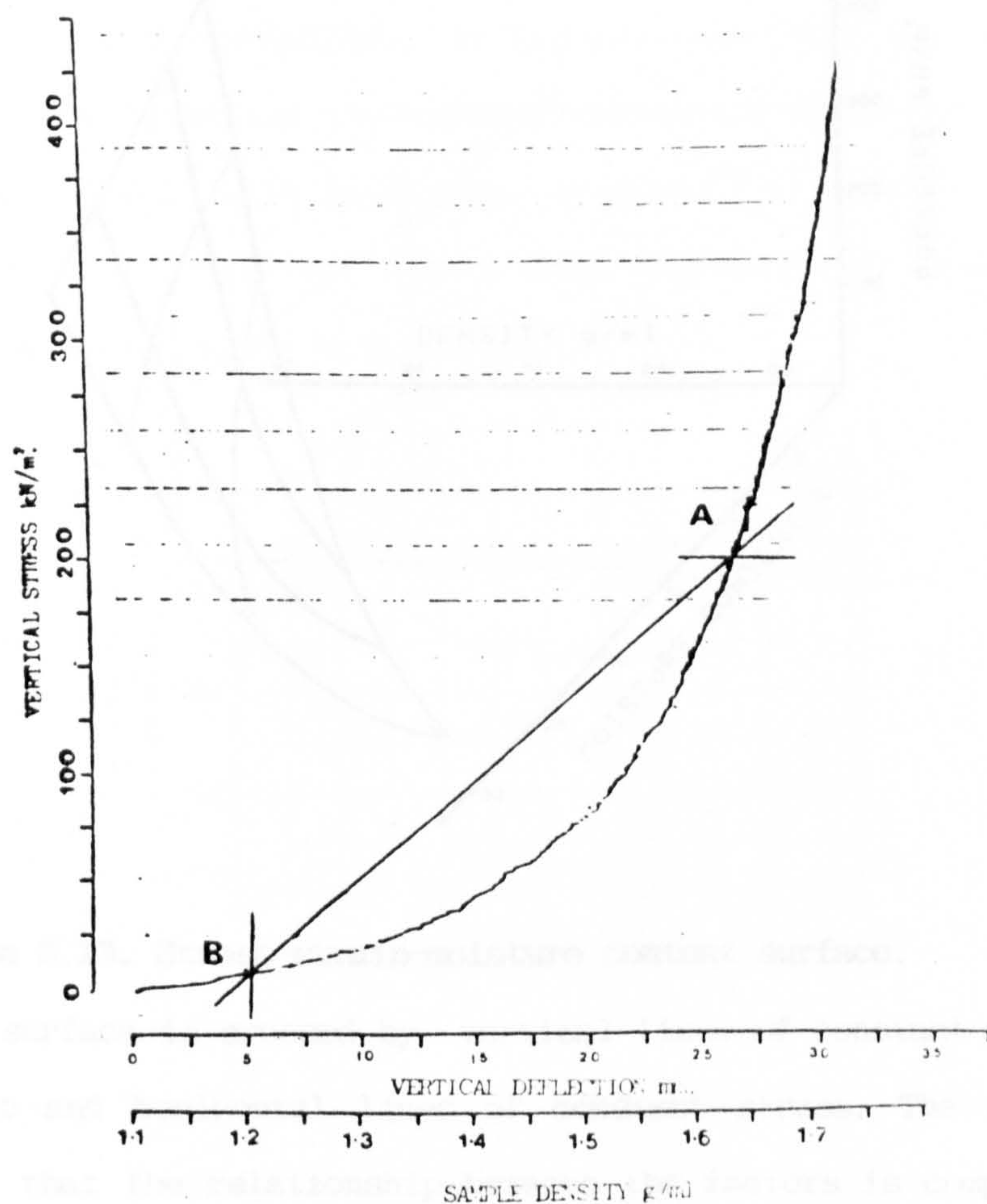


Figure 3.12. Linearized stress-strain characteristics.

To determine the influence of soil condition on Young's Modulus a series of confined compression tests were conducted on a range of light textured soils at various moisture contents in the range of 0 to 25% (dry basis). The stress-strain curves for a sandy loam soil at different moisture contents are plotted in figure (3.13).

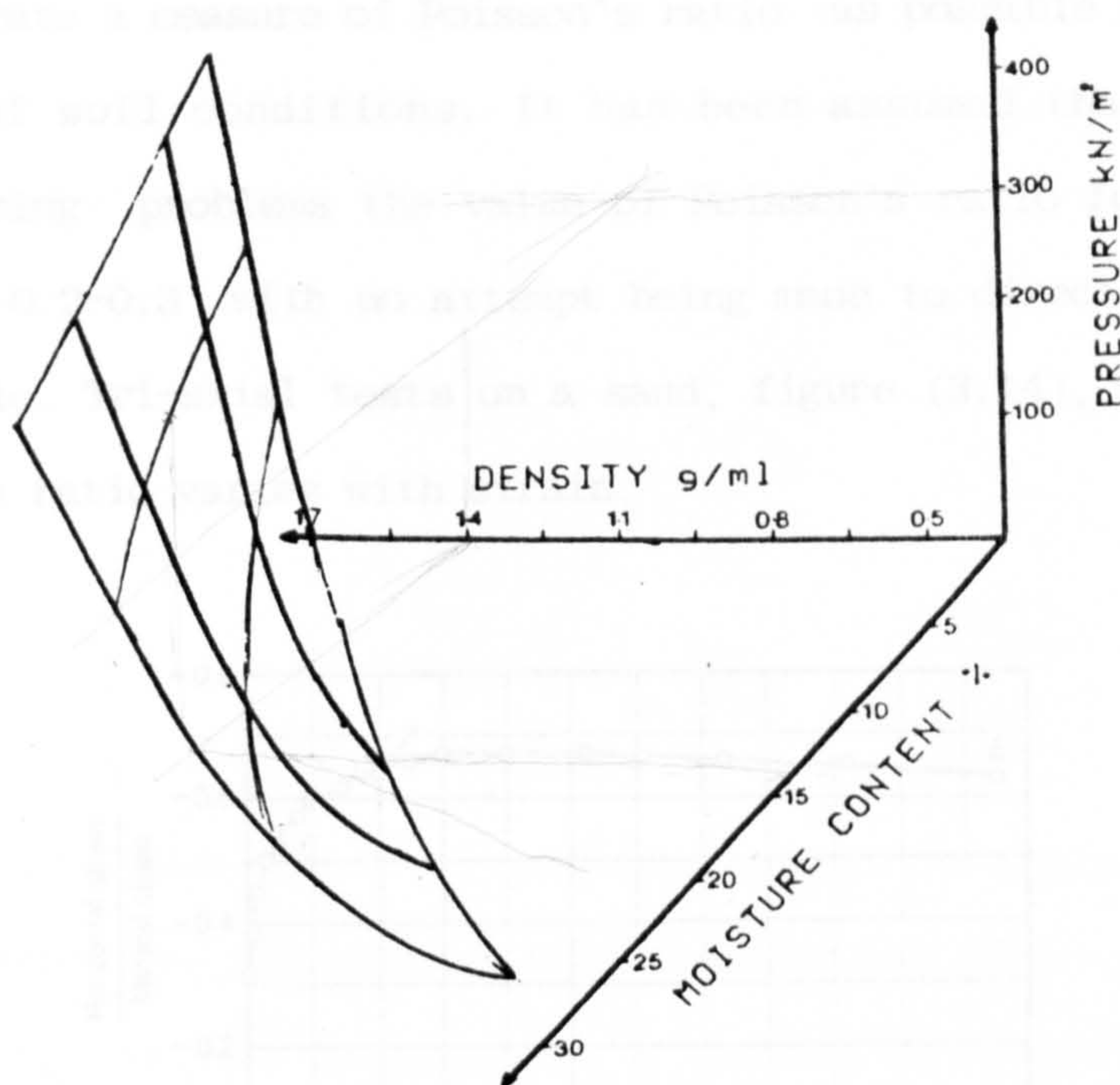


Figure 3.13. Stress-strain-moisture content surface.

The surface is crossed by vertical lines of constant moisture content and horizontal lines of constant stress. The surface shows that the relationship between the factors is complex and it is not possible to have a single relationship that covers a wide range of moisture contents. In order to model individual situations it was therefore advisable to perform a confined

compression test at that condition and use the results in the model. The simplicity of the confined compression test means it is possible to test undisturbed field samples.

3.5.5. MEASUREMENT OF POISSON'S RATIO

The Elastic equations, 3.17-3.21, show that the solution is affected by Poisson's ratio. It was important therefore, to get as accurate a measure of Poisson's ratio as possible for a wide range of soil conditions. It has been assumed that in most engineering problems the value of Poisson's ratio for soil is between 0.2-0.3 with no attempt being made to directly measure the ratio. Tri-axial tests on a sand, figure (3.14), have shown that the ratio varies with strain.

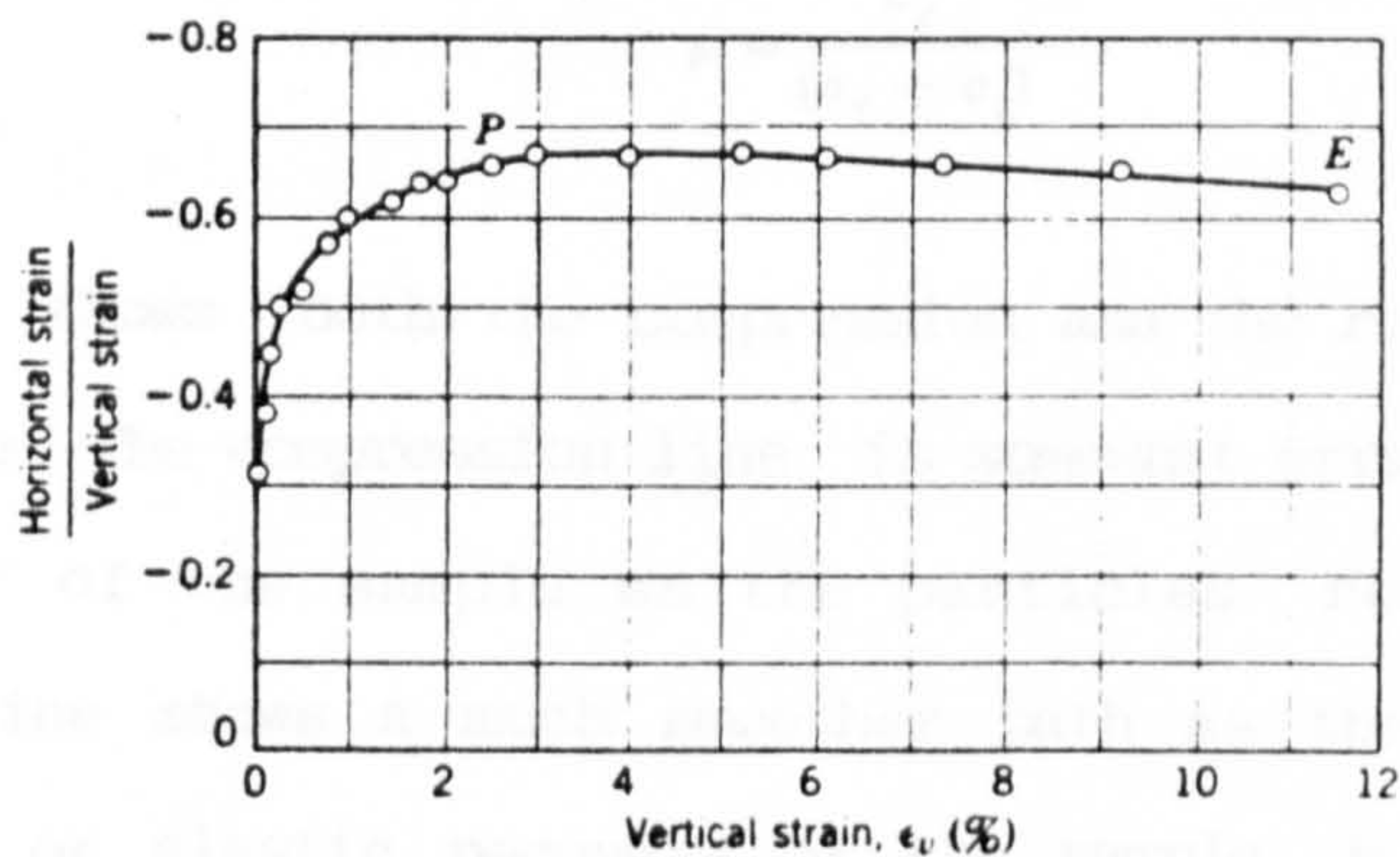


Figure 3.14 Variation of Poisson's ratio with strain.

(From Lambe and Whitman, 1979)

The ratio only becomes constant at very large strains, where the soil has failed, this value being greater than 0.5 and implies expansion of the sample. A Poisson's ratio of less than

0.5 only occurs at the start of compression where the sample is decreasing in volume. Because of this behaviour it is very difficult to make an exact evaluation of the Poisson's ratio using tri-axial tests. Using the confined compression cylinder however it was possible to directly monitor the vertical and lateral stress in the sample at any time. The lateral stress in the soil being equal to the hoop stress in the confining cylinder. A typical plot of these two factors is shown in figure (3.15). The slope of the lines is not a direct measure of the Poisson's ratio, but it can be found using the following relationships:-

$$\sigma_y = \frac{\mu}{1 - \mu} \sigma_z$$

$$\mu = \frac{\sigma_y}{(\sigma_y + \sigma_z)}$$

The plot shows both the compression and the release paths of the sample. The compression line is somewhat erratic due to the "working" of the sample as the particles rearranged. The release line shows a much smoother path as there was little reworking or elastic recovery of the sample. Both lines have roughly the same slope with the release line following the average path of the compression line. These plots show that the Poisson's ratio is constant during a confined compression test. The difference between the starting and finishing points on the lower axis was due to a small residual hoop stress in the soil sample at the end of the test as the soil was tightly packed in

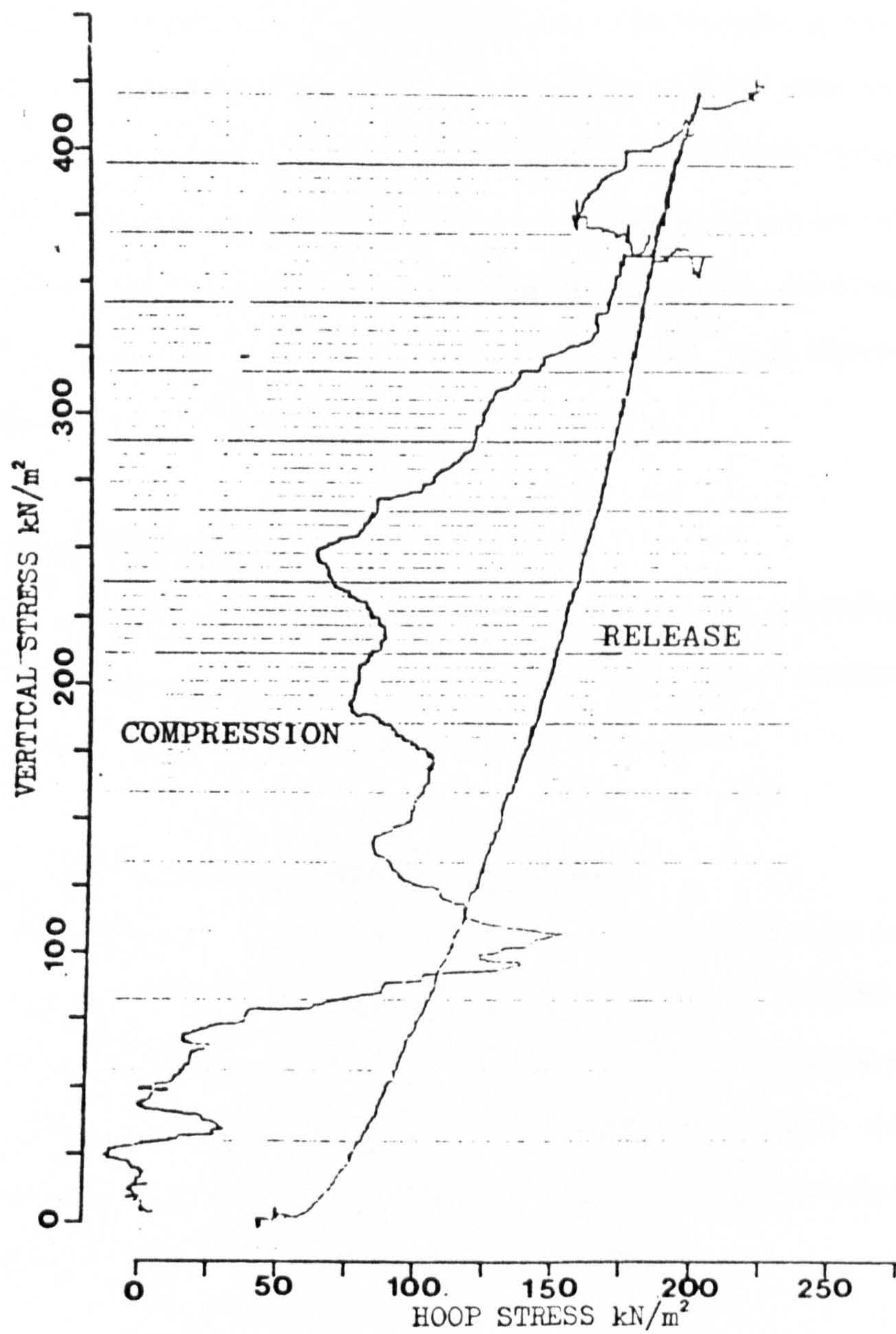


Figure 3.15. Variation of Poisson's ratio during compression.

the cylinder. It would be expected that Poisson's ratio is a constant, as it is a function of particle shape which would remain constant during compression. A series of tests were conducted on a range of light textured soils at different moisture contents and it was found that the Poisson's ratio was fairly constant and fell in the range 0.23 to 0.27. The value of Poisson's ratio used for the model work was therefore assumed to be 0.25. Using a constant value of Poisson's ratio greatly simplifies the calculations, the one set of basic data matrices could be used for all the calculations as they were independent of all inputs except Poisson's ratio.

3.5. TYRE INPUT DATA.

The objective with the tyre input data was to transform the complex situation at the tyre-soil interface into a simpler form that can be used by the model.

3.5.1. CONTACT AREA AND STRESS DISTRIBUTION.

The construction of the model allowed complex distributions of vertical, horizontal and lateral stresses over the contact area to be considered. Experimental evidence from other workers has shown that the distribution of stress over the contact area is complex, see figure (3.16), dependent on the inflation pressure, carcase stiffness and soil strength.

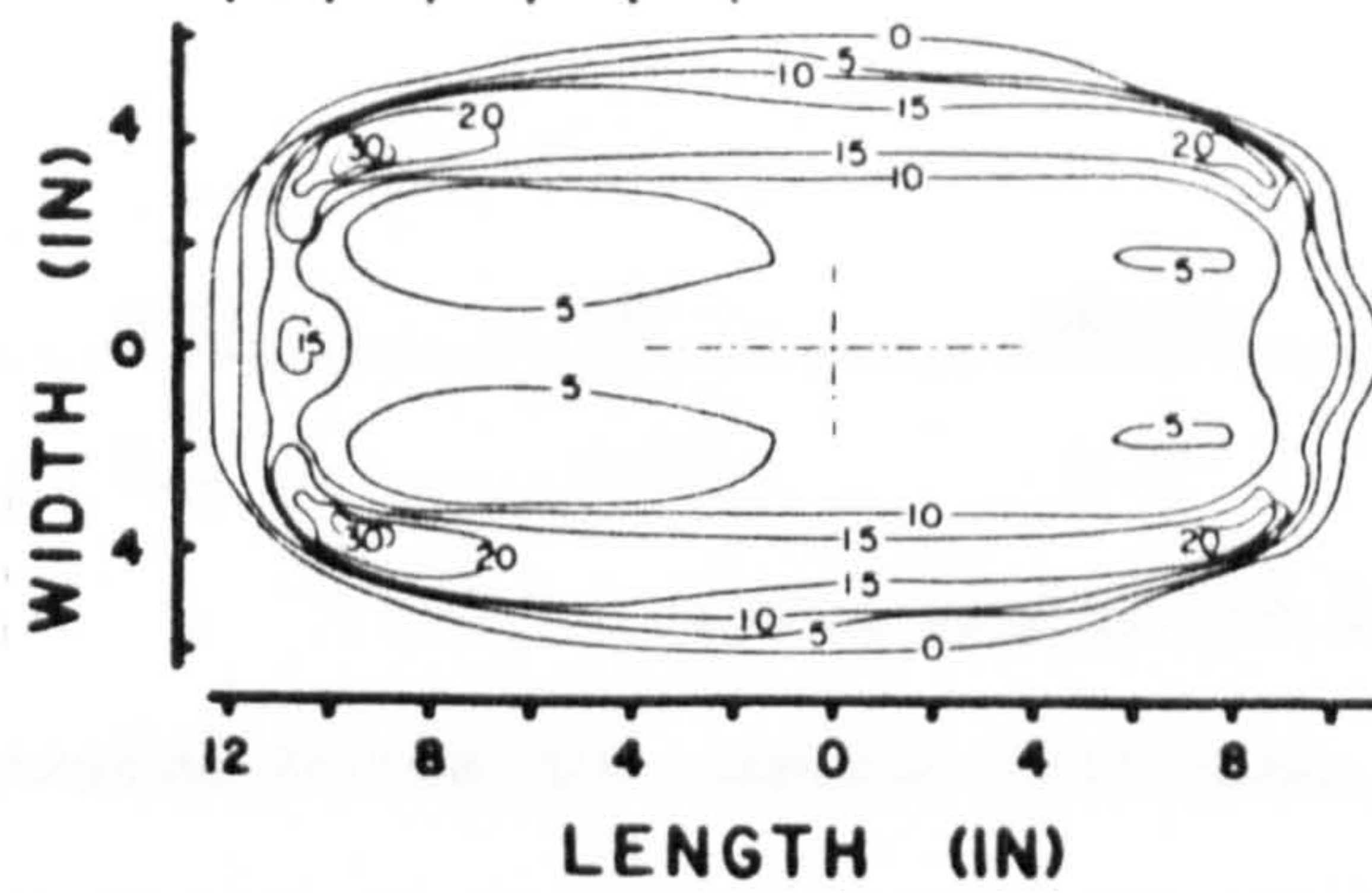


Figure 3.16. Variation of vertical contact stress over a tyre.

(From Vanden Berg and Gill 1962)

As a first approximation to this complex situation it was assumed that no lateral stress was exerted by the wheel. The vertical and horizontal stresses were also assumed to be constant across the tyre width only varying with length and following the stress pattern found by Vanden Berg and Gill (1960) for soft soil, figure (3.17).

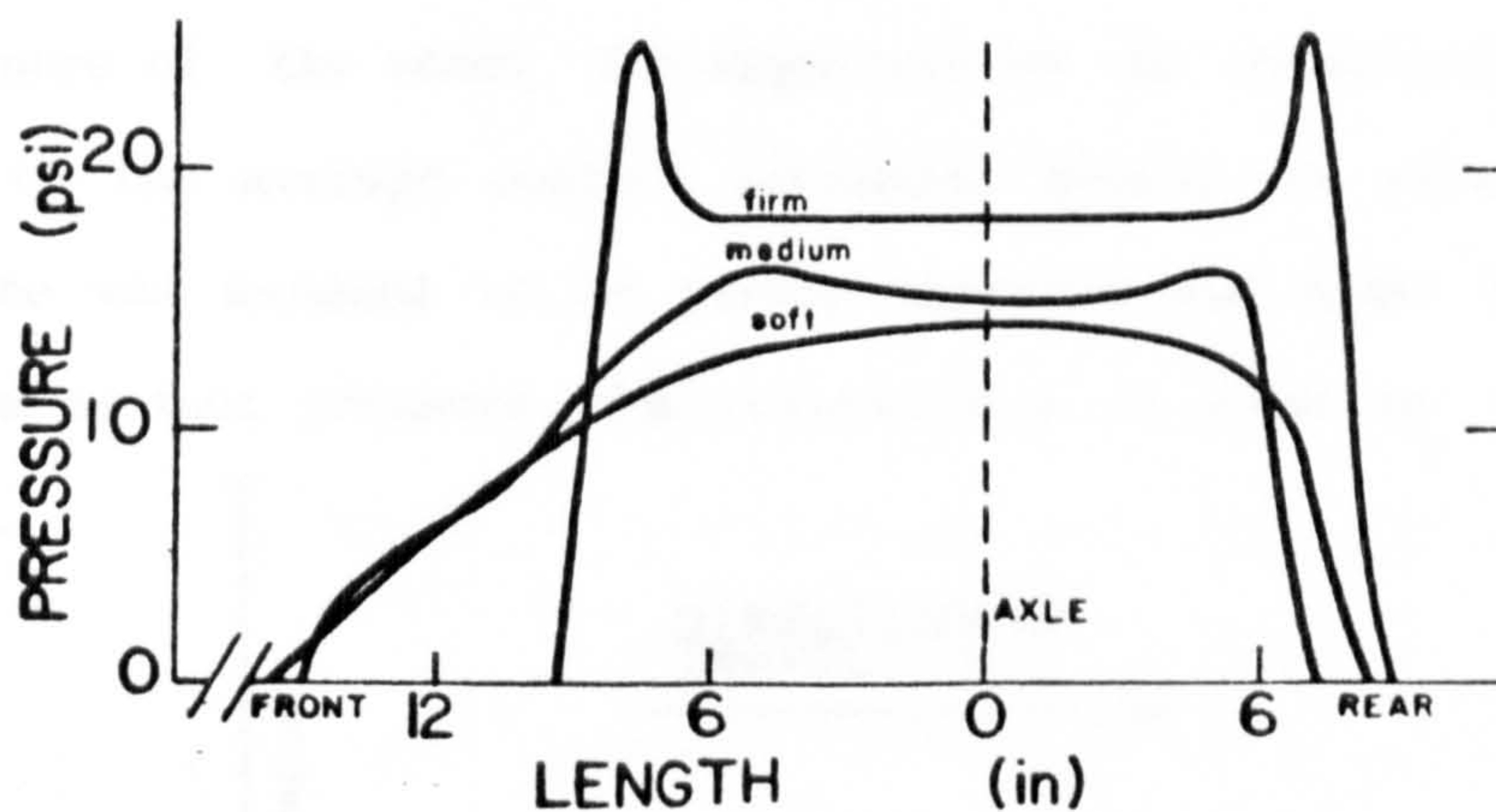


Figure 3.17. Variation of vertical stress along a tyre.

(From Vanden Berg and Gill 1962)

To account for the increase in the average contact pressure due to the carcass stiffness of the tyre a conversion factor, k , was introduced, see table (3.2).

ply rating	4-6	8	10-12	16
k	1.1	1.15	1.2	1.25

(From Koolen and Kuipers, 1983)

Table 3.2. Conversion factor for carcass stiffness.

The average contact stress was found by multiplying the inflation pressure by the appropriate k value for the ply rating of the tyre.

The vertical stress distribution, shown in figure (3.17) for soft soil, was modelled as a steadily increasing stress in front of the axle and a constant stress behind the the axle. The relationship developed to model this distribution assumed that in front of the axle the pressure was exerted radially out from the centre of the wheel, the magnitude of the resultant being equal to the average contact pressure. Behind the axle the pressure was assumed to be purely vertical and equal to the average contact pressure. The relationship is shown in figure (3.18).

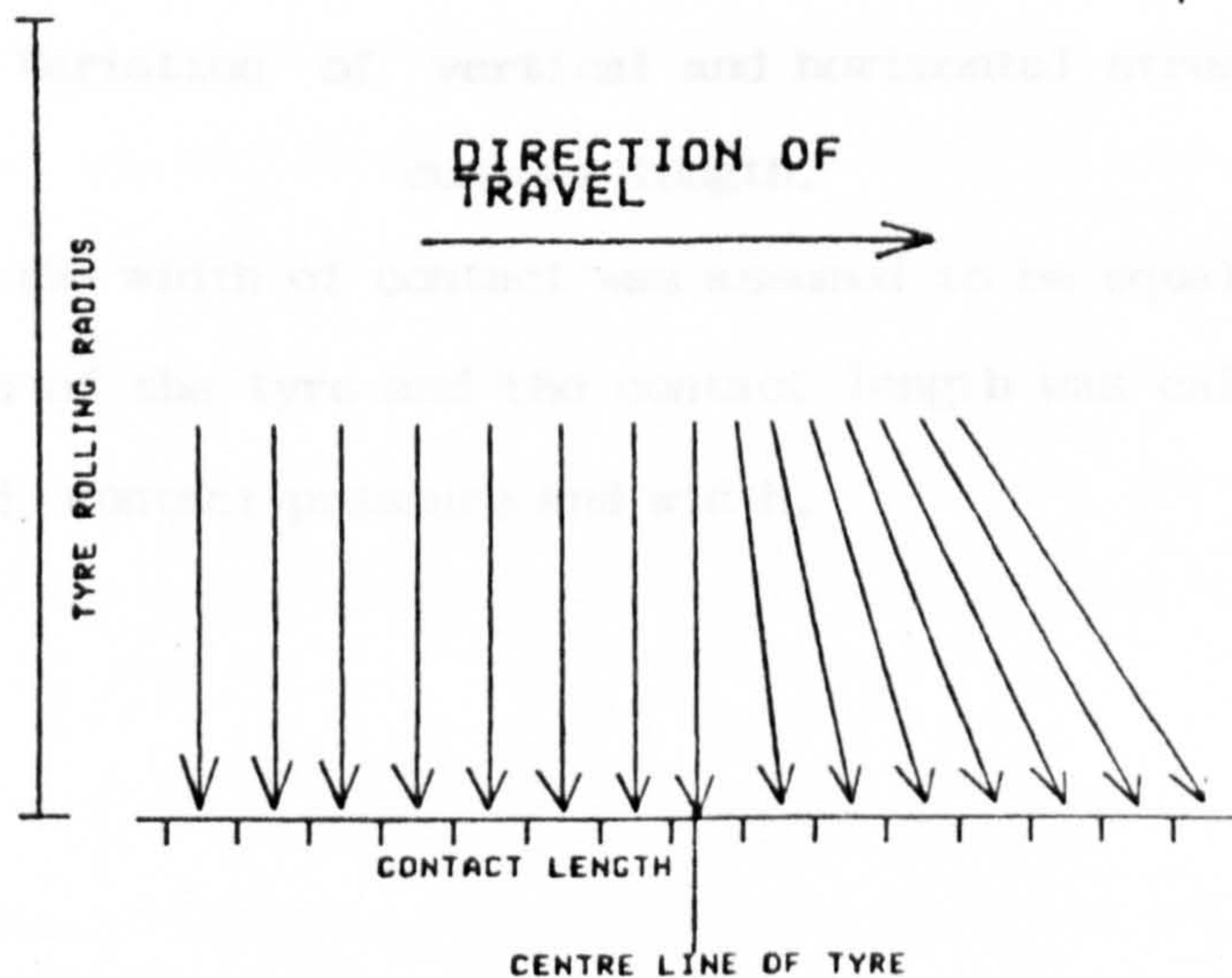


Figure 3.18. Model of the rolling action of the tyre.

The actual vertical and horizontal stress distributions when calculated yield the general distributions of stress shown in figure (3.19). The figure shows an increasing vertical stress in front of centre line of the tyre and a decreasing horizontal stress in the direction of travel.

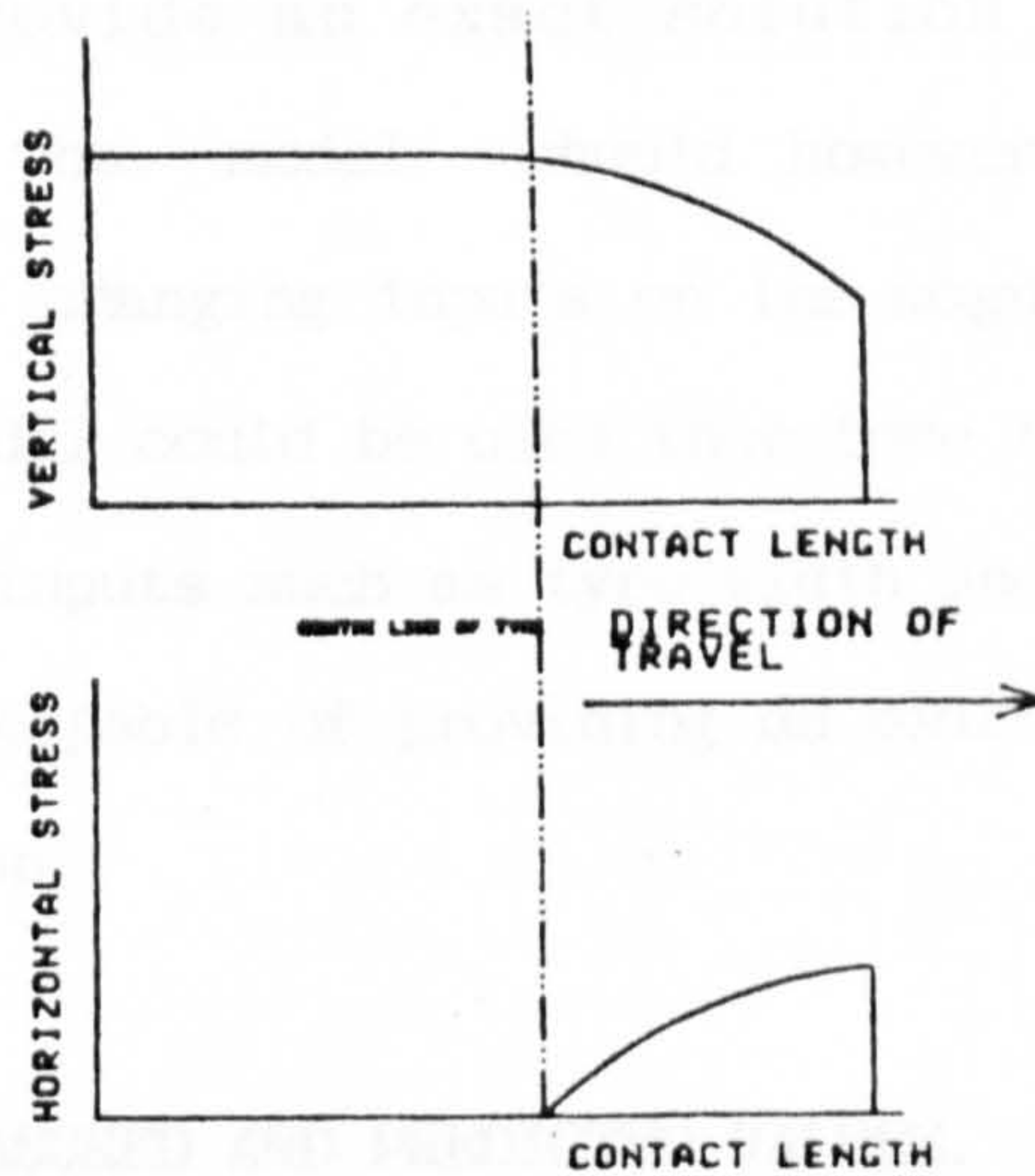


Figure 3.19. Variation of vertical and horizontal stress with contact length.

In the model the width of contact was assumed to be equal to the section width of the tyre and the contact length was calculated from the load, contact pressure and width.

4. VERIFICATION OF THE COMPUTER MODEL.

4.1. INTRODUCTION.

To verify the mathematical model of soil compaction the deformations found in practice in the soil bin were compared with those predicted by the model. Due to the assumptions and simplifications used to produce the model it was unlikely that the model would provide an exact solution to the soil deformation process. The model should however, be able to predict the effect of changing inputs on the magnitude of soil deformations. The model could be used therefore to predict the effect of changes in inputs such as tyre width and length, even though it may not be capable of providing an exact solution for an individual situation.

4.2. DISCUSSION OF MEASURED AND PREDICTED VALUES.

The measured and predicted vertical deflections for a load of 9 kN (table 7.A Appendix 2.2), are shown in table (4.1). Comparison of the measured and predicted deflections shows that the model predicted deflections of the right order of magnitude, with the vertical deflections being about 10 times greater than either the horizontal or lateral deflections. Although the predicted values were of the right order of magnitude there was a tendency for the model to overpredict the experimental data in two ways:-

- i) The deflections extended to a greater depth in the soil than

was expected from the measured results, this also meant that the surface deflections were too large.

ii) The deflections extended well outside the contact area of the tyre.

VERTICAL DEFLECTIONS. (mm)
Distance from centre line of tyre (mm).

DEPTH (mm)	350	300	250	200	150	100	50	0
0						// TYRE. //		
MEASURED.	0	0	0	-1	-2	16	39	42
PREDICTED.	10	12	15	19	27	48	58	61
50								
MEASURED.	0	0	0	0	0	14	35	39
PREDICTED.	10	12	15	19	27	39	48	51
100								
MEASURED.	0	0	0	0	4	12	27	30
PREDICTED.	10	12	15	19	25	33	39	41
150								
MEASURED.	0	0	0	0	3	10	20	17
PREDICTED.	10	12	15	18	23	27	31	32
200								
MEASURED.	0	0	0	0	2	8	12	10
PREDICTED.	10	12	14	17	20	23	26	26
250								
MEASURED.	0	0	0	0	1	6	8	5
PREDICTED.	10	12	14	16	18	20	22	22
300								
MEASURED.	0	0	0	0	0	2	3	3
PREDICTED.	10	11	13	14	16	17	18	19
350								
MEASURED.	0	0	0	0	0	0	0	0
PREDICTED.	10	11	12	13	14	15	16	16

Table 4.1. Comparison of measured and predicted vertical deflections.

The general pattern of overprediction shown in table 4.1 was present in the other two directions and in all the predicted values of the soil bin experiments.

4.3. MODIFICATIONS TO THE MATHEMATICAL MODEL.

Most of the over prediction was due to the model assuming that points out at infinity still had a deflection. The surface deflections outside the contact patch of the tyre were therefore made up of a very large number of small deflections extending to a great depth in the soil. In the following sections modifications are made to the model to reduce the overprediction by introducing a cut off strain. The cut off strain is a strain below which no permanent soil deformation occurs.

4.3.1. CUT OFF STRAIN EVALUATION.

The model assumes that all the elastic strains induced in the soil by the load are in fact plastic, that is, there is no recovery of the soil from the maximum deflection after the passage of the tyre. Other investigators, Gliemeroth (1953), Karafiath and Nowatzki (1978), have shown that although much of the deflection in the soil induced by the passage of a tyre is plastic there may be some elastic recovery once the load is removed. During the confined compression tests, conducted to measure the stress-strain characteristics of the soil, some of the samples were tested to see if there was any elastic recovery when the load was removed. It was found in all cases that if there was any recovery it was too small to be measured, this may not however be the case for stronger less compactable soils. Other tests were conducted using a repeated loading technique, where a sample was compressed until point A was reached, figure (4.1), the load was then released followed by reloading. When

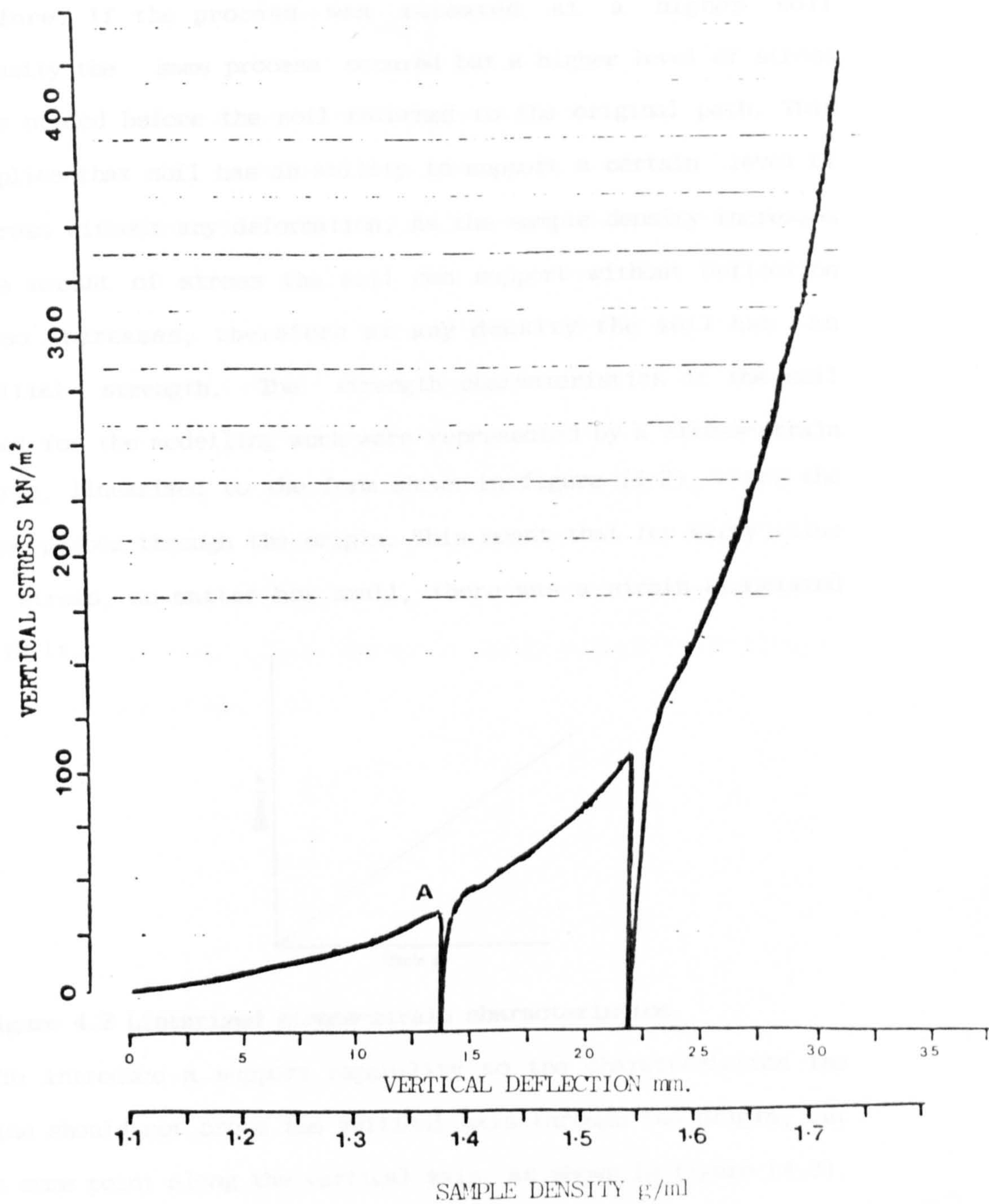


Figure 4.1. Cyclic loading of soil.

the loading cycle was restarted the soil did not deflect until the stress in the sample had reached the same value of stress as at point A. Once this stress value had been reached the stress-strain curve of the sample continued on the same path as before. If the process was repeated at a higher soil density the same process occurred but a higher level of stress was needed before the soil returned to the original path. This implies that soil has an ability to support a certain level of stress without any deformation. As the sample density increases the amount of stress the soil can support without deflection also increases, therefore at any density the soil has an initial strength. The strength characteristics of the soil used for the modelling work were represented by a stress-strain curve, linearized to the form shown in figure (4.2), where the line passed through the origin. This meant that for every value of stress, no matter how small, there was a strain associated with it.

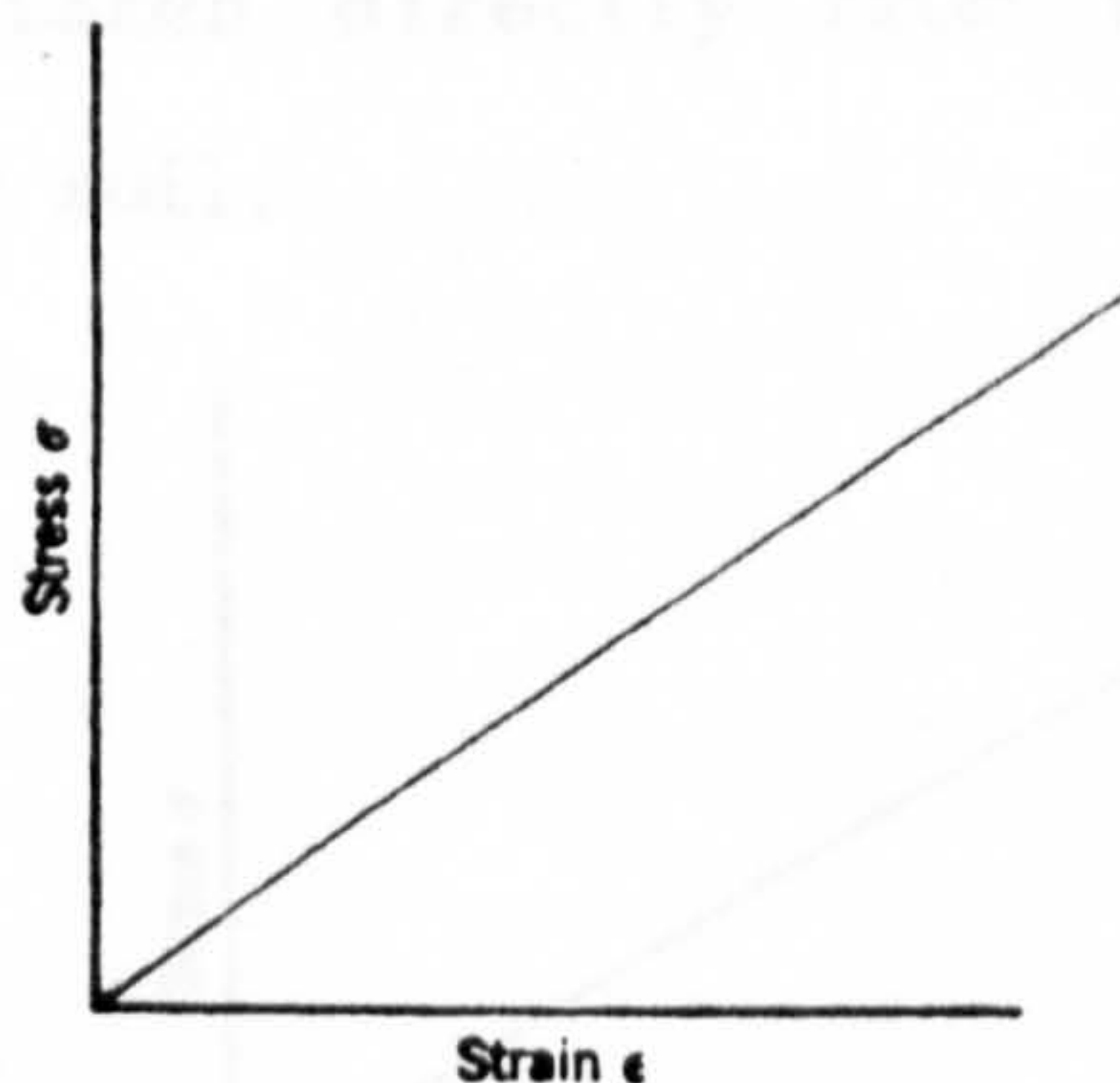


Figure 4.2 Linearized stress-strain characteristics.

To introduce a support capability to the characteristics the line should not cross the vertical axis through the origin, but at some point along the vertical axis, as shown in figure (4.3).

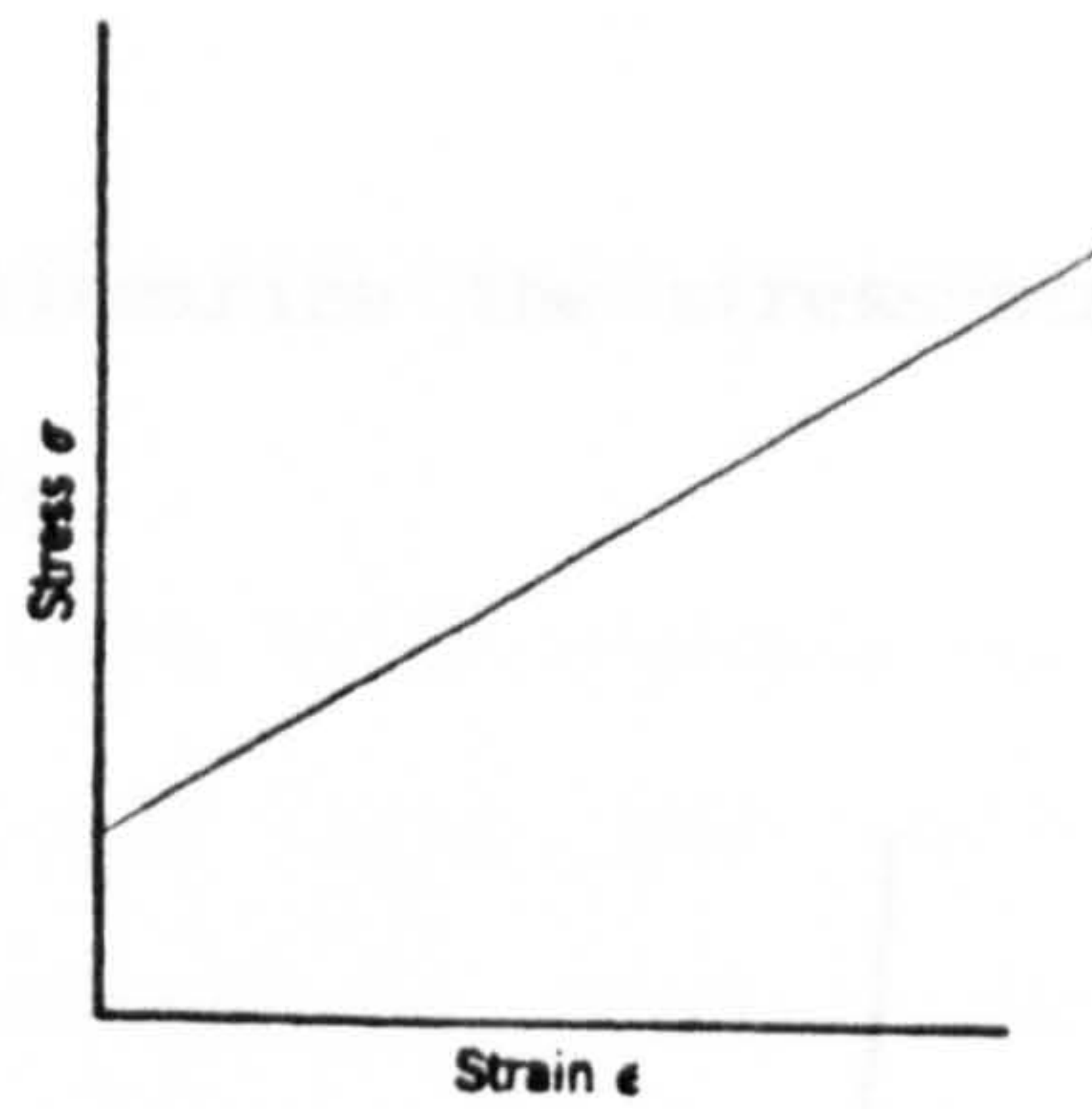


Figure 4.3. Offset stress-strain characteristics.

The value of the offset stress has to be overcome before the soil will deform. The offset could have been represented as either a stress or a strain. In this case, as deflections were being estimated by the model and the strain at any point in the soil could be calculated from the deformation of the two adjacent layers, it was easier to represent the support capability as a strain which had to be exceeded before any permanent deflection could take place rather than a stress. The strain needed was represented by a cut off strain (ϵ_c), figure (4.4), which was taken directly from the stress-strain characteristic of the soil.

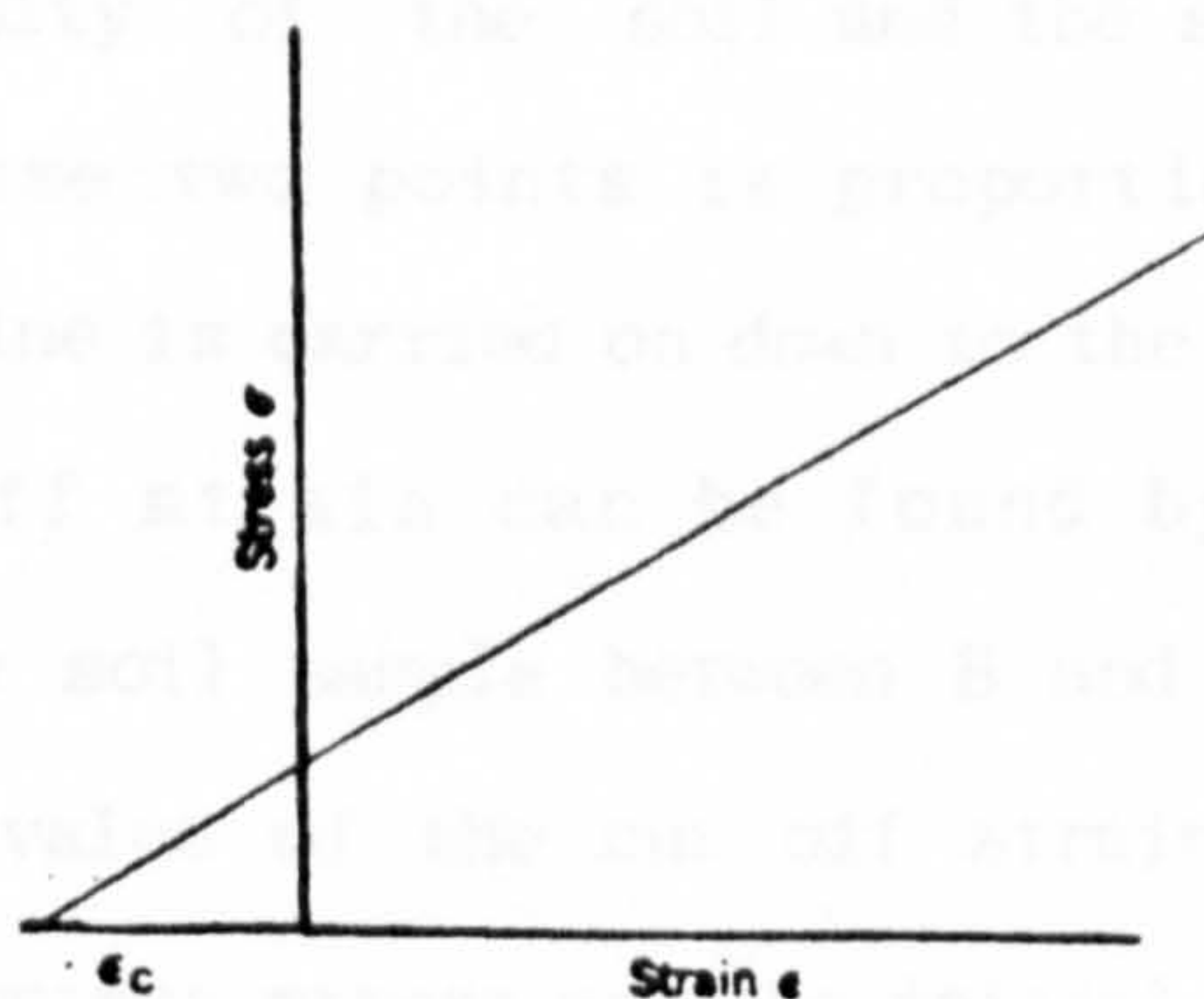


Figure 4.4. Representation of cut off strain.

To calculate the cut off strain for any soil condition, a line

was first drawn to linearize the stress-strain curve of the soil, see figure (4.5).

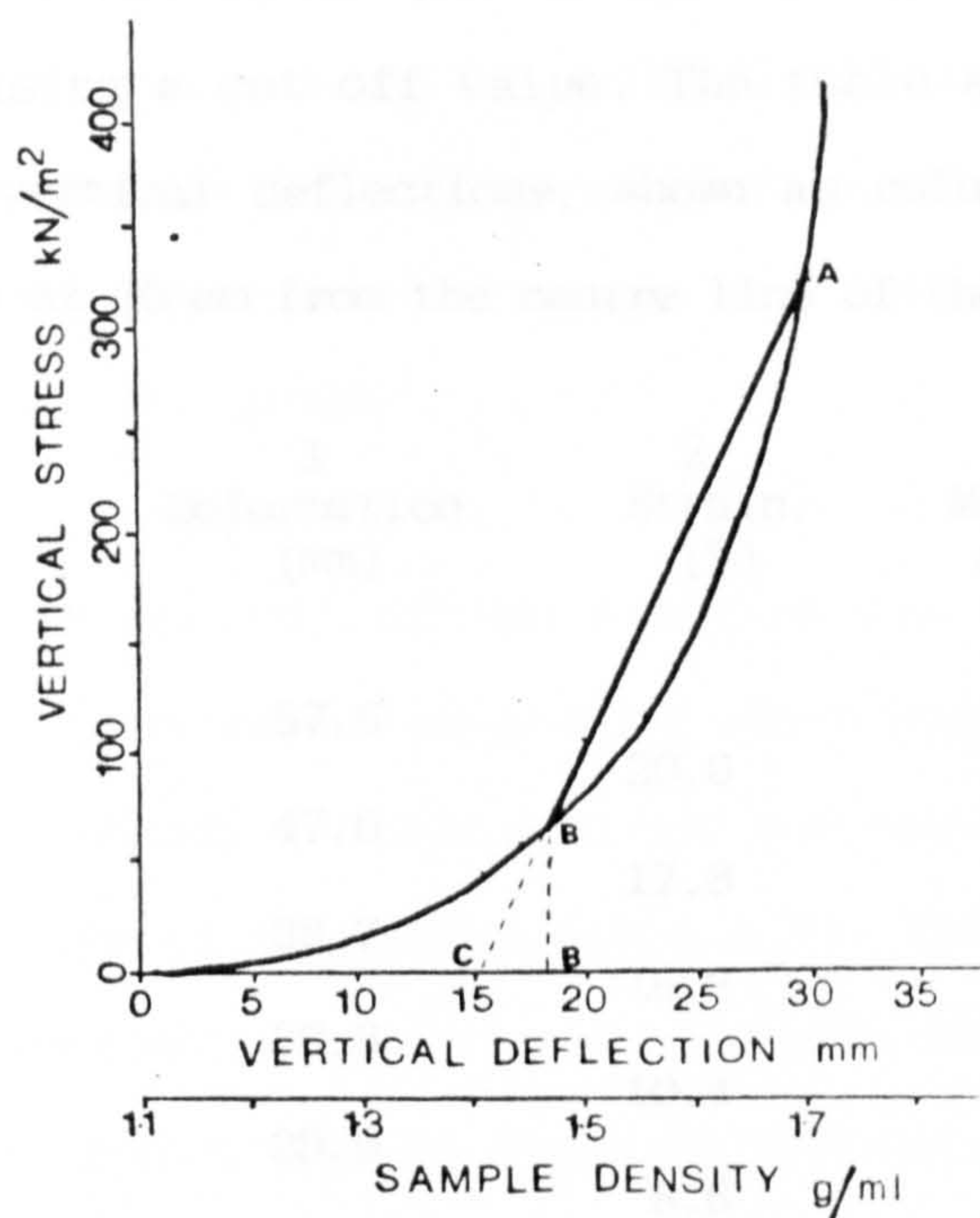


Figure 4.5. Calculation of cut off strain.

In figure 4.5 point A represents the contact stress at the interface between the tyre and the soil, point B represents the initial density of the soil and the slope of the line drawn between these two points is proportional to Young's Modulus. If this line is carried on down to the zero stress line at C, the cut off strain can be found by dividing the deformation of the soil sample between B and C by the sample length at B. The value of the cut off strain will vary with Young's Modulus, contact stress and the initial soil density.

4.3.2. APPLICATION OF CUT OFF STRAIN MODIFICATION TO PREDICTED RESULTS.

A) Vertical Deflections.

Table 4.2 shows an example of how the vertical strains were modified using a cut off value. The table shows a vertical column of vertical deflections, shown as column 1, taken from table (4.1) at 50 mm from the centre line of the wheel.

Depth. (mm)	1 Deformation. (mm)	2 Strain. (%)	3 Modified strain. (%)	4 Modified deformation. (mm)
0	57.6			35.4
		20.0	18.2	
50	47.6			26.3
		17.8	17.0	
100	38.7			18.3
		16.2	14.4	
150	30.6			11.1
		10.4	8.6	
200	25.9			6.8
		8.6	6.8	
250	21.6			3.4
		7.6	5.8	
300	17.8			0.5
		2.8	1.0	
350	16.4			0
		1.2	0	
400	15.8			0
		0.6	0	
450	15.5			0

Table 4.2. Deflection modification.

The strain, column 2, is calculated by dividing the difference in the deformation of two adjacent layers by the grid spacing. If the cut off strain is taken as 1.8% (table 4.3 Col.7), then any strain in column 2 below 1.8% will automatically be set to zero in column 3. Any strain in column 2 above 1.8% is reduced by 1.8% and put into column 3, as the first 1.8% will be supported without any permanent soil deformation. From the

modified strains the modified deflections are calculated using the reverse of the method of moving from column 1 to column 2. This process was repeated by the model for all the vertical deflections. For the X and Y deflections the same process was used but the centre line of the contact patch in the respective direction was taken as the origin and the strain calculated outwards from this origin.

Use of this cut off strain modification on the vertical deflections gave predicted results which correlated well with the measured values (compare modified deformations in table 4.2 with the measured values in table 4.1). The cut off strain correction reduced the deformations outside the contact area to zero, as the deflections at the soil surface were made up of a very large number of small strains that extended to a very great depth in the soil. The tendency of the model to overpredict the deformations below the tyre was also reduced by the cut off value and a point of zero deflection was established.

B) Horizontal and Lateral Deflections.

The horizontal loads at the soil surface were an attempt to model the large forward deflections in front of the tyre. The effect of these loads was to move the zero line of the horizontal deflections away from the centre of the contact patch and to generate large surface strains both in tension and compression. As the soil was assumed to be isotropic the same value of cut off strain should be applied for the modification

of the lateral and horizontal deflections. This modification proved to be less successful since a further assumption was involved, namely, that the soil had the same strength characteristics in tension as in compression. The soil is however very weak in tension making it difficult to model with one value of cut off strain. This was not a problem with a purely vertical load on the soil surface, as the magnitude of the deflections induced in the horizontal and lateral directions were only about 1/10 of the maximum vertical deflection. These small deflections reduced rapidly to zero after the first one or two layers using the cut off strain correction. Although the horizontal displacements can significantly effect soil compaction, see Bodman and Rubin (1948), to keep the model simple no further attempt was made to predict them. The original load distribution pattern, shown in figure (3.18) was simplified to a purely vertical load evenly distributed over the whole contact area with no horizontal loads at the soil surface. This meant that the model could not predict the horizontal deflection as it no longer represented a rolling tyre but a stationary tyre lowered onto the soil surface. Although this significantly changes the models ability to predict the three principle deflections it should be possible to gain sufficient information from the very simple case of the lowered wheel to aid in the reduction of wheel compaction.

4.4. COMPARISON OF MEASURED AND PREDICTED RESULTS FOLLOWING THE USE OF THE CUT OFF STRAIN.

4.4.1. INTRODUCTION.

The experimental work was conducted with sandy loam soil at 10% moisture content (dry basis), the stress-strain characteristics of the soil are shown in figure 4.6.

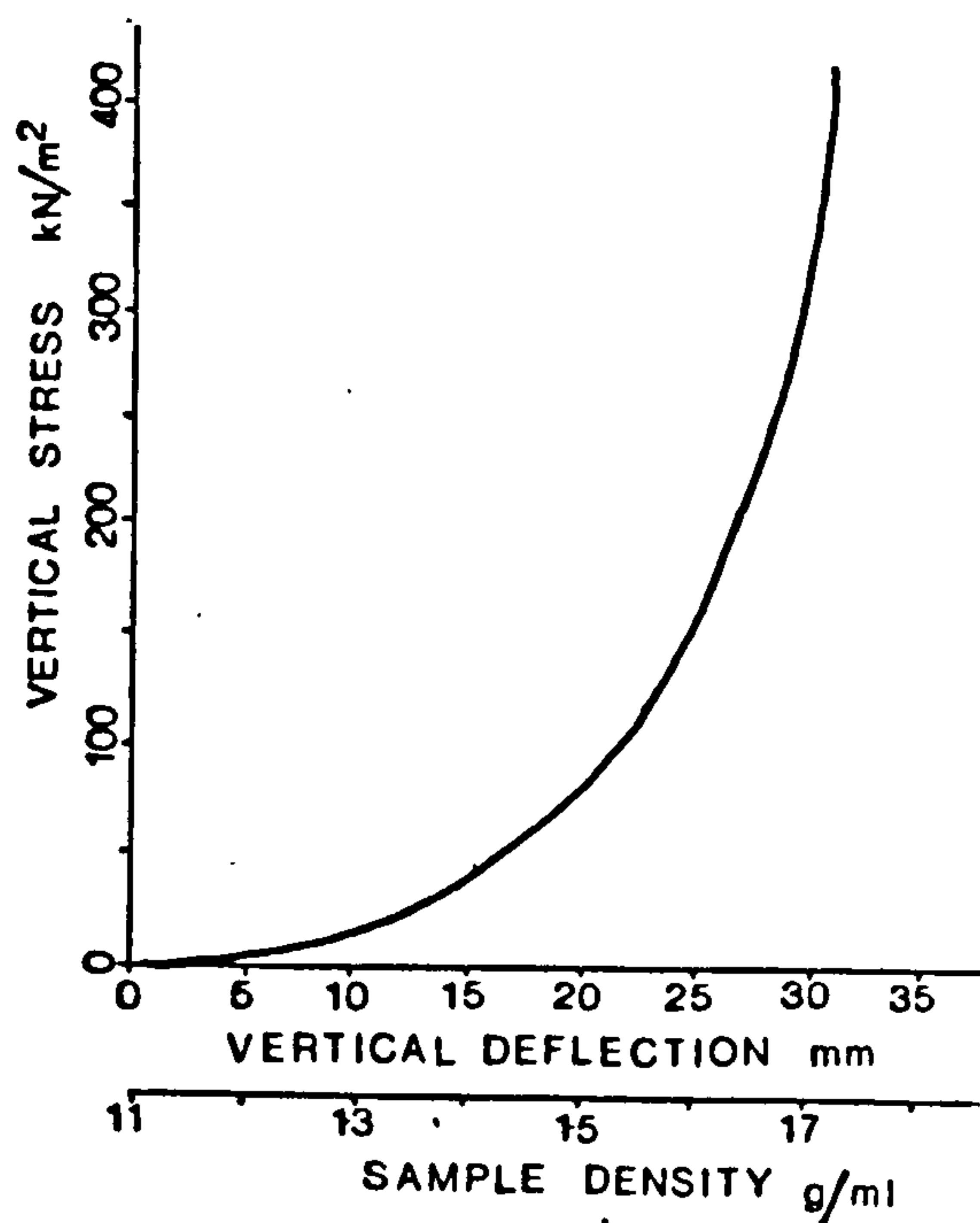


Figure 4.6. Soil stress-strain relationship.

The full size tyre used was a 6 ply grassland tyre with no tread pattern, 0.275m wide by 1.1m in diameter. The two small size wheels used were 0.1m and 0.05m wide, both with a diameter of 0.4m, a ply rating of 2 and a very shallow tread pattern. The input data for the model to predict the deflections is given below in Table 4.3.

Input	Contact Pressure kN/m ²	Contact Width m	Contact Length m	Wheel Load kN	Initial Density g/ml	Young's Modulus kN/m ²	Cut off Strain %
Load.							
1 TABLE 4.4	189	0.275	0.211	11	1.3	750	1.8
2 TABLE 4.5	189	0.275	0.165	9	1.3	750	1.8
3 TABLE 4.6	189	0.275	0.134	7	1.3	750	1.8
Density.							
1 TABLE 4.7	189	0.275	0.165	9	1.4	968	3.0
2 TABLE 4.8	189	0.275	0.165	9	1.5	1328	6.3
3 TABLE 4.9	189	0.275	0.165	9	1.6	1603	7.5
Pressure.							
1 TABLE 4.10	76	0.275	0.335	7	1.3	458	2.9
2 TABLE 4.11	189	0.275	0.134	7	1.3	750	1.8
3 TABLE 4.12	303	0.275	0.084	7	1.3	1031	1.0
Narrow tyre.							
1 TABLE 4.13	207	0.05	0.170	1.76	1.2	792	1.2
Standard tyre.							
1 TABLE 4.14	345	0.10	0.05	1.76	1.2	1214	1.1
2 TABLE 4.15	345	0.10	0.05	1.76	1.3	1340	2.3
3 TABLE 4.16	207	0.10	0.085	1.76	1.2	792	1.2
4 TABLE 4.17	207	0.10	0.085	1.76	1.3	838	2.6
Poisson's Ratio 0.25.							

Table 4.3. Input data for the model.

4.4.2. RESULTS AND DISCUSSION.

The measured and predicted vertical deflections for each of the experimental runs are given in tables 4.4 to 4.17. Only the vertical deflections are shown, as the horizontal and lateral deflections were not predicted by the model and were only apparent in the surface layer, with a maximum deflection of 1-2 mm. The size of the deflections in the lateral and horizontal directions showed however that the model predicts, with the input conditions used, a punch failure below the tyre.

Comparison of the vertical deflections for the full size experiments shows a good correlation, table 4.4, although at the centre line of the wheel the model underpredicts the surface deformation and overpredicts the depth to which the deformations

		Distance from centre line of wheel (mm).							
		350	300	250	200	150	100	50	0
Depth (mm).									
		Tyre							
0	MEASURED	0	-1	-4	-7	-8	20	41	42
	PREDICTED	0	0	0	0	0	31	37	39
50	MEASURED	0	0	0	0	4	18	39	41
	PREDICTED	0	0	0	0	0	23	29	31
100	MEASURED	0	0	0	0	3	13	29	30
	PREDICTED	0	0	0	0	0	16	21	22
150	MEASURED	0	0	0	0	3	9	20	20
	PREDICTED	0	0	0	0	0	10	14	15
200	MEASURED	0	0	0	0	2	6	15	14
	PREDICTED	0	0	0	0	0	7	9	10
250	MEASURED	0	0	0	0	0	4	9	10
	PREDICTED	0	0	0	0	0	5	6	6
300	MEASURED	0	0	0	0	0	2	4	4
	PREDICTED	0	0	0	0	0	3	4	4
350	MEASURED	0	0	0	0	0	0	1	1
	PREDICTED	0	0	0	0	0	2	2	2

TABLE 4.4 Wheel load 11 kN., @189 kN/m², @1.3 g/ml.

		Distance from centre line of wheel (mm).							
		350	300	250	200	150	100	50	0
Depth (mm).									
		Tyre							
0	MEASURED	0	0	0	-1	-2	16	39	42
	PREDICTED	0	0	0	0	0	27	35	38
50	MEASURED	0	0	0	0	0	14	35	39
	PREDICTED	0	0	0	0	0	19	26	29
100	MEASURED	0	0	0	0	4	12	27	30
	PREDICTED	0	0	0	0	0	14	18	19
150	MEASURED	0	0	0	0	3	10	20	17
	PREDICTED	0	0	0	0	0	8	11	13
200	MEASURED	0	0	0	0	2	8	12	10
	PREDICTED	0	0	0	0	0	5	7	8
250	MEASURED	0	0	0	0	1	6	8	5
	PREDICTED	0	0	0	0	0	3	3	4
300	MEASURED	0	0	0	0	0	2	3	3
	PREDICTED	0	0	0	0	0	1	1	2
350	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.5 Wheel load 9 kN., @189 kN/m², @1.3 g/ml.

Depth (mm).	Distance from centre line of wheel (mm).							
	350	300	250	200	150	100	50	0
						Tyre		
0 MEASURED	0	0	0	0	0	12	30	33
PREDICTED	0	0	0	0	0	23	28	29
50 MEASURED	0	0	0	0	0	11	28	30
PREDICTED	0	0	0	0	0	15	20	21
100 MEASURED	0	0	0	0	0	10	20	23
PREDICTED	0	0	0	0	0	9	12	13
150 MEASURED	0	0	0	0	2	8	14	15
PREDICTED	0	0	0	0	0	5	7	8
200 MEASURED	0	0	0	0	1	4	9	9
PREDICTED	0	0	0	0	0	3	4	5
250 MEASURED	0	0	0	0	0	2	2	5
PREDICTED	0	0	0	0	0	1	2	2
300 MEASURED	0	0	0	0	0	0	1	1
PREDICTED	0	0	0	0	0	0	1	1
350 MEASURED	0	0	0	0	0	0	0	0
PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.6 Wheel load 7 kN., @189 kN/m², @1.3 g/ml.

Depth (mm).	Distance from centre line of wheel (mm).							
	350	300	250	200	150	100	50	0
						Tyre		
0 MEASURED	0	0	0	0	0	22	24	25
PREDICTED	0	0	0	0	0	16	20	21
50 MEASURED	0	0	0	0	0	18	21	23
PREDICTED	0	0	0	0	0	10	14	14
100 MEASURED	0	0	0	0	0	12	13	15
PREDICTED	0	0	0	0	0	6	9	9
150 MEASURED	0	0	0	0	0	7	8	9
PREDICTED	0	0	0	0	0	3	5	5
200 MEASURED	0	0	0	0	0	3	4	5
PREDICTED	0	0	0	0	0	1	2	2
250 MEASURED	0	0	0	0	0	0	2	3
PREDICTED	0	0	0	0	0	0	1	1
300 MEASURED	0	0	0	0	0	0	0	0
PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.7 Soil density 1.4 g/ml. @189 kN/m², @ 9kN.

		Distance from centre line of wheel (mm).							
		350	300	250	200	150	100	50	0
Depth (mm).		Tyre							
0	MEASURED	0	0	0	0	0	5	8	8
	PREDICTED	0	0	0	0	0	3	5	5
50	MEASURED	0	0	0	0	0	3	5	6
	PREDICTED	0	0	0	0	0	1	3	3
100	MEASURED	0	0	0	0	0	1	3	3
	PREDICTED	0	0	0	0	0	0	1	1
150	MEASURED	0	0	0	0	0	0	1	1
	PREDICTED	0	0	0	0	0	0	0	0
200	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.8 Soil density 1.5 g/ml., @189 kN/m², @ 9kN.

		Distance from centre line of wheel (mm).							
		350	300	250	200	150	100	50	0
Depth (mm).		Tyre							
0	MEASURED	0	0	0	0	0	0	2	3
	PREDICTED	0	0	0	0	0	0	0	0
50	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.9 Soil density 1.6 g/ml., @189 kN/m², @ 9kN.

		Distance from centre line of wheel (mm).							
		350	300	250	200	150	100	50	0
Depth (mm).		Tyre							
0	MEASURED	0	0	0	0	0	18	20	21
	PREDICTED	0	0	0	0	0	18	19	20
50	MEASURED	0	0	0	0	4	16	18	19
	PREDICTED	0	0	0	0	0	13	14	15
100	MEASURED	0	0	0	0	4	11	14	14
	PREDICTED	0	0	0	0	0	9	10	11
150	MEASURED	0	0	0	0	0	4	6	7
	PREDICTED	0	0	0	0	0	5	6	7
200	MEASURED	0	0	0	0	0	0	1	2
	PREDICTED	0	0	0	0	0	2	4	5
250	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	1	2	2
300	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.10 Contact pressure 76kN/m²., @1.3 g/ml, @7 kN.

		Distance from centre line of wheel (mm).							
		350	300	250	200	150	100	50	0
Depth (mm).								Tyre	
0	MEASURED	0	0	0	0	0	15	28	32
	PREDICTED	0	0	0	0	0	22	28	29
50	MEASURED	0	0	0	0	0	9	24	30
	PREDICTED	0	0	0	0	0	15	20	21
100	MEASURED	0	0	0	0	2	7	18	24
	PREDICTED	0	0	0	0	0	9	12	13
150	MEASURED	0	0	0	0	1	5	10	12
	PREDICTED	0	0	0	0	0	5	7	8
200	MEASURED	0	0	0	0	0	4	7	8
	PREDICTED	0	0	0	0	0	3	4	5
250	MEASURED	0	0	0	0	0	3	1	4
	PREDICTED	0	0	0	0	0	1	2	2
300	MEASURED	0	0	0	0	0	0	0	1
	PREDICTED	0	0	0	0	0	0	1	1
350	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.11 Contact pressure 189 kN/m²., @1.3 g/ml, @7kN.

		Distance from centre line of wheel (mm).							
		350	300	250	200	150	100	50	0
Depth (mm).								Tyre	
0	MEASURED	0	0	-3	-4	-5	25	43	47
	PREDICTED	0	0	0	0	0	29	34	35
50	MEASURED	0	0	0	0	0	20	40	42
	PREDICTED	0	0	0	0	0	21	25	27
100	MEASURED	0	0	0	0	3	16	30	31
	PREDICTED	0	0	0	0	0	14	17	19
150	MEASURED	0	0	0	0	0	9	16	17
	PREDICTED	0	0	0	0	0	9	11	12
200	MEASURED	0	0	0	0	0	5	9	10
	PREDICTED	0	0	0	0	0	6	7	8
250	MEASURED	0	0	0	0	0	3	5	5
	PREDICTED	0	0	0	0	0	4	5	5
300	MEASURED	0	0	0	0	0	0	2	2
	PREDICTED	0	0	0	0	0	2	3	3
350	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	2	2

TABLE 4.12 Contact pressure 303 kN/m²., @1.3 g/ml, @7kN.

		Distance from centre line of wheel (mm).							
		175	150	125	100	75	50	25	0
Depth (mm).									
0	MEASURED	0	0	0	0	0	0	6	9
	PREDICTED	0	0	0	0	0	0	8	8
25	MEASURED	0	0	0	0	0	0	5	8
	PREDICTED	0	0	0	0	0	0	5	5
50	MEASURED	0	0	0	0	0	1	3	4
	PREDICTED	0	0	0	0	0	0	3	3
75	MEASURED	0	0	0	0	0	1	1	2
	PREDICTED	0	0	0	0	0	0	2	2
100	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	1	1
125	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.13 Narrow tyre., @207 kN/m², @1.3 g/ml, @1.76 kN.

		Distance from centre line of wheel (mm).							
		175	150	125	100	75	50	25	0
Depth (mm).									
0	MEASURED	0	0	0	-1	-2	3	10	11
	PREDICTED	0	0	0	0	0	11	13	13
25	MEASURED	0	0	0	0	0	3	8	10
	PREDICTED	0	0	0	0	0	7	9	9
50	MEASURED	0	0	0	0	0	2	6	7
	PREDICTED	0	0	0	0	0	4	5	5
75	MEASURED	0	0	0	0	0	1	3	4
	PREDICTED	0	0	0	0	0	2	3	3
100	MEASURED	0	0	0	0	0	1	2	2
	PREDICTED	0	0	0	0	0	1	2	2
125	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	1	1
150	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.14 Soil density 1.2 g/ml @ 345 kN/m².

		Distance from centre line of wheel (mm).							
		175	150	125	100	75	50	25	0
Depth (mm).									Tyre
0	MEASURED	0	0	0	0	0	1	5	7
	PREDICTED	0	0	0	0	0	7	9	9
25	MEASURED	0	0	0	0	0	0	3	5
	PREDICTED	0	0	0	0	0	4	5	5
50	MEASURED	0	0	0	0	0	0	2	3
	PREDICTED	0	0	0	0	0	2	3	3
75	MEASURED	0	0	0	0	0	0	1	1
	PREDICTED	0	0	0	0	0	0	1	1
100	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.15 Soil density 1.3 g/ml @ 354 kN/m², @1.76 kN.

		Distance from centre line of wheel (mm).							
		175	150	125	100	75	50	25	0
Depth (mm).									Tyre
0	MEASURED	0	0	0	0	-1	2	6	7
	PREDICTED	0	0	0	0	0	8	10	10
25	MEASURED	0	0	0	0	0	2	6	7
	PREDICTED	0	0	0	0	0	4	6	6
50	MEASURED	0	0	0	0	0	1	5	6
	PREDICTED	0	0	0	0	0	2	3	3
75	MEASURED	0	0	0	0	0	0	2	2
	PREDICTED	0	0	0	0	0	1	1	1
100	MEASURED	0	0	0	0	0	0	1	1
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.16 Soil density 1.2 g/ml @ 207 kN/m², @1.76 kN.

		Distance from centre line of wheel (mm).							
		175	150	125	100	75	50	25	0
Depth (mm).									Tyre
0	MEASURED	0	0	0	0	0	1	3	5
	PREDICTED	0	0	0	0	0	6	8	8
25	MEASURED	0	0	0	0	0	0	2	4
	PREDICTED	0	0	0	0	0	3	5	5
50	MEASURED	0	0	0	0	0	0	1	2
	PREDICTED	0	0	0	0	0	1	2	2
75	MEASURED	0	0	0	0	0	0	0	1
	PREDICTED	0	0	0	0	0	0	1	1
100	MEASURED	0	0	0	0	0	0	0	0
	PREDICTED	0	0	0	0	0	0	0	0

TABLE 4.17 Soil density 1.3 g/ml @ 207 kN/m², @1.76 kN.

extend. Discrepancies between the measured and predicted values could be due to the following factors:-

i) The linearization of the stress-strain curve. The model uses a linearized stress-strain characteristic to simulate the strength of the soil. Even though the chosen relationship satisfies the boundary conditions of the soil there are likely to be errors induced by the procedure. This linearizing method tended to over estimate the soil strength at depth (B) and underestimate the soil strength at the surface (A), this is shown by figure (4.7). The slope of the line at any point is proportional to Young's Modulus, the steeper the slope the greater the value of Young's Modulus and the stronger the soil. The linearized soil strength is marked on the figure, A represents the condition at the tyre soil interface, B represents the condition deep in the soil. The slope of the linear Young's Modulus at A is less than the actual slope, the model therefore assumes weaker soil at the surface. The opposite is true of B where the model assumes the soil is stronger. The effect of using a model based on a non-linear Young's Modulus would be to reduce the strain at the soil surface and increase the strain at depth. Table 4.18 shows the difference in measured and predicted strain, the results are taken from table 4.6 under the centre line of the wheel.

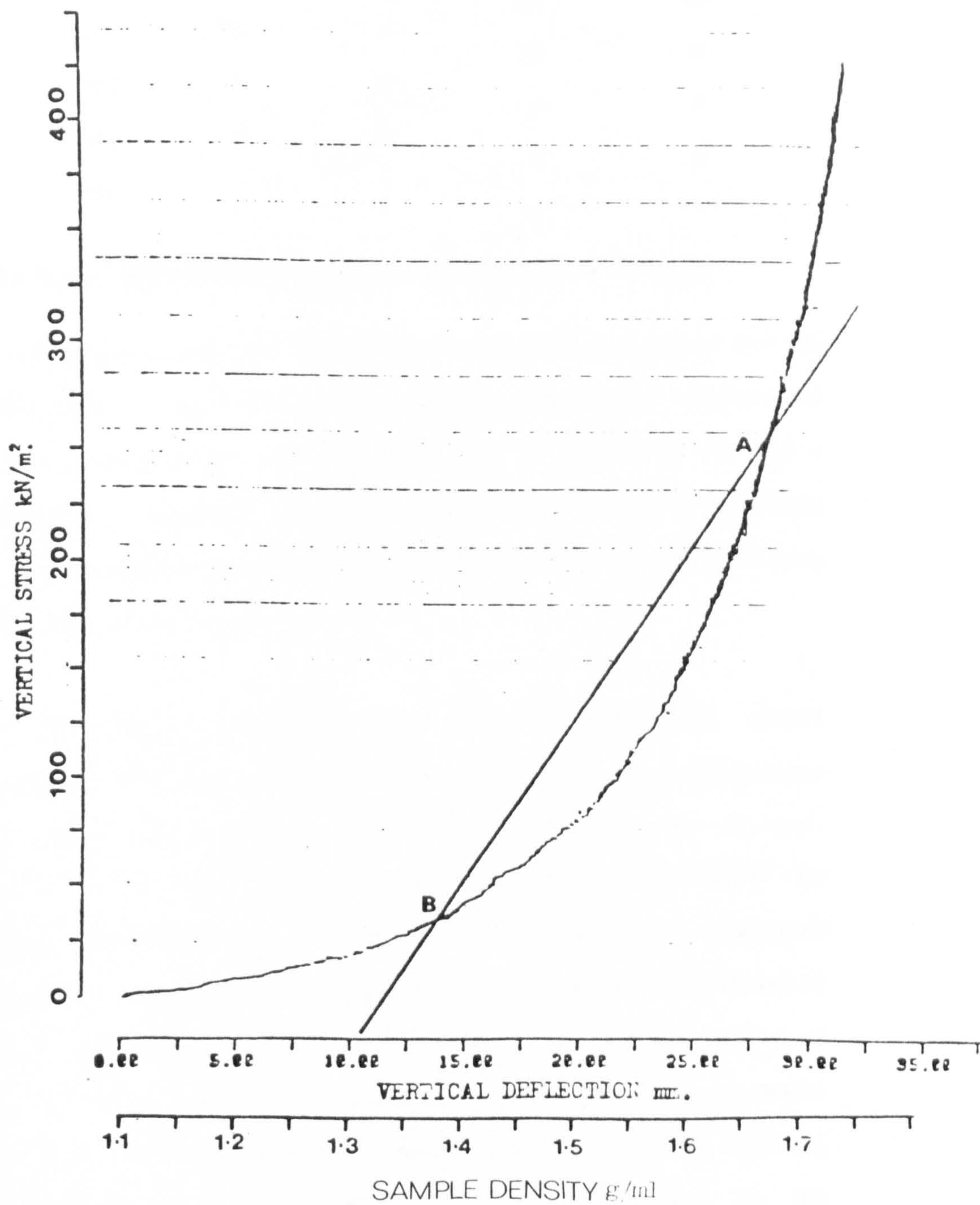


Figure 4.7. Linearized stress-strain characteristics.

Depth (mm)	Deflection (mm)		Strain (%)	
	Measured	Predicted	Measured	Predicted
0	33	29		
			6	16
50	30	21		
			14	16
100	23	13		
			16	10
150	15	8		
			12	6
200	9	5		
			8	8
250	5	2		
			8	2
300	1	1		
			2	2

Table 4.18 Comparison of measured and predicted strains.

The table shows that if the surface strains were reduced and the strain deep in the soil were increased a significant improvement in the correlation would result. It is possible to use a non-linear stress-strain relationship in an iterative process, but to accomplish this in three dimensions would involve a very large and complex model.

ii) The simplification of the surface loads. The model assumed a very simple distribution of load at the soil surface where the tyre did not produce any horizontal component of load. This is by no means true of the field situation where the rolling resistance of the wheel is due to horizontal reactions between the deforming soil and the tyre. Addition of horizontal loads at the surface would induce shear in the surface layers of soil and would increase the vertical deflection. Also the model did not predict the slight increase in the width of the vertical soil deformation as the depth increased, table 4.5, or the

curved shape of the rut at the surface, figure 4.8; these two problems are linked.

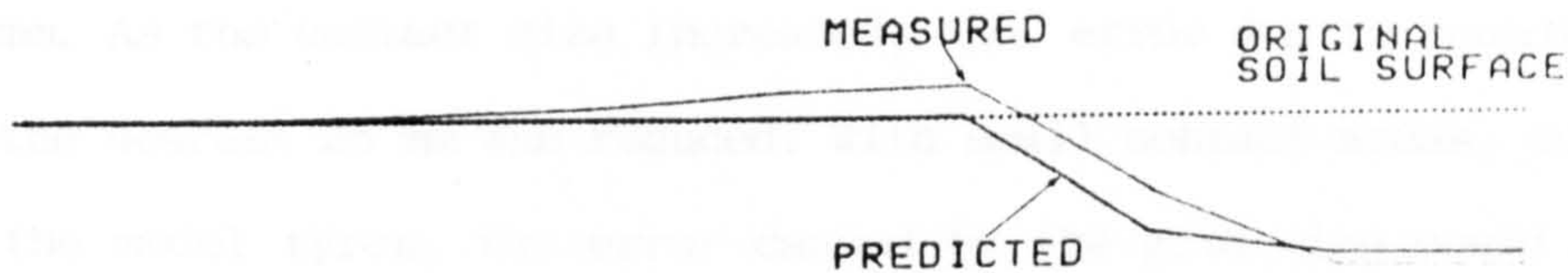


Figure 4.8 Comparison of measured and predicted surface deformation.

Although the model assumed that the load on the soil surface was purely vertical and carried evenly over the whole contact patch, the true pattern of stress distribution at the interface is in fact very complex. The shape of the carcass of the tyre also affects the way the load is transmitted to the soil. In the case of the tyres used in this study their carcass shape was rounded. This tended to reduce the magnitude of the vertical stress and increase the lateral stress at the edge of the contact area. The effect of this would be to reduce the rut depth at the edge of the contact area and spread the vertical deformations out as the depth increased.

iii) The presence of a rigid bottom to the soil bin. In the experimental work the soil bins used had rigid bottoms some distance below the final layer of beads, whereas the model assumed that the soil was infinitely deep.

iv) The grid size used for the model work. It was possible to use any size of grid, but the smaller the grid size used the

larger the number of points to be calculated and the slower the model ran on the computer. The size of the grid used was 25 mm this limited the dimensions of the contact area to multiples of 25 mm. As the contact size increased, the error due to rounding to the nearest 25 mm was reduced. With small contact areas, such as the model tyres, the error caused by the grid size could be quite large.

v) Soil strength. No account was taken of the effect of soil strength on the contact area of the tyre. At a high soil strength the contact area of the tyre is small in comparison to the contact area on a weak soil.

Taking the results as a whole the model showed that it can predict with reasonable accuracy the deformations in a compactable sandy loam soil for a wide range of input conditions. More significantly, the model showed that it can quite accurately model the effect of changes in the input conditions. The model will therefore be a useful tool for assessing the sensitivity of soil compaction to various input conditions.

5. COMPUTER INVESTIGATION INTO THE SENSITIVITY OF SOIL TO COMPACTION.

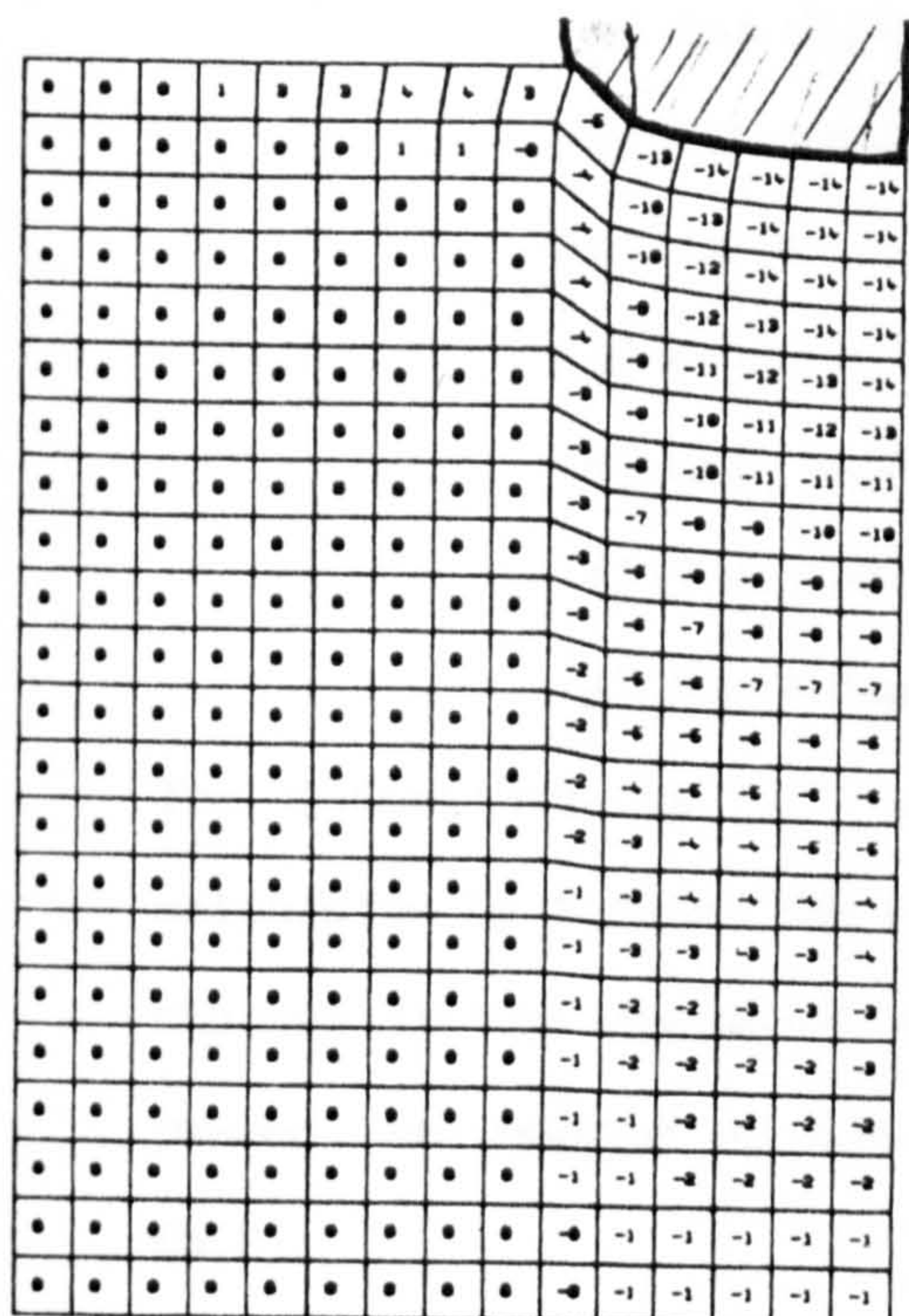
5.1. INTRODUCTION.

In the previous section it has been shown that the model can, with reasonable accuracy, predict the deformations on coarse textured soils when subject to externally applied loads. The model can therefore be used to develop a better understanding of how the input conditions of the soil effect compaction. The model allowed all but one of the inputs to be held constant and by monitoring the change in the output of the model, the sensitivity of the soil to compaction resulting from that input was be found. This was a useful feature of the model as in the field the inputs are all inter-related. The inputs chosen were those that are easily varied in a farming situation, such as tyre pressure and axle load, also the effect of density interactions was monitored. Such variables as soil moisture content, though undoubtedly an important factor influencing compactability can not easily be varied by the operator of an agricultural machine.

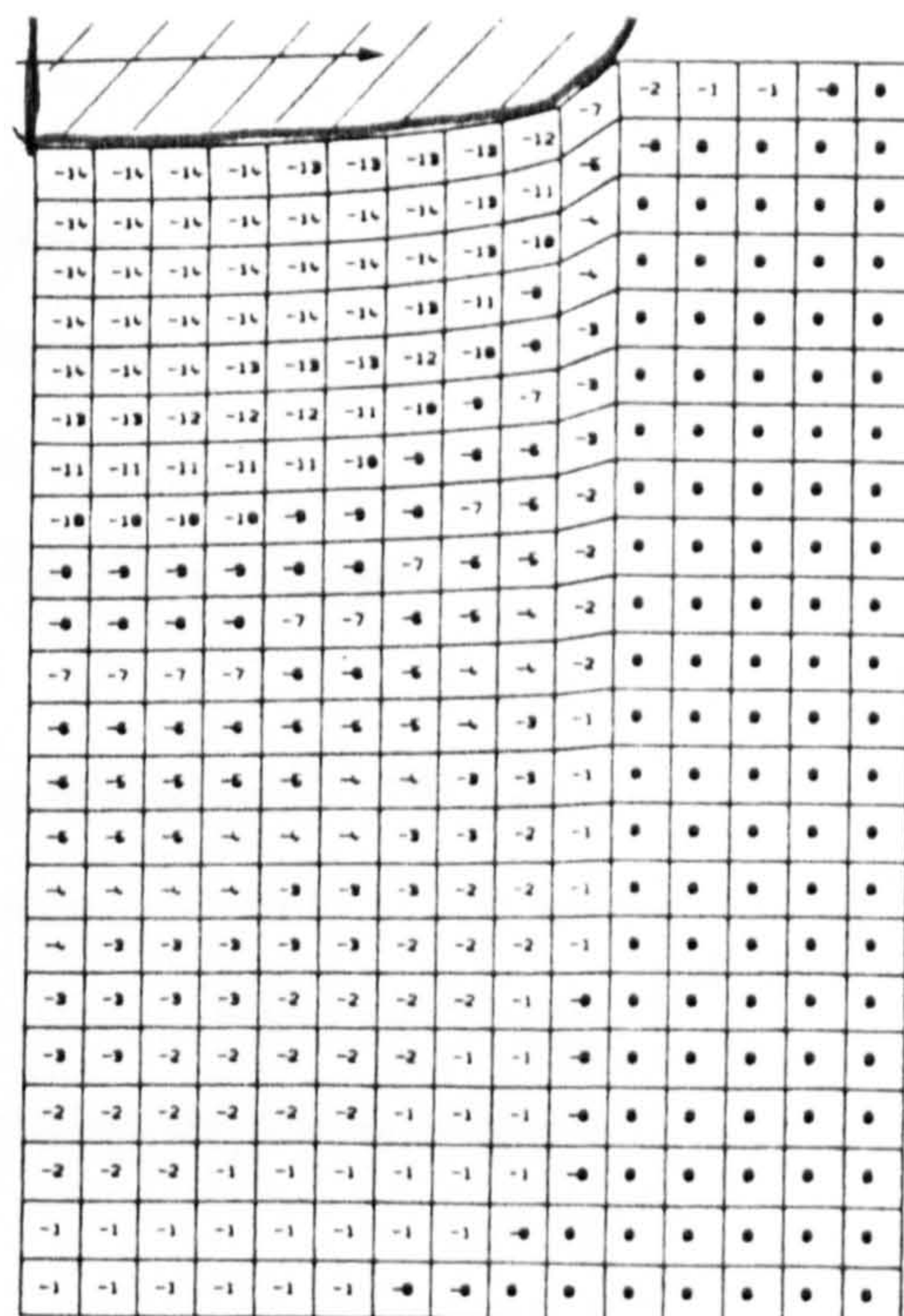
5.2. PRESENTATION OF RESULTS.

The output of the computer model was the deflection of each of the grid points in the three mutually perpendicular directions and the % volume change of each of the elemental cubes. The volume change of each cube was calculated from the deflections of the eight corners. The simplest way of representing such a large amount of data is shown in figure (5.1 a,b), these two

figures are (a) an end view across the axle of the tractor after the wheel has passed, (b) a side view along the centre of the tyre.



END VIEW



SIDE VIEW

Figure 5.1. Graphical representation of the results.

On each of the figures the position of the tyre is marked. The two figures show the resulting compaction after the tractor has passed and the process of the compaction as it occurs under the wheel. These two figures give a good graphical representation of how the soil has deformed and the resulting % volume change due to the deformation. This form of presentation of results made it difficult however to directly compare two or more treatments, therefore a number of pertinent indicators were chosen to describe the situation and provide an easy means of treatment comparison.

The following indicators were found to best describe the situation:-

- a) rut depth.
- b) rut width.
- c) value of max. % volume change.
- d) depth of max. % volume change.
- e) max. depth of disturbance.
- f) % volume change at each level of change.
- g) sum-volume change.

The definition of "a" to "e" are selfexplanatory, "f" was calculated by finding the number of occurrences of each % volume changes in the compacted soil left behind after the wheel had passed. An example of how this was done is shown using figure (5.2).

Using the figure it is possible to see that a 12% volume reduction occurred once, a 10% volume reduction occurred once and a 4% volume reduction occurred four times. These values give a good picture of the distribution of the levels of compaction, showing for instance if there was a large amount of low level compaction or a large amount of a high level of compaction. As the results were taken from figures such as figure 5.2 they only covered half the soil width disturbed from the centreline of the tyre outwards, the full effect of a tyre could be found by multiplying the solution by two. The value of "g" was calculated by multiplying the % volume change by the number of occurrences and summing for all the values found in "f", this figure gave a global value of the amount of soil

0	0	0	0	0	0	0	1	2	3	3	3	-7		
0	0	0	0	0	0	0	0	0	0	0	0	-6	-17	-17
0	0	0	0	0	0	0	0	0	0	0	0	-5	-13	-16
0	0	0	0	0	0	0	0	0	0	0	0	-6	-12	-14
0	0	0	0	0	0	0	0	0	0	0	0	-5	-10	-11
0	0	0	0	0	0	0	0	0	0	0	0	-4	-9	-9
0	0	0	0	0	0	0	0	0	0	0	0	-3	-8	-8
0	0	0	0	0	0	0	0	0	0	0	0	-2	-6	-7
0	0	0	0	0	0	0	0	0	0	0	0	-2	-5	-6
0	0	0	0	0	0	0	0	0	0	0	0	-2	-4	-5
0	0	0	0	0	0	0	0	0	0	0	0	-2	-4	-4
0	0	0	0	0	0	0	0	0	0	0	0	-1	-3	-3
0	0	0	0	0	0	0	0	0	0	0	0	-1	-2	-2
0	0	0	0	0	0	0	0	0	0	0	0	-1	-2	-2
0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1
0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.2. % volume change distribution calculation.

compaction of each situation, again the results only cover half the width of soil disturbed.

5.3. COMPUTER INVESTIGATION.

5.3.1. INTRODUCTION.

The following investigations were conducted:-

a)The effect of contact geometry (length and width) on soil compaction for three levels of wheel load.

b)The effect of contact pressure on soil compaction for three levels of wheel load.

c)The effect of initial soil density on soil compaction for three levels of contact pressure.

Each investigation will be considered in turn.

5.3.2. TYRE GEOMETRY.

An investigation was conducted into the effect of the shape of the contact patch of the tyre on the compaction of soil. The contact pressure and area of contact were kept constant whilst the shape of the contact area was varied from a long thin to a short wide contact. The change in shape of the area was expressed as an aspect ratio, found from the ratio of length/width of the contact area. As the contact pressure and the soil density were kept constant the Young's Modulus and cut

off strain were also constant. In order to monitor the effect of different levels of wheel load the contact patch shape was varied for three areas of contact. The input data for the model is given in Table (5.1).

5.3.3. RESULTS AND DISCUSSION.

The full results are given in Appendix (5.1) and summarised in table (5.2). The results show that rut depth increased as the load on the wheel increased. There was also some small variation in the rut depth with changes in the aspect ratio of the contact areas. A square contact area had the largest rut depth, this was due to the square area having the smallest circumference. The rut width is not shown as it was found that in all cases the rut width always equalled the contact width of the area, as would be expected with a punch failure. The maximum volume change remained fairly constant no matter what the load or shape of the contact area. This indicates that the level of the maximum compaction may be related to the contact pressure. This was not confirmed by the experimental results where a change in load from 7 to 11 kN. increased the level of the maximum volume change from 15 to 21% (Appendix 2.2 table 6.D and 8.D.). Some of the difference could have been due to the large grid size used, such that when the volume was calculated it gave the average volume change for the cube and not the maximum value. The depth of maximum compaction (volume change) varied quite considerably with aspect ratio making it difficult to confirm any pattern in the results. Some experimenters have found that

TYRE GEOMETRY.

Input variables:-

Moisture content	10%
Initial soil density	1.3g/ml.
Ground contact pressure	238 kN/m ² .
Soil Young's modulus	957.5 kN/m ² .
Cut off strain	2.9%
Poisson's Ratio	0.25

Load 1 12kN.

	Geometry				
	1	2	3	4	5
width (m)	0.125	0.175	0.225	0.275	0.425
length (m)	0.425	0.275	0.225	0.175	0.125

Load 2 18kN.

	Geometry				
	1	2	3	4	5
width (m)	0.175	0.225	0.275	0.325	0.425
length (m)	0.425	0.325	0.275	0.225	0.175

Load 3 25kN.

	Geometry				
	1	2	3	4	5
width (m)	0.225	0.275	0.325	0.375	0.475
length (m)	0.475	0.375	0.325	0.275	0.225

Aspect ratio.

Load (kN)	1	2	3	4	5
12	3.4	1.57	1	.63	.29
18	2.4	1.4	1	.69	.411
25	2.1	1.36	1	.73	.47

Table 5.1

A. RUT DEPTH (mm).

Load (kN)	Aspect ratio				
	1	2	3	4	5
12	27	30	32	29	27
18	35	37	39	37	35
25	43	45	46	45	43

B. MAXIMUM VOLUME CHANGE (%).

Load (kN)	Aspect ratio				
	1	2	3	4	5
12	17	16	17	16	16
18	17	17	17	17	16
25	17	17	17	17	16

C. DEPTH OF MAXIMUM VOLUME CHANGE (mm).

Load (kN)	Aspect ratio				
	1	2	3	4	5
12	50	25-75	75	50-75	50
18	25-50	50-75	50-100	50-75	50-100
25	25-50	100	75-100	100	50-125

D. DEPTH OF DISTURBANCE (m).

Load (kN)	Aspect ratio				
	1	2	3	4	5
12	0.400	0.400	0.425	0.400	0.400
18	0.500	0.500	0.525	0.500	0.500
25	0.600	0.600	0.625	0.600	0.600

Table 5.2 a,d

LOAD 12 kN					
Percent volume change	Number of Occurrences.				
	Aspect Ratio				
	3.4	1.57	1	0.63	0.29
5	0	0	0	0	0
4	0	0	1	1	0
3	3	3	2	1	1
2	1	1	0	0	0
1	1	0	1	1	0
0	294	280	266	255	218
-1	10	10	11	14	22
-2	7	7	9	10	16
-3	3	6	8	11	13
-4	4	5	6	6	9
-5	4	5	5	5	8
-6	4	4	6	4	7
-7	2	2	1	3	4
-8	2	2	3	4	3
-9	2	2	3	2	5
-10	1	2	2	3	3
-11	1	2	3	2	4
-12	1	2	1	3	1
-13	1	2	3	2	10
-14	1	1	1	4	5
-15	0	1	7	5	7
-16	1	6	4	7	6
-17	2	0	1	0	0
-18	0	0	0	0	0
-19	0	0	0	0	0
-20	0	0	0	0	0
TOTAL	-239	-365	-489	-564	-792

Table 5.2 e.

	LOAD 18 kN				
Percent volume change	Number of Occurrences.				
	Aspect Ratio				
	2.4	1.4	1	0.69	0.41
5	0	0	0	0	0
4	0	1	2	2	1
3	4	3	2	1	1
2	1	0	0	0	0
1	0	1	0	1	0
0	266	249	228	215	187
-1	13	14	18	22	25
-2	9	12	13	15	19
-3	6	7	13	12	16
-4	6	10	8	10	10
-5	6	5	7	6	12
-6	5	5	7	7	6
-7	4	4	4	6	7
-8	3	3	6	5	4
-9	3	3	2	2	5
-10	3	3	4	5	3
-11	2	4	3	3	5
-12	3	4	4	3	5
-13	1	1	2	3	7
-14	1	3	3	5	8
-15	1	4	10	5	4
-16	3	5	4	10	16
-17	3	3	4	2	0
-18	0	0	0	0	0
-19	0	0	0	0	0
-20	0	0	0	0	0
TOTAL	-427	-589	-743	-839	-1030

Table 5.2 f.

LOAD 25 kN					
Percent volume change	Number of Occurrences.				
	Aspect Ratio				
	2.17	1.36	1	0.73	0.47
5	0	0	0	0	0
4	2	2	2	2	2
3	4	3	3	2	1
2	0	0	0	0	0
1	2	3	1	0	0
0	228	208	186	171	132
-1	23	25	30	31	43
-2	14	17	21	23	23
-3	10	13	14	17	21
-4	9	10	13	12	16
-5	9	10	11	12	14
-6	7	6	7	8	11
-7	4	6	5	7	8
-8	5	2	7	6	7
-9	5	5	6	6	4
-10	4	7	4	3	8
-11	5	5	5	6	6
-12	4	5	5	8	4
-13	1	2	5	2	13
-14	3	4	4	11	6
-15	2	5	11	6	8
-16	6	11	8	15	24
-17	4	2	5	2	0
-18	0	0	0	0	0
-19	0	0	0	0	0
-20	0	0	0	0	0
TOTAL	-687	-859	-1044	-1152	-1426

Table 5.2 g

the depth is related to half the width of the tyre. From the Theories of Elasticity applied to isotropic soils, the expected observation would be that the depth is a function of the shorter of either the length or width of contact patch. On careful examination of the results it is possible to see the expected pattern of an increase in depth with an increase in area, the deepest maximum occurring when the area was square, reducing as either the length or width reduced. Estimates of the maximum depth of disturbance show that the aspect ratio of the tyre did not change this depth. Increasing the load and the area of contact significantly increased the depth to which soil was compressed.

The most interesting results are provided by the pattern of the volume changes, see table (5.2 e-g), which indicates the number of occasions that a particular volume change was recorded. The zero volume change line gives a measure of the volume of soil undisturbed, which as the area of soil in the model was always the same, gave a measure of the amount of soil compressed.

Number of occurrences of zero volume change				
Aspect ratio				
3.4	1.57	1	0.63	0.29
294	280	266	255	218

(From Table 5.2 e)

The table shows that as the contact became longer and thinner (aspect ratio increasing) the area of soil undisturbed increased, as the area of soil with zero volume change increased. This showed that a long thin tyre contact was causing

less soil to be compressed than a short fat one.

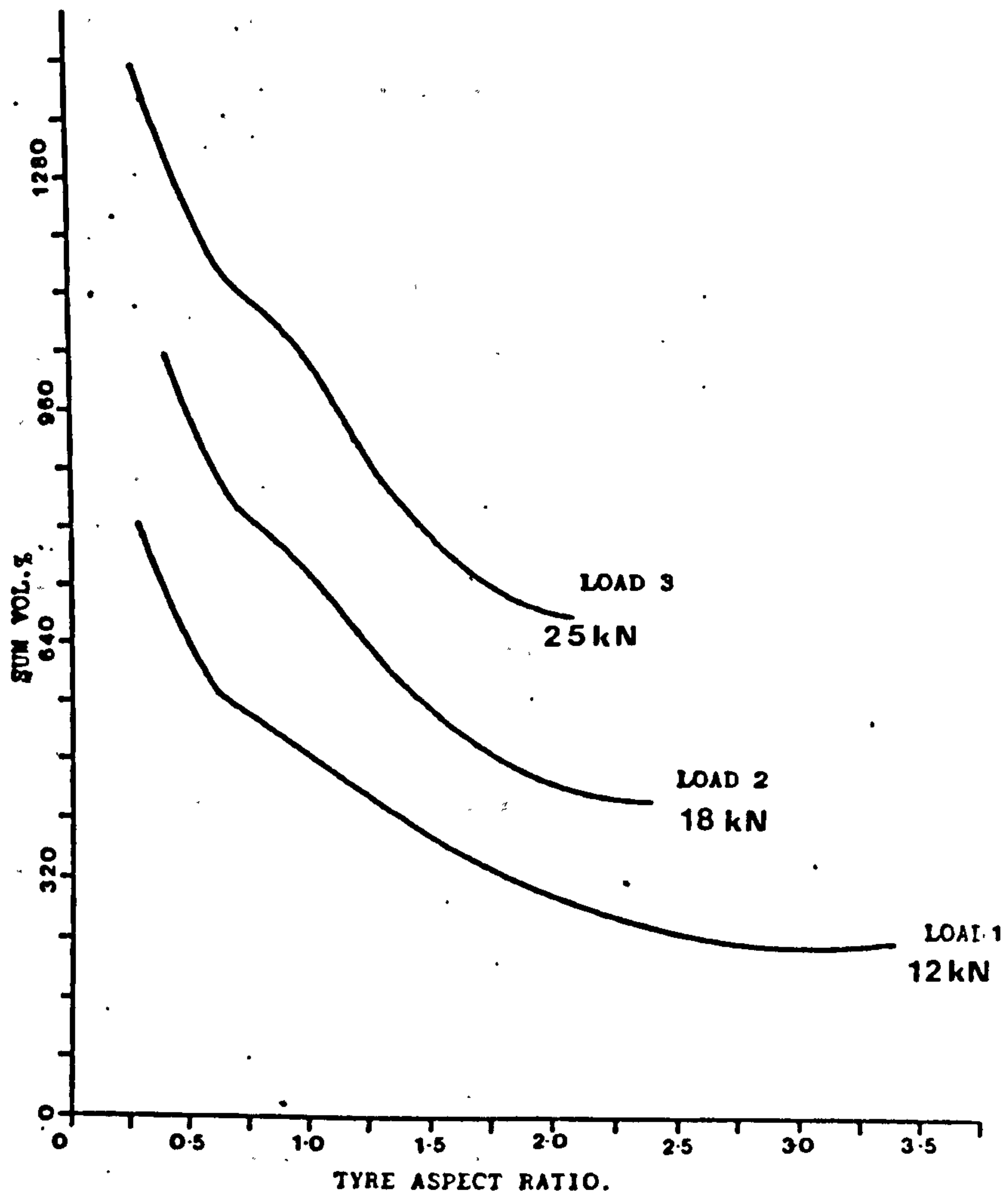


Figure 5.3 Sensitivity of compaction to load and aspect ratio.

The summed volume changes are plotted in figure (5.3) which shows that the level of the load effects the magnitude of the total volume change. The slope of the graph at any point indicates the sensitivity of soil to compaction due to the inputs. The slope of the graphs shows that the sensitivity of soil to compaction is strongly dependent on the aspect ratio of the tyre and independent of the level of the load. As the contact shape becomes longer and thinner, the sensitivity

reduces to a minimum value at an aspect ratio of 2.5, further reductions in the width do not significantly reduce the amount of soil compaction.

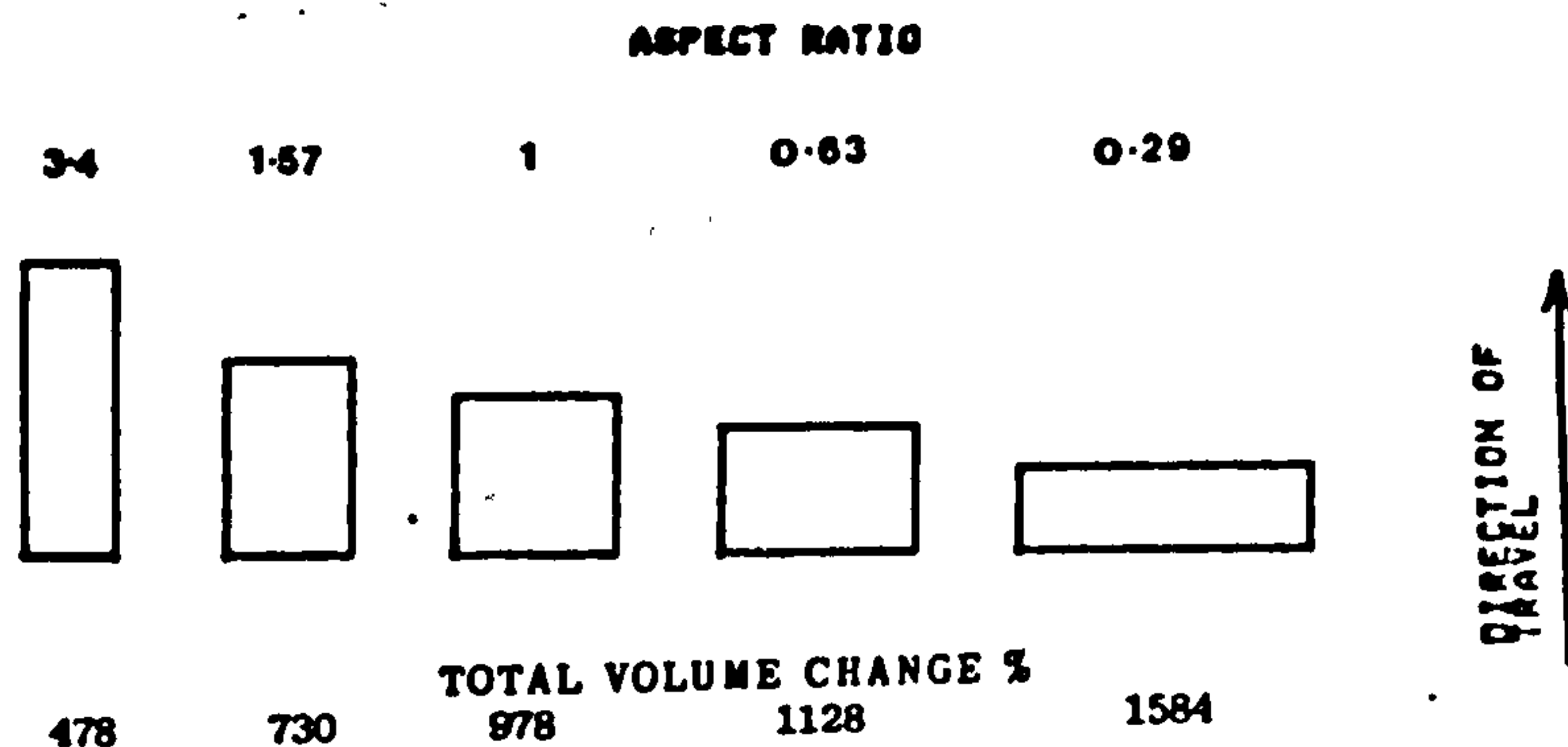


Figure 5.4 The effect of contact shape on soil compaction.

Figure 5.4 shows the contact shapes and the total volume change of the soil due to the shape of contact on the soil surface for a constant contact load of 12 kN. The figure shows that the contact shape has a significant effect on the amount of soil damaged, as shown by the increasing number below, with large reductions in the total compaction when the width of the contact was reduced and the length increased for the same contact area. This was due to the process by which soil compacts below the tyre. As the tyre rolled it compressed the soil until the strength increases to the point where it could support the pressure on the surface without further deformation. With a long thin contact after the front of the tyre had passed and compressed the soil the rest of the tyre caused very little further deformation. This situation does not represent a true field condition as it assumes no shear stresses are applied to

the soil by the tyre. Experimenters such as Bodman and Rubin (1948), figure (5.5), have shown that shearing causes an increase in the compaction.

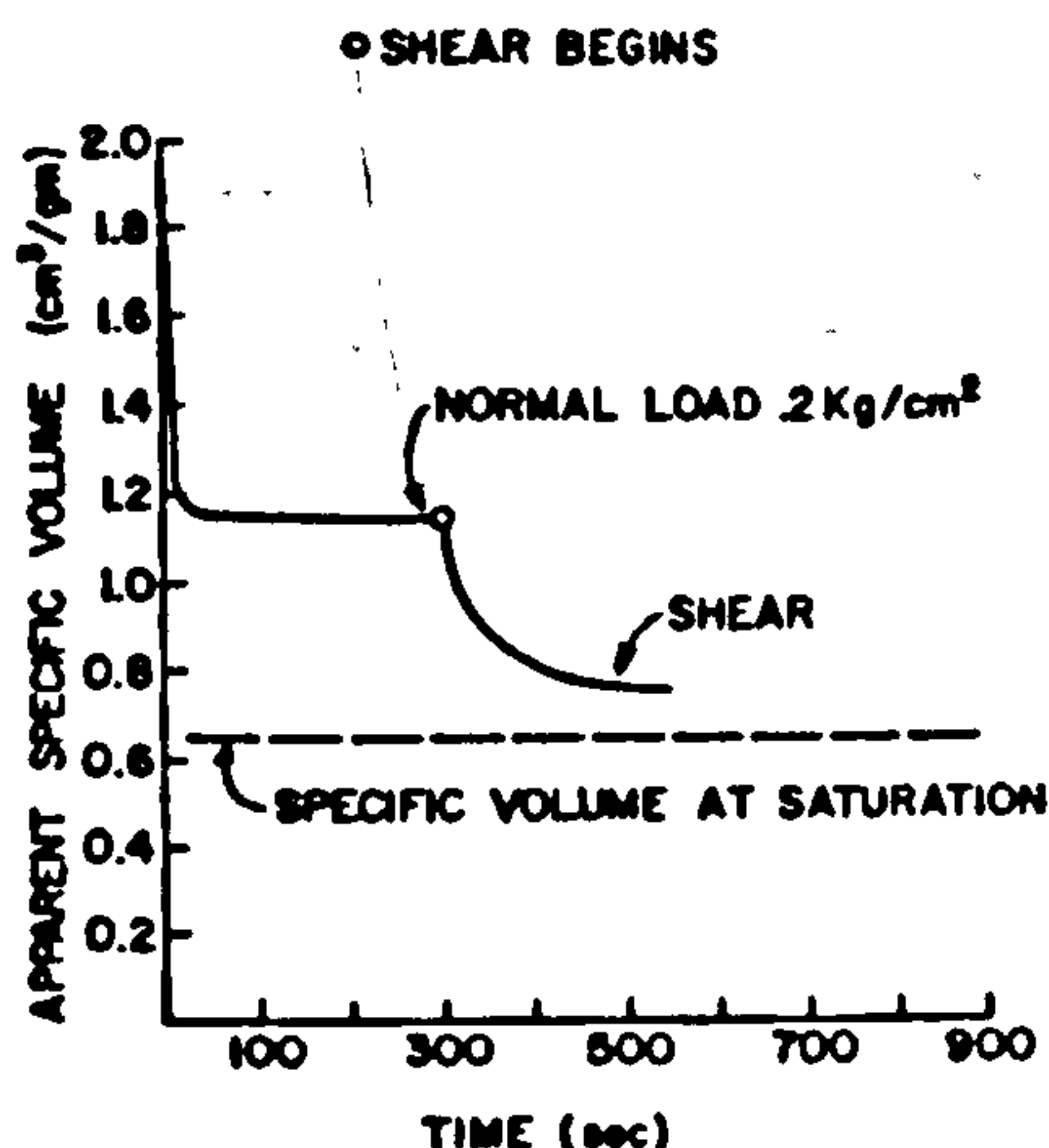


Figure 5.5. The effect of shear on soil specific volume.

If shear were applied to the soil surface, in the case of a long thin tyre the shear deformation per unit width would be greater than that for a short wide tyre. This would tend to distort the results more in favour of the wider tyre for lower levels of compaction.

5.3.4. CONTACT PRESSURE.

An investigation was conducted into the effect on soil compaction of changes in the contact pressure at a constant soil density, for three levels of load. The wheel was assumed to have a constant contact width of 0.275m, changes in inflation pressure only varying the length of contact. This assumption may not be strictly true but due to the lack of a generally accepted theory of the effect of inflation pressure on contact width, it provided a good approximation. It was also assumed

that the tyre had no carcass stiffness so that the inflation pressure was equal to the contact pressure. The length of contact was calculated from the load and inflation pressure of the wheel. It was not possible to use the full range of pressures for each load as the length would become too long for the model to cope with. As the contact pressure affects the Young's Modulus and cut off strain, the individual value for each pressure had to be found from the confined compression test. The input data for the model is summarised in table (5.3).

5.3.5. RESULTS AND DISCUSSION.

The full results are given in Appendix (5.2), summarised in table (5.4 a,g). The results show that rut depth increased with load and inflation pressure, however a decrease in pressure at low pressures had a more significant effect than a decrease at higher pressure for a given wheel load. This is clearly shown by figure (5.6), where significant reductions in rut depth can be achieved by further reductions of inflation pressure below 120 kN/m². The maximum volume change shows the same result as before, where changes in the load did not significantly effect the value of the maximum. An increase in inflation pressure however, significantly increased the level to which the soil was compressed. It is difficult to draw conclusions from the depth of the maximum compaction, however, the depth did decrease as the inflation pressure increased and the length of contact decreased.

GROUND CONTACT PRESSURE

Input variables:-

Moisture content	10%
Initial soil density	1.3 g/ml
Contact patch width	0.250 m
Poisson's Ratio	0.25

Contact length (m).

Load (kN)	Contact pressure kN/m ² .						
	79.2	118.8	158.4	198.0	237.6	277.2	316.8
5	0.253	0.169	0.126	-	-	-	-
10	0.506	0.338	0.253	0.202	-	0.144	-
15	-	0.508	0.379	0.303	0.253	-	0.189

Soil properties

	Contact pressure kN/m ² .						
	79.2	118.8	158.4	198.0	237.6	277.2	316.8
Young's Modulus	485	606	711	843	920	1039	1142
Cut off strain (%)	5.9	4.5	3.8	3.5	3.2	2.9	2.5

Table 5.3

		A RUT DEPTH (mm)						
		Contact pressure kN/m ² .						
Load (kN)		79.2	118.8	158.4	198.0	237.6	277.2	316.8
5		10	16	17	-	-	-	-
10		13	23	25	26	-	26	-
15		-	26	31	33	35	-	37

B MAXIMUM VOLUME CHANGE (%)							
	Contact pressure kN/m ² .						
Load (kN)	79.2	118.8	158.4	198.0	237.6	277.2	316.8
5	7	11	13	-	-	-	-
10	7	11	14	15	-	18	-
15	-	11	14	15	17	-	19

C DEPTH OF MAXIMUN VOLUME CHANGE (mm)							
	Contact pressure kN/m².						
Load (kN)	79.2	118.8	158.4	198.0	237.6	277.2	316.8
5	25-100	50-75	50	-	-	-	-
10	50-125	50-100	75	25-75	-	50	-
15	-	50-125	25-100	25-100	25-75	-	25-75

D DEPTH OF MAXIMUM DISTURBENCE. (m)							
	Contact pressure kN/m ² .						
Load (kN)	79.2	118.8	158.4	198.0	237.6	277.2	316.8
1	0.25	0.275	0.275	-	-	-	-
2	0.325	0.375	0.375	0.35	-	0.6	0.6
3	-	0.45	0.45	0.45	0.45	-	0.475

Table 5.4 a,d

LOAD 5 kN.

Percent volume change	Number of Occurrences.		
	Contact pressure kN/m ²		
	79.2	118.8	158.4
5	0	0	0
4	0	0	0
3	0	0	0
2	0	0	0
1	0	0	1
0	300	291	290
-1	9	7	8
-2	7	8	7
-3	4	7	5
-4	8	4	7
-5	6	3	2
-6	4	3	3
-7	7	3	2
-8	0	6	3
-9	0	6	1
-10	0	3	3
-11	0	4	6
-12	0	0	3
-13	0	0	4
-14	0	0	0
-15	0	0	0
-16	0	0	0
-17	0	0	0
-18	0	0	0
-19	0	0	0
-20	0	0	0
TOTAL	-170	-290	-323

Table 5.4 e

LOAD 10 kN

Percent volume change	Number of Occurrences.				
	Contact pressure kN/m ²				
	79.2	118.8	158.4	198.0	277.2
5	0	0	0	0	0
4	0	1	1	1	1
3	0	0	0	0	0
2	0	0	1	1	1
1	1	1	0	0	0
0	281	263	263	267	268
-1	15	13	12	12	15
-2	7	12	11	11	8
-3	9	9	7	8	8
-4	9	5	8	5	5
-5	7	6	5	6	6
-6	11	5	4	3	3
-7	5	4	4	4	4
-8	0	5	3	2	1
-9	0	8	3	3	4
-10	0	8	3	2	0
-11	0	5	5	3	3
-12	0	0	6	4	2
-13	0	0	7	6	1
-14	0	0	2	3	2
-15	0	0	0	4	4
-16	0	0	0	0	4
-17	0	0	0	0	6
-18	0	0	0	0	0
-19	0	0	0	0	0
-20	0	0	0	0	0
TOTAL	-227	-414	-485	-472	-510

Table 5.4 f

LOAD 15 kN

Percent volume change	Number of Occurrences.				
	Contact pressure kN/m ²				
	118.8	158.4	198.0	237.6	316.8
5	0	0	0	0	0
4	2	2	2	2	1
3	0	1	1	1	2
2	0	0	0	0	0
1	1	0	0	0	1
0	245	244	244	244	243
-1	16	14	16	16	17
-2	15	15	12	13	12
-3	12	9	9	8	8
-4	6	10	9	7	9
-5	7	6	7	7	5
-6	8	4	5	5	4
-7	4	4	3	5	6
-8	7	5	4	3	3
-9	8	4	5	3	2
-10	10	5	3	2	3
-11	4	5	2	5	1
-12	0	6	5	2	4
-13	0	8	7	2	1
-14	0	3	6	3	2
-15	0	0	5	8	2
-16	0	0	0	4	3
-17	0	0	0	5	6
-18	0	0	0	0	5
-19	0	0	0	0	5
-20	0	0	0	0	0
TOTAL	-480	-581	-617	-670	-718

Table 5.4 g

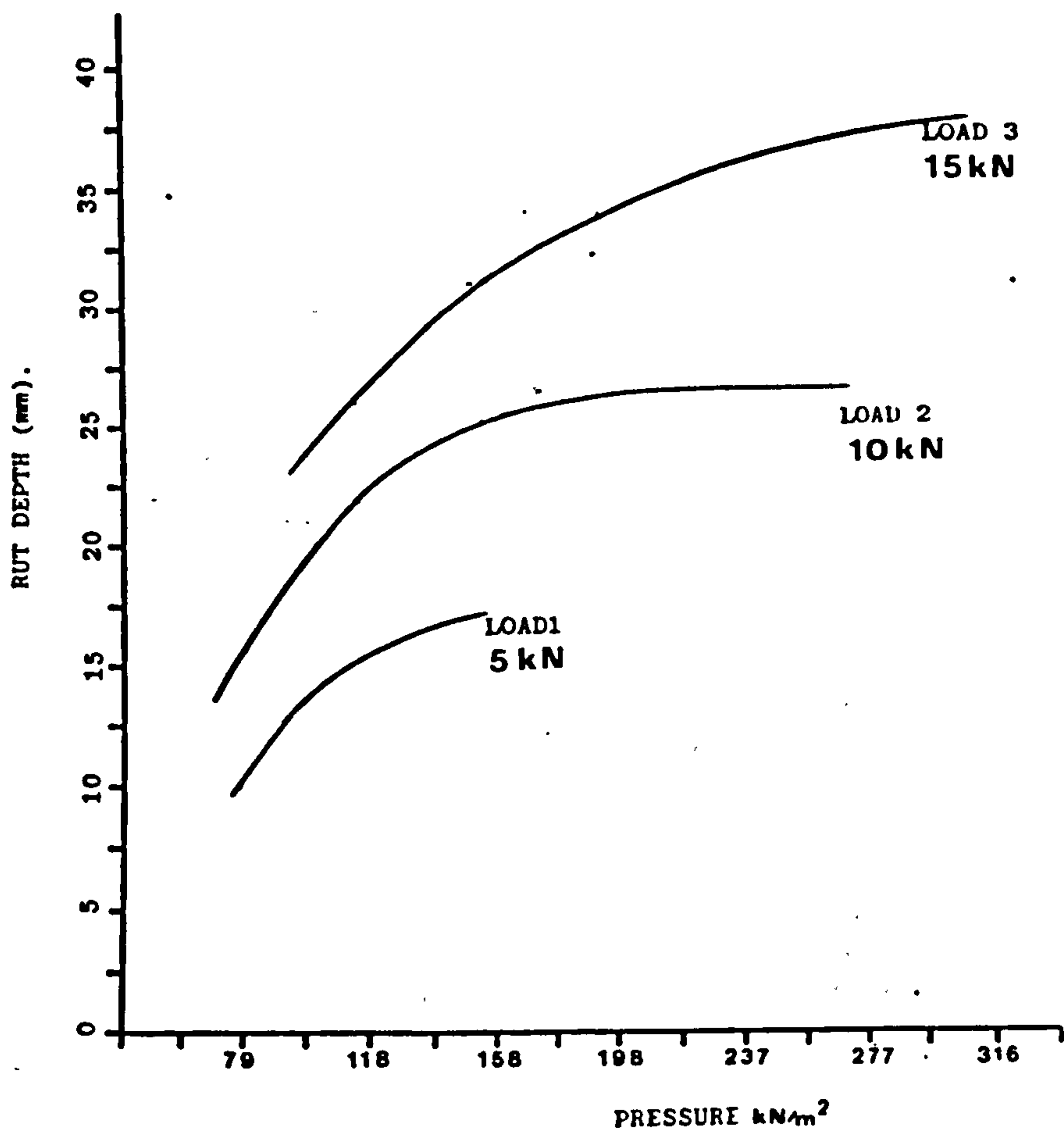


Figure 5.6. Variation of rut depth with load and pressure.

An increase in inflation pressure had only a slight effect on the depth of disturbance, whereas an increase in the load significantly increased the depth to which soil damage extended. A doubling of the load at constant pressure increased the depth of disturbance by 40%, tripling of the load increased the depth by 60%. The number of occurrences of zero volume change for variations in load and pressure are shown below.

	Number of occurrences of zero volume change			
	Contact pressure kN/m ²			
Load (kN).	118	158	198	237
10	263	263	267	268
15	244	244	244	243

(From Table 5.4 f,g)

The above figures show that changes in the amount of soil compressed by an increase in the inflation pressure were small

in comparison to the effect of an increase in wheel load at a constant contact pressure. The summed % volume changes are shown in figure (5.7) which when compared with figure (5.6) show that the graphs follow the same path.

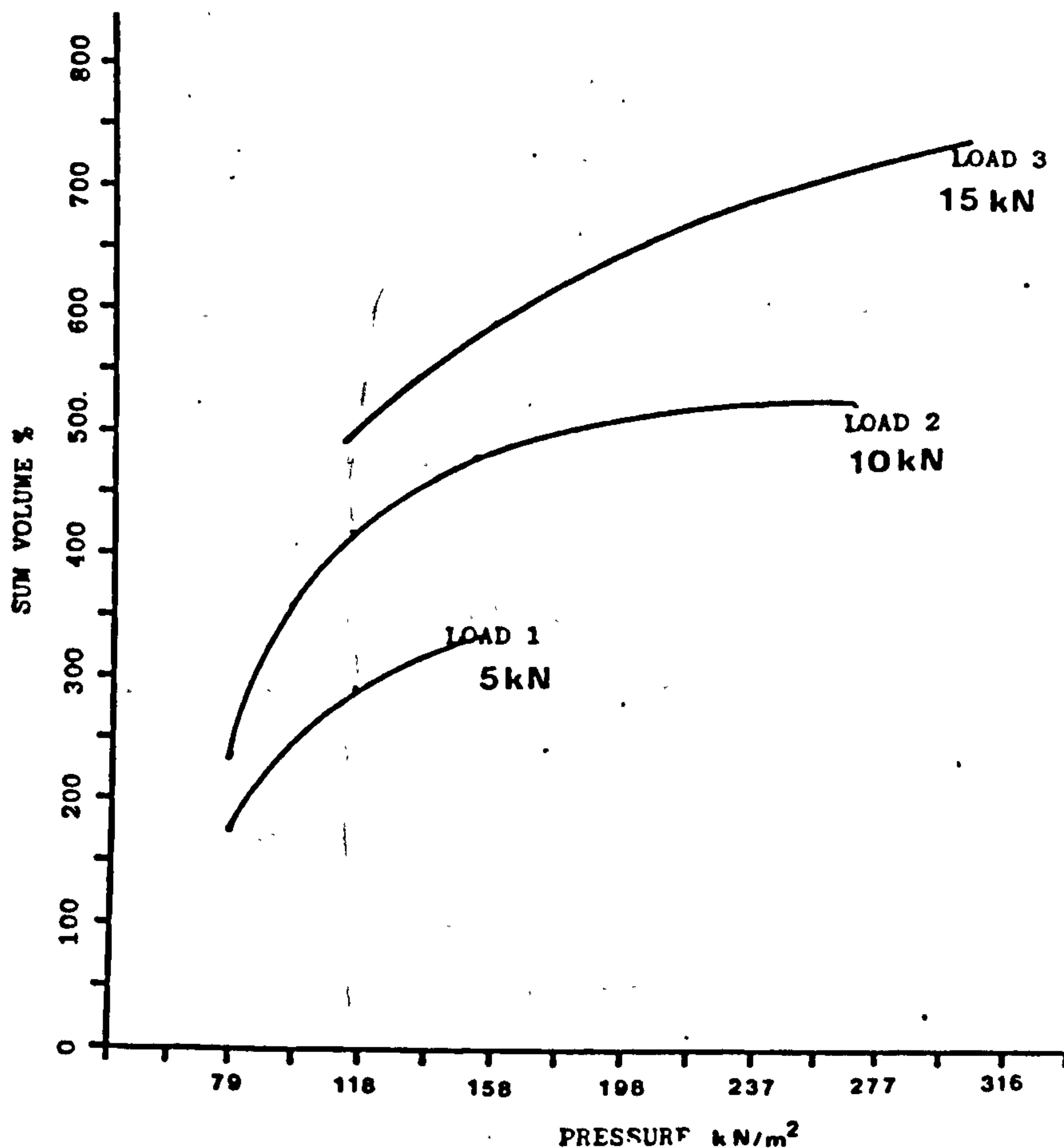


Figure 5.7. Sensitivity of soil compaction to load and pressure.

This indicates that rut volume is a good way of quickly monitoring in the field the amount of soil compaction caused by a wheel. The results show that load affects the amount of soil compacted and inflation pressure affects the level to which the disturbed soil was compressed. Figure (5.7) shows the same

result as figure (5.6) where reductions of inflation pressure below 120 kN/m^2 will significantly reduce the amount of soil compaction.

5.3.6. SOIL DENSITY.

An investigation was carried out into the effect of different initial soil densities on the compaction of the soil for three levels of contact pressure. Changes in the soil's initial density changed the strength of the soil and hence the Young's Modulus and cut off strain. The length of contact of the tyre was calculated from the pressure and the load for a given width of contact. A range of densities and pressures were chosen to cover as wide a range of field situations as possible. The input data for the model is shown in table (5.5).

5.3.7. RESULTS AND DISCUSSION.

The results, given in tables (5.6 a,g) show that as the initial density and hence the strength of the soil increased the rut depth was reduced for a constant contact pressure. This reduction continued until a point was reached where the soil was capable of supporting the contact pressure without any deformation. As the soil density increased the value of the maximum volume change decreased, as the soil had to deform less to increase its strength/density enough to support the contact pressure. It is possible to calculate the maximum final density of the soil from the volume changes, this was done at a constant contact pressure of 280 kN/m^2 .

SOIL INITIAL DENSITY

Input variables:-

Contact load	9 kN.
Contact patch width	0.250 m
Poisson's Ratio	0.25

Contact pressure kN/m²

	70	140	280
Contact Length. (m)	0.514	0.257	0.128

Soil properties
@ 10% moisture content.

		Initial soil density g/ml				
Pressure (kN/m²)		1.2	1.3	1.4	1.5	1.6
70	Young's modulus (kN/m²)	361	447	475	-	-
	Cut off strain (%)	3.0	5.8	12.0	-	-
140	Young's Modulus (kN/m²)	567	711	965	1109	-
	Cut off strain (%)	1.8	3.8	7.0	10.5	-
280	Young's Modulus (kN/m²)	898	1142	1468	1941	2488
	Cut off strain (%)	1.2	2.5	5.6	8.1	11.2

Table 5.5

A RUT DEPTH (mm)

Pressure. (kN/m ²)	Initial soil density g/ml				
	1.2	1.3	1.4	1.5	1.6
70	40	17	0	-	-
140	47	26	7	0	-
280	47	29	12	3	0

B MAXIMUM VOLUME CHANGE (%)

Pressure. (kN/m ²)	Initial soil density g/ml				
	1.2	1.3	1.4	1.5	1.6
70	14	8	-	-	-
140	20	14	6	-	-
280	27	19	11	4	-

C DEPTH OF MAXIMUM VOLUME CHANGE (mm)

Pressure. (kN/m ²)	Initial soil density g/ml				
	1.2	1.3	1.4	1.5	1.6
70	0-125	50-125	-	-	-
140	25-75	75	25-50	-	-
280	50	25	50	25	-

D DEPTH OF DISTURBANCE. (m)

Pressure. (kN/m ²)	Initial soil density g/ml				
	1.2	1.3	1.4	1.5	1.6
70	0.65	0.35	-	-	-
140	0.6	0.375	0.2	-	-
280	0.575	0.375	0.2	0.125	-

Table 5.6 a,d

Contact pressure kN/m²							
70				140			
Percent volume change	Number of Occurrences.						
	Initial soil density g/ml						
	1.2	1.3	1.4	1.2	1.3	1.4	1.5
5	0	0	0	0	0	0	0
4	2	0	0	2	1	0	0
3	3	1	0	2	0	0	0
2	0	0	0	2	1	0	0
1	3	0	0	3	0	0	0
0	204	273	345	197	263	308	345
-1	33	15	0	34	13	8	0
-2	18	9	0	21	10	5	0
-3	15	9	0	11	8	9	0
-4	12	7	0	9	7	4	0
-5	8	6	0	5	5	5	0
-6	8	9	0	8	4	6	0
-7	5	10	0	8	4	0	0
-8	6	6	0	4	3	0	0
-9	7	0	0	4	4	0	0
-10	6	0	0	4	2	0	0
-11	5	0	0	4	6	0	0
-12	4	0	0	2	5	0	0
-13	5	0	0	3	8	0	0
-14	13	0	0	2	1	0	0
-15	0	0	0	3	0	0	0
-16	0	0	0	3	0	0	0
-17	0	0	0	2	0	0	0
-18	0	0	0	5	0	0	0
-19	0	0	0	5	0	0	0
-20	0	0	0	8	0	0	0
TOTAL	-786	-287	0	-968	-480	-122	0

Table 5.6 e,f

Contact pressure kN/m ²				
280				
Percent volume change	Number of Occurrences.			
	Initial soil density g/ml			
	1.2	1.3	1.4	1.5
5	0	0	0	0
4	0	1	0	0
3	4	1	0	0
2	2	0	0	0
1	4	1	0	0
0	192	259	304	324
-1	37	17	7	5
-2	24	8	5	7
-3	14	8	2	5
-4	8	8	5	4
-5	5	4	2	0
-6	6	4	3	0
-7	6	3	3	0
-8	4	4	7	0
-9	5	1	2	0
-10	3	3	1	0
-11	4	1	4	0
-12	1	1	0	0
-13	3	4	0	0
-14	0	0	0	0
-15	2	2	0	0
-16	1	5	0	0
-17	0	3	0	0
-18	1	4	0	0
-19	4	3	0	0
-20	0	0	0	0
-21	1	0	0	0
-22	1	0	0	0
-23	2	0	0	0
-24	5	0	0	0
-25	2	0	0	0
-26	3	0	0	0
-27	3	0	0	0
TOTAL	-998	-582	-220	-50

Table 5.6 g

Initial density g/ml	Maximum volume change %	Maximum final soil density g/ml
1.2	27	1.524
1.3	19	1.547
1.4	11	1.554
1.5	4	1.56

The results show that the final maximum density, no matter what the initial soil density was were all close to the same value. The model therefore shows that the density of the soil increased to a density, independant of the initial density, where it could support the applied pressure. Table (5.6 d) shows that small increases in the initial density of the soil significantly reduced the depth to which soil was compacted, an increase in density from 1.2 to 1.3 g/ml reduced the depth to which the compaction extended by 60%. The summed volume changes, figure (5.8) shows that for small changes in the soil strength large reductions in the amounts of soil compaction can be achieved. In this case the soil strength before compaction was governed by the soil's initial density. In the field the strength of the soil will be governed by other factors in addition to the density such as moisture content.

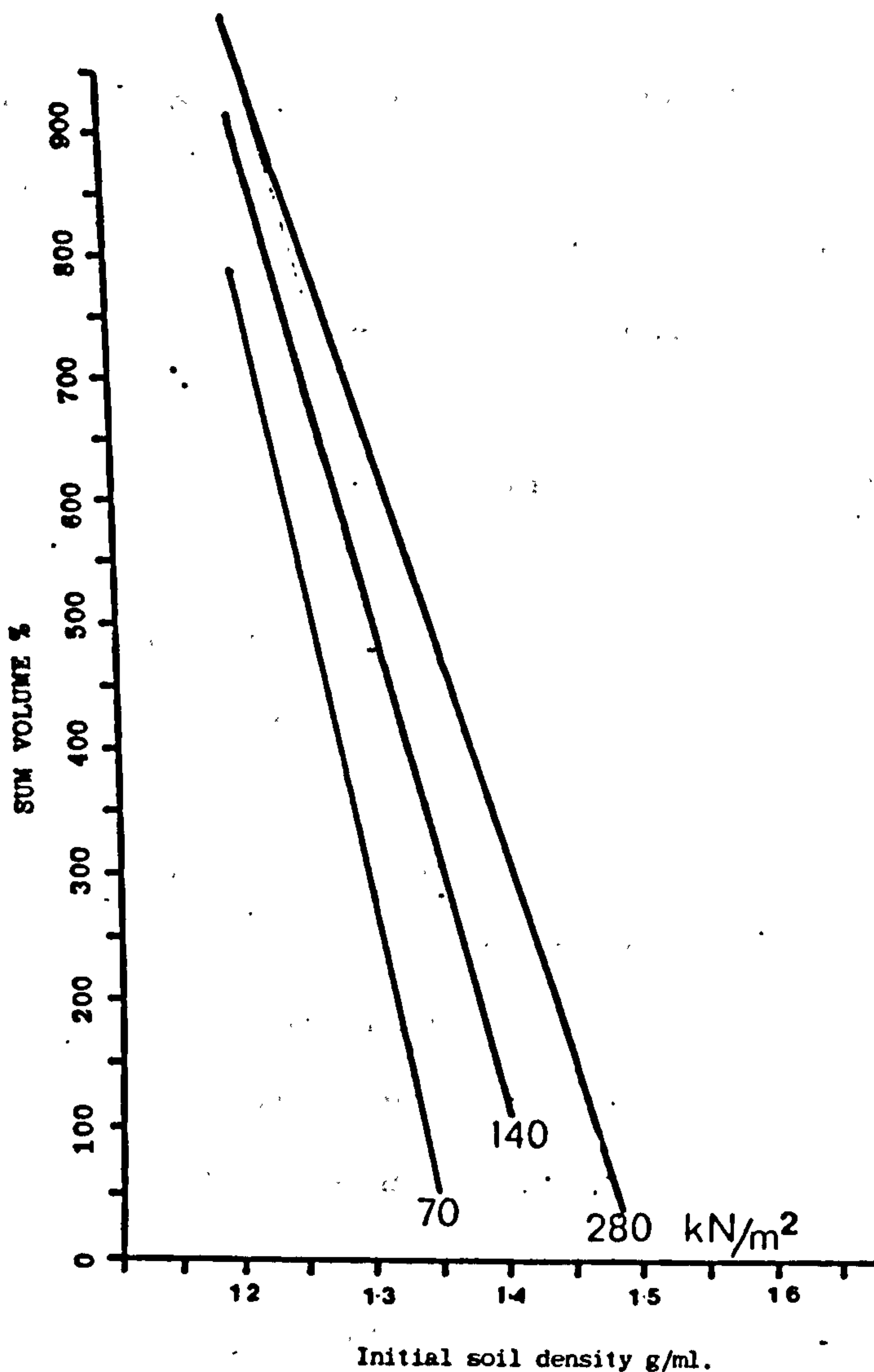


Figure 5.8. Sensitivity of compaction to soil strength.

5.4. OVERALL DISCUSSION.

The results of the investigations using the model have shown that real reductions in the compaction of soil can be achieved by operating with the correct shape of tyre-soil contact at a low inflation pressure and load. The actual amount of soil compacted can be reduced by using tyres that have a contact length 2.5 times longer than the width at an inflation pressure below 120 kN/m². In order to confirm the findings of

the model they were compared with the published results of other experimenters.

Soane et al. (1980) in their comprehensive review of compaction states that it is a commonly held belief that the depth of maximum compaction occurs at a depth equal to half the width of the tyre. Fekete (1972) also states that an increase in the width of a tyre will increase the depth of maximum compaction. The model agrees with these results as long as the contact width is less than the contact length, should this not be so the depth would vary with the contact length. Fekete also concluded that a reduction in compaction could only be obtained from an increase in the width of the tyre if the increase was associated with a reduction in the contact pressure. This observation is also confirmed by the findings of this study, where simply increasing the width increases the amount of soil compaction and reductions in the contact pressure reduce the level and amount of compaction. Dickson et al. (1979) testing single and dual wheels at a constant inflation pressure and load showed that rut depth reduced slightly with dual wheels. If however the rut volume is taken as a measure of the amount of soil compaction the compaction increased by 40% by doubling the width. The model also shows approximately a 40% increase in the summed volume change by doubling the contact width. Mogilevets and Khallyyev (1977) found that the vertical stress in a soil at a depth of 400 mm, increased as the tyre width increased for the same load and pressure. This is also shown by the model, as the width of contact increases from 0.175 to 0.325 m the volume of soil that

is compressed to a high level is increased and extends deeper into the soil, figure (5.9).

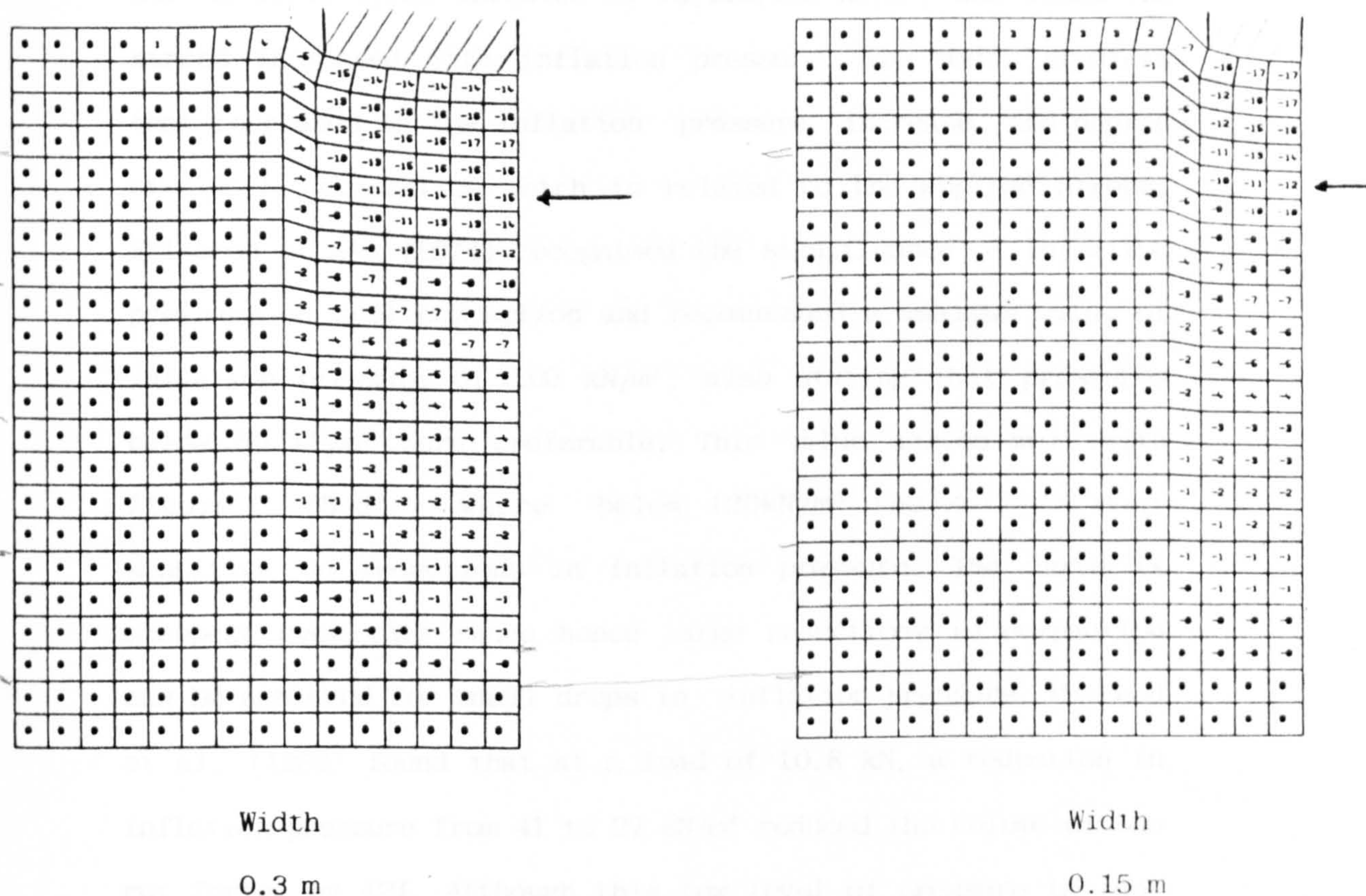


Figure 5.9 The effect of tyre width on soil compaction.

By taking a point at a depth of 112mm below the original soil surface (arrowed), it is clear that the level of compaction rises from a 12% volume decrease to a 15% decrease at the same depth as the width of contact doubles. As magnitude of the volume change and stress are related, the stress must therefore also be greater.

There have only been a limited number of studies where the degree of compaction has been related to the inflation pressure

of the tyre. Christov (1969) measured the stress distribution at 300 mm below tyres inflated at 78,118,158 kN/m², and found the stress increased with inflation pressure. The model predicts that increases in the inflation pressure increase the degree of soil compaction which is related to the applied stress. Eriksson et al. (1974) recognised the significance of inflation pressure on soil compaction and recommended a maximum value of inflation pressure of 100 kN/m², also stating that pressures below 50 kN/m² were preferable. This value agrees well with figure (5.8) where below 120kN/m² the soil is most sensitive to reductions in inflation pressure. The curve is steepest over this range hence large reductions in compaction can be achieved for small drops in inflation pressure. McLeod et al. (1966) found that at a load of 10.8 kN, a reduction in inflation pressure from 41 to 27 kN/m² reduced the volume of the rut formed by 42%. Although this low level of pressure is not covered by this study, by reducing pressure by the same degree from 118 to 79 kN/m² at a load of 10kN, the rut volume is reduced by 43%. Sohne (1958) studied the effects of loads and the distribution of the loads on the resulting pressures in the soil profile and concluded, "the pressure in the upper layer is determined by the specific pressure at the surface, ... the pressure in deeper soil layers is determined by the amount of load." The same conclusion was also reached by Taylor (1982) who states that compaction in the upper layers is determined by the contact pressure, while compaction in the deeper layers is determined by the amount of load, Danfors (1974) also found that

increases in the wheel load tended to have a more significant effect on the subsoil, these effects are also shown by the model as is confirmed in figure (5.9). Henshall and Dickson (1980) have shown that by increasing the load on a tyre from 10 to 15 kN at a constant pressure the rut depth does not significantly increase. By using similar values in the model, table (5.2 a) at 118kN/m^2 for the same increase in load the rut depth only increases from 23 to 26 mm. Another important phenomena found by Taylor (1982) was the effect of contact shape on the compaction, he noted that a long narrow footprint was most desirable for good traction and reduced soil compaction. The model also showed that a long thin contact patch would reduce soil compaction.

6. OVERALL DISCUSSION AND CONCLUSIONS.

The experimental and model work were confined to a sandy loam soil and hence further experimental work is required to check whether the type of soil failure found for a sandy loam soil is present in other soil types. The experimental technique of burying beads in a regular pattern to monitor the trajectory of the soil, although very time-consuming, provided valuable data on the mode and extent of soil failure. The technique of burying beads does not lend itself to field tests but a more representative result could be obtained if a non uniform soil density profile was used in a soil bin. The results showed that the type of soil failure was a punch failure, figure (6.1,a) and not a general shear failure, figure (6.1,b).

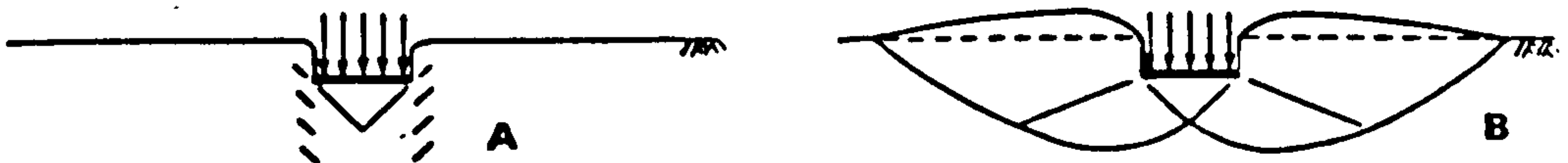


Figure 6.1. Failure modes.

A punch failure is characterised by a failure pattern that is not easily observed as no obvious shear planes occur. As the load increases the vertical movement of the contact area is accompanied by compression of the soil below the load. Continued penetration of the load is made possible by shearing around the perimeter of the contact area. The soil outside the contact

area remains relatively uninvolved in the compression so there is little movement of soil outside the area of contact. With this type of failure the vertical deflections are the most significant in causing soil compaction. Large soil deflections were also monitored in the direction of travel, these deflections increased as the soil strength decreased and decreased as the vertical deformations decreased. At high loads and contact pressures some surface heave was produced at the edge of the wheel, this indicated that the mode of soil failure at the surface was changing to a shear failure. To get full shear failure of the soil a strong and relatively incompressible soil would have to be used with high contact loads and pressures.

The experimental work was conducted at two scales approx 1:4 and 1:1, the type of soil failure observed in both cases was the same. The experimental results show that soil compaction is a process that takes place under the wheel as it rolls over the soil surface, with as much as 80% of the vertical deformation occurring in front of the centre line of the axle. The results also showed that an increase in pressure increased the deflections, an increase in soil density reduced the deflections and an increase in the load increased the deflections. As was expected, it was found that the maximum volume change in the soil occurred at a depth in the soil and not at the tyre/soil interface.

It is possible to use Elastic Theory to predict plastic soil deformations because during loading the soil behaves as an elastic material, it is not until the load is removed that the soil become plastic ie no recovery. The mathematical model of the compression process assumes, for simplicity, a linear stress-strain characteristic for the soil. The value of the Modulus of Elasticity being calculated from the slope of a line drawn on the measured stress-strain curve. The two end points of the line are the contact pressure applied to the soil surface and the initial soil density, these two points were chosen as they represent the full range of possible conditions present in the soil. This approximation underpredicts the soil strength at the surface and overpredicts the strength at depth, which in turn makes the model overpredict the surface strains and underpredict the strains at depth. The model could be rewritten to use an iterative process so as to model the true nonlinear stress-strain characteristics of the soil. The effect of this would significantly increase the accuracy of prediction but at the cost of speed of computation. In conjunction with the nonlinear Modulus, a non-homogeneous soil could be modelled by the introduction of some further constraints on the model. Once a way can be found to have two cut off strains, one for tension the other for compression, deformations in the horizontal and lateral directions can be considered and there should then be no problem in modelling the deflections due to the rolling resistance and draught load of the wheel. The accuracy of the model can be further improved by having a more

complex surface load distribution. If a theory can be developed to accurately model the change in contact length and width with changes in soil strength and inflation pressure the model could be used to predict the compaction of soils in the field.

In its present simple form the model can predict, with reasonable accuracy, the vertical soil deformation below a wheel. More significantly the model allowed the prediction of the trends in the magnitude of the vertical deflection due to different tyre configurations for a range of soil conditions. This allowed the sensitivity of soil to compaction due to various tyres, over a range of soil conditions, to be estimated. Using the model in this way showed that the sensitivity was not linearly related to the input conditions and significant reductions in the level and amount of soil compaction could be achieved with the appropriate tyre configurations.

The confined compression test used to monitor the stress-strain characteristics of the soil proved to be a quick and simple way of assessing the compressibility of the soil over a range of conditions. The compressibility of a soil relates directly to its compactability. Confined compression tests on a wide range of soils were conducted by Larson et al. (1980), they found that type and quantity of the clay present affected the compression index. Extensive confined compression tests were also conducted by Eriksson (1982) using various types of loading such as

static, dynamic and a pulsing load. But care must be taken when using a confined compression test as it is not a universal test for all soil conditions. In the case of a dry sand a confined compression test would indicate that the soil was relatively incompressible and capable of supporting a high load. In reality however, the mode of soil failure would have changed from a compression failure to a bearing capacity failure, the support capability of which is not measured by a confined compression test. The same change of failure would also occur when using an incompressible clay soil. It should however be possible to put an upper limit on the compressibility of a soil, this upper limit being the change point in the mode of failure. The upper limit could be expressed as a maximum Young's Modulus or, as is already used in foundation engineering, a rigidity index, I , defined as :

$$I = \frac{G}{c + \sigma \tan \phi}$$

Either of these values would be able to indicate the approximate point where the mode of failure changed.

The future development of the mathematical prediction of soil compaction using the methods described here could follow several paths:

i) Putting the emphasis on the close modelling of the input conditions as discussed previously. This approach would significantly increase the complexity of the model but would increase the accuracy of the solution.

ii) Putting the emphasis more on the side of getting a

close approximation for a wide range of soil conditions for use in the field in conjunction with a simple confined compression test. In this case a general solution, without using a P/E value in the model, could be produced for a number of wheel configurations. The general solution could be produced in the same form as Newmark's Influence Charts, Newmark (1942). To produce an actual solution the pressure of the tyre (P) and soil strength (E), measured from a confined compression test, would have to be found. The solution found would relate input configuration and soil strength to compaction. Although the solution is more general than case (i) there would be no need for any complex computations, and the process should be simple enough to be carried out in the field.

iii) Putting the emphasis fully onto a confined compression test. The effect on the solution of the model of changes in the tyre inputs is small in comparison to the Young's Modulus. As long as the compaction is caused by a punch failure the confined compression test will give a representative value of soil strength and compactability over the range between contact pressure and initial soil density. By using the results of Larson et al. (1980) for a range of field soils, their compressibility and Young's Modulus could be found and hence their susceptibility to compaction. If a relationship was developed that related Young's Modulus and contact area to compaction, soils could then be classified as to their compactability at different moisture contents. In such a relationship the effect of pressure would be accounted for in

the Modulus, load would be accounted for by the area and the effect of the shape of the area could be accounted for by a conversion factor. This approach would provide the most general solution but it would give a quick and easy means of soil classification with respect to compactability and a measure of the amount of compaction caused by different tyre configurations all from a single soil test.

Comparison of the results obtained from the model and published experimental work showed good correlation. Using the model to predict the sensitivity of soil to compaction showed that a long thin contact area would give a minimum amount of compaction. If the contact pressure and load were kept at a low level the compaction level would be low. The model showed that the effect of an increase in the load was to increase the amount of soil compacted, ie the area of soil compressed and the depth to which the compaction extended for a constant contact area. The effect of an increase in the contact pressure was to increase the compaction level, ie the final soil density would be higher and increase the depth to which the soil was compacted. The model agreed with the published work that compaction is more sensitive to increases in load than inflation pressure. The results also showed that the depth of maximum compaction was related to half the shorter of either the contact length or width. The surface rut volume can be used as a quick "in field" means of determining the amount of soil damage caused by a certain tyre configuration. This is because the surface rut

volume is the sum of all the deformations. The model also showed that significant reductions in the amount of soil compaction could be achieved by a small increase in the soil strength.

The following conclusions can be drawn from the work but are limited to a light sandy loam soil.

i) Most of the soil deformation occurs directly under the wheel, with small deflections in the lateral direction. The soil deformations in the horizontal direction were large and always in the direction of travel. The size of the deformations was related to soil strength and rut depth. The vertical deformations were the most significant in causing compaction and extended to the greatest depth in the soil. The combination of these experimental observations lead to the conclusion that the mode of soil failure below the wheel was a punch failure.

ii) Soil compaction is a process which occurs mainly (80%) in front of the centre line of the axle.

iii) Elasticity Theory can be used to predict the deformation of soil below wheels once modifications have been made to account for the initial soil strength.

iv) A confined compression test can be used to obtain the stress-strain characteristics, Young's Modulus and Poisson's ratio, E and μ required for an Elastic model.

✓ v) For a constant load and contact pressure an aspect ratio of 2.5 (length/width) will produce a minimum amount of soil compaction.

vi) The depth of the maximum compaction below the centre of the wheel is related to half the shorter of the contact dimensions.

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APPENDICES

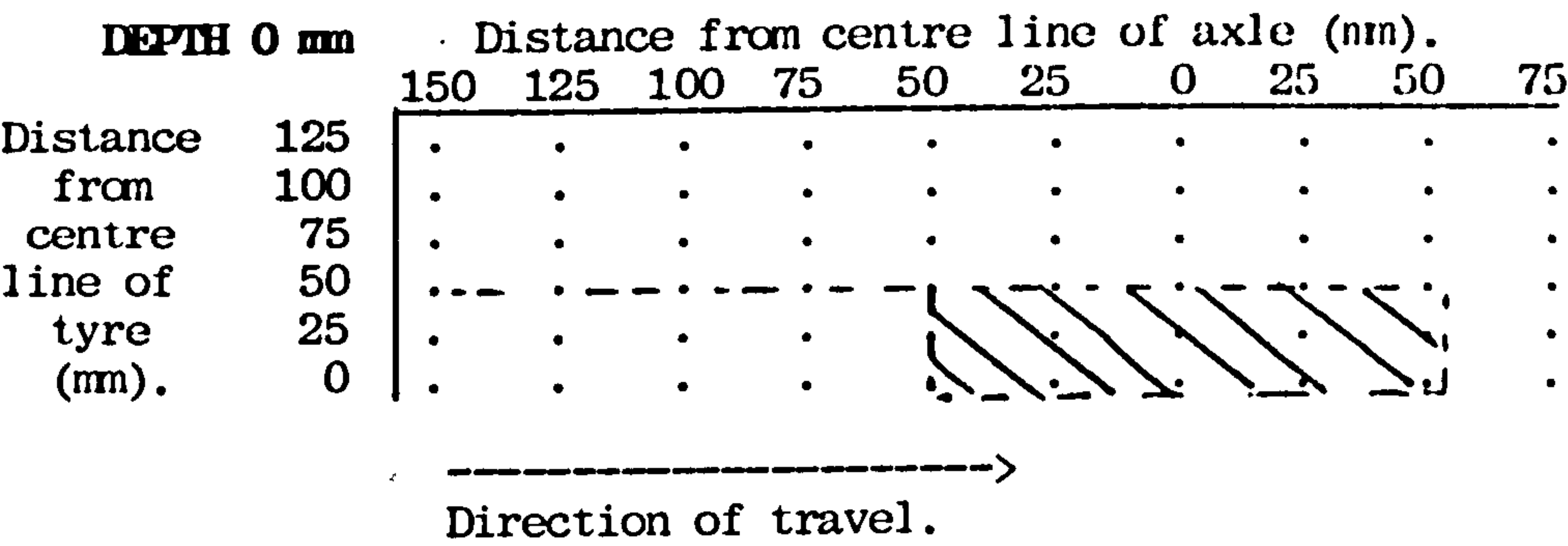
APPENDIX 2.1

Results of small scale work.

Table number	Inflation pressure kN/m ²	Initial soil density g/ml	Tyre width mm
1	345	1.2	100
2	345	1.3	100
3	207	1.2	100
4	207	1.3	100
5	207	1.2	50

Subscripts.

- A Vertical deflection mm.
- B Horizontal deflection mm.
- C Horizontal deflection mm.
- D Volume change %.



The dotted line shows the path of the tyre and the shaded area shows the position of the tyre when stopped.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	-1	-1	0	0	0	0	0	0	0	0
centre	75	-2	-2	0	0	0	0	0	0	0	0
line of	50	3	3	3	3	3	3	2	0	0	0
tyre	25	10	10	10	10	10	9	8	6	2	0
(mm).	0	11	11	11	11	11	9	8	5	3	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	3	3	3	3	3	3	2	1	0	0
tyre	25	8	8	8	8	8	7	6	4	2	0
(mm).	0	10	10	10	10	9	9	7	5	3	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	2	2	2	2	2	2	2	1	0	0
tyre	25	6	6	6	6	6	5	4	3	1	0
(mm).	0	7	7	7	7	7	6	5	3	1	0

DEPTH 75 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	1	1	1	1	1	1	1	0	0
tyre	25	3	3	3	3	3	3	2	1	1	0
(mm).	0	4	4	4	4	4	4	3	2	1	0

DEPTH 100 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	1	1	1	1	1	0	0	0	0
tyre	25	1	1	1	1	1	1	1	0	0	0
(mm).	0	2	2	2	2	2	1	1	0	0	0

DEPTH 125 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 1.A. Vertical defs., @345 kN/m², @1.2g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	1	1	0	0	0	0	0	0	0	0
line of	50	10	10	10	10	9	5	3	1	0	0
tyre	25	12	12	11	12	12	10	7	4	1	0
(mm).	0	14	12	12	12	11	12	7	4	2	1

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	2	2	2	2	2	1	1	0	0	0
tyre	25	3	3	3	3	3	2	2	2	1	0
(mm).	0	3	3	3	3	3	3	3	2	1	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	1	1	1	1	1	0	0	0	0
tyre	25	2	2	2	2	2	2	2	2	1	0
(mm).	0	2	2	2	2	2	2	2	2	1	0

DEPTH 75 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 1.B. Horizontal defs., @345 kN/m², @1.2g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	-3	-1	0	0	0	0	0	0	0	0
line of	50	-5	-4	-2	-2	-2	-2	0	0	0	0
tyre	25	-1	-1	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 1.C. Lateral defs., @345 kN/m², @1.2g/ml.

DEPTH 12 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	+2	+1	0	0	0	0	0	0	0
from	87	+1	+2	0	0	0	0	0	0	0
centre	62	2	3	4	5	9	4	2	0	0
line of	37	+13	0	+1	1	8	7	9	6	2
tyre (mm)	12	4	6	5	8	8	13	12	9	4

DEPTH 37 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	2	2	2	2	3	2	1	6	0
line of	37	6	6	6	6	8	6	4	4	3
tyre (mm)	12	10	10	10	9	10	9	8	10	7

DEPTH 62 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	2	2	2	2	2	3	1	0	0
line of	37	8	7	7	8	7	7	5	3	1
tyre (mm)	12	12	11	11	12	10	8	7	5	2

DEPTH 87 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	1	2	0	0
line of	37	4	5	5	4	4	4	4	1	1
tyre (mm)	12	8	9	9	8	9	8	6	3	2

DEPTH 112 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	2	2	2	2	2	1	0	0	0
line of	37	4	4	4	4	4	3	1	0	0
tyre (mm)	12	6	6	6	6	5	4	2	0	0

DEPTH 137 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	0	0	0	0	0	0	0	0	0
tyre (mm)	12	0	0	0	0	0	0	0	0	0

Table 1.D. % Volume change, @354 kN/m², @ 1.2 g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	1	1	1	1	1	1	1	0	0	0
	25	5	5	5	5	5	4	4	3	1	0
		0	7	7	7	7	7	6	5	3	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	3	3	3	3	3	3	2	2	1	0
		0	5	5	5	5	5	4	4	2	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	2	2	2	2	2	2	1	1	0	0
		0	3	3	3	3	2	2	1	0	0

DEPTH 75 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	1	1	1	1	1	0	0	0	0	0
		0	1	1	1	1	1	0	0	0	0

DEPTH 100 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0

DEPTH 125 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0

Table 2.A. Vertical defs., @345 kN/m², @1.3g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	3	3	3	3	2	2	1	1	0	0
	0	3	3	3	2	2	2	2	1	0	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
	0	1	1	1	1	1	0	0	0	0	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

Table 2.B. Horizontal defs., @345 kN/m², @1.3g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	-1	-1	-1	-1	-1	-1	-1	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

Table 2.C. Lateral defs., @345 kN/m², @1.3g/ml.

DEPTH 12 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	2	2	2	2	2	2	1	0	0
line of	37	8	8	8	9	7	6	3	2	0
tyre (mm)	12	6	6	7	7	6	6	6	5	1

DEPTH 37 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	2	2	2	2	2	3	3	2	1
tyre (mm)	12	6	6	6	6	6	6	5	2	2

DEPTH 62 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	2	2	2	2	1	0	0	0	0
tyre (mm)	12	4	4	4	4	3	1	0	0	0

DEPTH 87 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	0	0	0	0	0	0	0	0	0
tyre (mm)	12	0	0	0	0	0	0	0	0	0

Table 2.D. % Volume change, @354 kN/m², @ 1.3 g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	-1	-1	0	0	0	0	0	0	0	0
line of	50	2	2	2	2	2	2	1	0	0	0
tyre	25	6	6	6	6	6	6	5	4	1	0
(mm).	0	7	7	7	7	7	7	6	4	2	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	2	2	2	2	2	2	1	1	0	0
tyre	25	6	6	6	6	6	5	5	3	1	0
(mm).	0	7	7	7	7	6	6	6	4	2	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	1	1	1	1	1	1	0	0	0
tyre	25	5	5	5	5	5	4	3	2	1	0
(mm).	0	6	6	6	6	6	6	4	2	1	0

DEPTH 75 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	2	2	2	2	2	2	1	1	0	0
(mm).	0	2	2	2	2	2	2	2	1	0	0

DEPTH 100 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	1	1	1	1	1	1	1	0	0	0
(mm).	0	1	1	1	1	1	1	1	0	0	0

DEPTH 125 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 3.A. Vertical defs., @207 kN/m², @1.2g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	1	1	0	0	0	0	0	0	0	0
line of	50	8	8	8	8	6	3	1	1	0	0
tyre	25	10	10	10	10	10	6	3	2	1	0
(mm).	0	10	10	10	10	10	6	4	4	2	1

DEPTH 25 mm		Distance from centr line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	1	1	1	1	0	0	0	0	0
tyre	25	2	2	2	2	2	2	1	1	0	0
(mm).	0	2	2	2	2	2	2	2	1	0	0

DEPTH 75 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	1	1	1	1	1	1	1	0	0	0
(mm).	0	1	1	1	1	1	1	1	0	0	0

DEPTH 100 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 3.B. Horizontal defs., @207 kN/m², @1.2g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	-1	-1	0	0	0	0	0	0	0	0
line of	50	-3	-3	-2	-1	-1	1	0	0	0	0
tyre	25	-1	-1	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 3.C. Lateral defs., @207 kN/m², @1.2g/ml.

DEPTH 12 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	+1	0	0	0	0	0	0	0	0
centre	62	2	3	0	4	5	2	+1	0	0
line of	37	+4	+3	-2	-0	8	7	1	3	1
tyre (mm)	12	+1	0	+2	1	11	8	3	6	2

DEPTH 37 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	2	2	2	2	0	1	1	1	0
line of	37	4	4	4	4	3	5	5	3	0
tyre (mm)	12	4	4	4	3	5	6	10	6	1

DEPTH 62 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	2	2	2	2	2	2	1	0	0
line of	37	8	8	8	8	7	6	5	2	1
tyre (mm)	12	14	14	14	14	13	10	8	4	2

DEPTH 87 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	2	2	2	2	2	1	1	1	0
tyre (mm)	12	4	4	4	4	4	3	3	2	0

DEPTH 112 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	2	2	2	2	2	2	1	0	0
tyre (mm)	12	4	4	4	4	4	4	2	0	0

Table 3.D. % Volume change, @207 kN/m², @ 1.2 g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	1	1	1	1	1	1	0	0	0
tyre	25	3	3	3	3	3	3	2	2	1	0
(mm).	0	5	5	5	5	5	5	4	3	2	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	2	2	2	2	2	2	1	1	0	0
(mm).	0	4	4	4	4	4	4	3	2	1	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	1	1	1	1	1	1	0	0	0	0
(mm).	0	2	2	2	2	2	2	1	1	0	0

DEPTH 75 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	1	1	1	1	1	1	0	0	0	0

DEPTH 100 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 4.A. Vertical defs., @207 kN/m², @1.3g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	2	2	2	2	1	1	0	0	0	0
	0	2	2	2	2	2	1	1	0	0	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
	0	1	1	1	1	0	0	0	0	0	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

Table 4.B. Horizontal defs., @207 kN/m², @1.3g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	-1	-1	-1	-1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance from centre line of tyre (mm).	125	0	0	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

Table 4.C. Lateral defs., @207 kN/m², @1.3g/ml.

DEPTH 12 mm		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	2	2	2	2	2	2	1	0	0
line of	37	6	6	6	6	4	5	3	2	1
tyre (mm)	12	2	2	2	5	5	5	5	4	2

DEPTH 37 mm		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	2	2	2	2	2	2	2	1	0
tyre (mm)	12	6	6	6	7	6	6	5	3	1

DEPTH 62 mm		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	2	2	2	2	2	1	0	0	0
tyre (mm)	12	4	4	4	4	4	3	2	1	0

DEPTH 87 mm		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	0	0	0	0	0	0	0	0	0
tyre (mm)	12	2	2	2	2	2	1	1	1	0

DEPTH 112 mm		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	0	0	0	0	0	0	0	0	0
tyre (mm)	12	0	0	0	0	0	0	0	0	0

Table 4.D. % Volume change, @207 kN/m², @ 1.3 g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	6	6	6	6	6	5	5	3	1	0
(mm).	0	9	9	9	9	9	9	8	6	3	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	5	5	5	5	5	4	3	2	1	0
(mm).	0	8	8	8	8	8	7	5	4	2	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	1	1	1	1	1	0	0	0	0
tyre	25	3	3	3	3	3	3	2	2	1	0
(mm).	0	4	4	4	4	4	4	3	2	1	0

DEPTH 75 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	1	0	1	1	0	1	0	0	0	0
tyre	25	1	1	1	1	1	1	1	0	0	0
(mm).	0	2	2	2	2	2	2	1	1	0	0

DEPTH 100 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	1	1	1	0	0	0	0	0

DEPTH 125 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 5.A. Vertical defs., @207 kN/m², @1.2g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	2	2	2	2	2	1	1	1	0	0
(mm).	0	3	3	3	3	3	3	2	1	1	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	1	1	1	1	1	1	1	0	0	0

DEPTH 50 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 5.B. Horizontal defs., @207 kN/m², @1.2g/ml.

DEPTH 0 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	-1	-1	0	-1	-1	-1	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

DEPTH 25 mm		Distance from centre line of axle (mm).									
		150	125	100	75	50	25	0	25	50	75
Distance	125	0	0	0	0	0	0	0	0	0	0
from	100	0	0	0	0	0	0	0	0	0	0
centre	75	0	0	0	0	0	0	0	0	0	0
line of	50	0	0	0	0	0	0	0	0	0	0
tyre	25	0	0	0	0	0	0	0	0	0	0
(mm).	0	0	0	0	0	0	0	0	0	0	0

Table 5.C. Lateral defs., @207 kN/m², @1.2g/ml.

DEPTH 12 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	4	3	3	4	5	4	3	2	0
tyre (mm)	12	$\frac{4}{2}$	$\frac{3}{3}$	$\frac{3}{3}$	$\frac{4}{2}$	$\frac{5}{4}$	$\frac{4}{8}$	$\frac{3}{10}$	$\frac{2}{5}$	2

DEPTH 37 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	+2	+2	+2	+2	+2	+1	0	0	0
line of	37	2	2	2	2	1	1	1	0	0
tyre (mm)	12	12	12	12	12	10	7	6	3	1

DEPTH 62 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	1	1	0	1	1	0	0	0	0
line of	37	5	5	4	5	5	3	3	3	1
tyre (mm)	12	8	8	8	8	8	7	6	5	2

DEPTH 87 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	1	1	2	1	1	1	0	0	0
line of	37	3	3	4	3	3	3	1	0	0
tyre (mm)	12	6	5	4	4	5	5	3	1	0

DEPTH 112 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	0	0	0	0	0	0	0	0	0
tyre (mm)	12	0	1	2	2	1	0	0	0	0

DEPTH 137 mm

		Distance of cube centre from centre line of axle (mm).								
		137	112	87	62	37	12	12	37	62
Distance	112	0	0	0	0	0	0	0	0	0
from	87	0	0	0	0	0	0	0	0	0
centre	62	0	0	0	0	0	0	0	0	0
line of	37	0	0	0	0	0	0	0	0	0
tyre (mm)	12	0	0	0	0	0	0	0	0	0

Table 5.D. % Volume change, @207 kN/m², @ 1.2 g/ml.

APPENDIX 2.2

Results of full scale work.

Table number.	Initial soil density. g/ml.	Wheel load. kN.	Inflation pressure. kN/m ²
6	1.3	11	173
7	1.3	9	173
8	1.3	7	173
9	1.4	9	173
10	1.5	9	173
11	1.6	9	173
12	1.4	7	69
13	1.4	7	173
14	1.4	7	276

Subscripts.

- A Vertical deflection mm.
- B Horizontal deflection mm.
- C Lateral deflection mm.
- D Volume change %.

		Distance from centre line of wheel (mm)								Position of wheel
		350	300	250	200	150	100	50	0	
Depth (mm)	0	.	.	.	.	.	Tyre			
	50	.	.	.	.	.	.	.	.	
	100	.	.	.	.	.	.	.	.	
	150	.	.	.	.	.	.	.	.	
	200	.	.	.	.	.	.	.	.	
	250	.	.	.	.	.	.	.	.	
	300	.	.	.	.	.	.	.	.	
	350	.	.	.	.	.	.	.	.	
	400	.	.	.	.	.	.	.	.	

		Distance from centre line of wheel (mf)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	-1	-4	-7	-8	20	41	42
(mm)	50	0	0	0	0	4	18	39	41
	100	0	0	0	0	3	13	29	30
	150	0	0	0	0	3	9	20	20
	200	0	0	0	0	2	6	15	14
	250	0	0	0	0	0	4	9	10
	300	0	0	0	0	0	2	4	4
	350	0	0	0	0	0	0	1	1
	400	0	0	0	0	0	0	0	0

TABLE 6.A. Vertical defs,. Load 11 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	-1	-3	-4	0	0
(mm)	50	0	0	0	0	-2	-2	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 6.B. Lateral defs,. Load 11 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	3	9	27	38	38
(mm)	50	0	0	0	0	5	12	25	25
	100	0	0	0	0	4	7	14	14
	150	0	0	0	0	0	4	8	8
	200	0	0	0	0	0	0	3	5
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 6.C. Horizontal defs,. Load 11 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	+1	+5	+10	+14	+9	+2	3
(mm)	75	0	0	0	3	6	13	21
	125	0	0	0	0	4	13	19
	175	0	0	0	1	4	8	11
	225	0	0	0	2	4	8	10
	275	0	0	0	0	4	7	11
	325	0	0	0	0	2	5	6

TABLE 6.D. % Volume change, Load 11 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	-1	-2	16	39	42
(mm)	50	0	0	0	0	0	14	35	39
	100	0	0	0	0	4	12	27	30
	150	0	0	0	0	3	10	20	17
	200	0	0	0	0	2	8	12	10
	250	0	0	0	0	1	6	8	5
	300	0	0	0	0	0	2	3	3
	350	0	0	0	0	0	0	0	0

TABLE 7.A. Vertical defs,. Load 9 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	-1	-3	0	0	0
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 7.B. Lateral defs,. Load 9 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	3	16	23	23	23
(mm)	50	0	0	0	4	12	15	15	16
	100	0	0	0	0	8	11	12	12
	150	0	0	0	0	0	3	5	5
	200	0	0	0	0	0	0	3	5
	250	0	0	0	0	0	0	2	2
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 7.C. Horizontal defs,. Load 9 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	0	0	0	+1	+3	6	7
(mm)	75	0	0	0	+4	+2	10	17
	125	0	0	0	1	3	9	20
	175	0	0	0	1	3	10	15
	225	0	0	0	1	3	6	9
	275	0	0	0	1	5	9	7
	325	0	0	0	0	2	5	6

TABLE 7.D. % Volume change, Load 9 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	12	30	33
(mm)	50	0	0	0	0	0	11	28	30
	100	0	0	0	0	0	10	20	23
	150	0	0	0	0	2	8	14	15
	200	0	0	0	0	1	4	9	9
	250	0	0	0	0	0	2	2	5
	300	0	0	0	0	0	0	1	1
	350	0	0	0	0	0	0	0	0

TABLE 8.A. Vertical defs,. Load 7 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	0	0	0
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 8.B. Lateral defs,. Load 7 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	10	12	13
(mm)	50	0	0	0	0	0	2	4	7
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 8.C. Horizontal defs,. Load 7 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	0	0	0	0	1	3	5
(mm)	75	0	0	0	0	1	9	15
	125	0	0	0	+2	0	9	11
	175	0	0	0	1	5	9	11
	225	0	0	0	1	3	9	11
	275	0	0	0	0	2	3	5
	325	0	0	0	0	0	1	2

TABLE 8.D. % Volume change, Load 7 kN., @1.3 g/ml, @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	22	24	25
(mm)	50	0	0	0	0	0	18	21	23
	100	0	0	0	0	0	12	13	15
	150	0	0	0	0	0	7	8	9
	200	0	0	0	0	0	3	4	5
	250	0	0	0	0	0	0	2	3
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 9.A. Vertical defs,. Density 1.4 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	0	0	0
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 9.B. Lateral defs,. Density 1.4 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	4	20	29	36
(mm)	50	0	0	0	0	0	12	13	13
	100	0	0	0	0	0	3	4	7
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 9.C. Horizontal defs,. Density 1.4 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	0	0	0	0	4	7	5
(mm)	75	0	0	0	0	6	14	16
	125	0	0	0	0	5	10	11
	175	0	0	0	0	4	8	8
	225	0	0	0	0	3	5	4
	275	0	0	0	0	0	2	5
	325	0	0	0	0	0	0	0

TABLE 9.D. % Volume change, Density 1.4 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	5	8	8
(mm)	50	0	0	0	0	0	3	5	6
	100	0	0	0	0	0	1	3	3
	150	0	0	0	0	0	0	1	1
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 10.A. Vertical defs,. Density 1.5 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	0	0	0
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 10.B. Lateral defs,. Density 1.5 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	10	11	11
(mm)	50	0	0	0	0	0	3	4	4
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 10.C. Horizontal defs,. Density 1.5 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	0	0	0	0	2	5	5
(mm)	75	0	0	0	0	2	4	5
	125	0	0	0	0	1	3	4
	175	0	0	0	0	0	1	2
	225	0	0	0	0	0	0	0
	275	0	0	0	0	0	0	0
	325	0	0	0	0	0	0	0

TABLE 10.D. % Volume change, Density 1.5 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	0	2	3
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 11.A. Vertical defs,. Density 1.6 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	0	0	0
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 11.B. Lateral defs,. Density 1.6 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	0	0	0
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 11.C. Horizontal defs,. Density 1.6 g/ml, @9 kN., @173 kN/m² f

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	0	0	0	0	0	2	5
(mm)	75	0	0	0	0	0	0	0
	125	0	0	0	0	0	0	0
	175	0	0	0	0	0	0	0
	225	0	0	0	0	0	0	0
	275	0	0	0	0	0	0	0
	325	0	0	0	0	0	0	0

TABLE 11.D. % Volume change, Density 1.6 g/ml, @9 kN., @173 kN/m².

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	18	20	21
(mm)	50	0	0	0	0	4	16	18	19
	100	0	0	0	0	4	11	14	14
	150	0	0	0	0	0	4	6	7
	200	0	0	0	0	0	0	1	2
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 12.A. Vertical defs,. Pressure 69 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	-1	-2	0
(mm)	50	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 12.B. Lateral defs,. Pressure 69 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	11	12	12
(mm)	50	0	0	0	0	0	5	5	5
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 12.C. Horizontal defs,. Pressure 69 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
								Tyre
Depth	25	0	0	0	+3	+1	2	4
(mm)	75	0	0	0	0	+5	9	9
	125	0	0	0	4	11	15	15
	175	0	0	0	0	4	9	10
	225	0	0	0	0	0	1	3
	275	0	0	0	0	0	0	0
	325	0	0	0	0	0	0	0

TABLE 12.D. % Volume change, Pressure 69 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	15	28	32
(mm)	50	0	0	0	0	0	9	24	30
	100	0	0	0	0	2	7	18	24
	150	0	0	0	0	1	5	10	12
	200	0	0	0	0	0	4	7	8
	250	0	0	0	0	0	3	1	4
	300	0	0	0	0	0	0	0	1
	350	0	0	0	0	0	0	0	0

Table 13.A. Vertical defs,. Pressure 173 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	0	-3	0	0
(mm)	50	0	0	0	0	-1	-1	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 13.B. Lateral defs,. Pressure 173 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	4	16	30	38
(mm)	50	0	0	0	0	0	4	12	20
	100	0	0	0	0	0	2	7	13
	150	0	0	0	0	0	0	3	7
	200	0	0	0	0	0	0	0	3
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 13.C. Horizontal defs,. Pressure 173 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	0	0	0	1	9	6	6
(mm)	75	0	0	0	+1	0	7	12
	125	0	0	0	1	3	10	20
	175	0	0	0	1	3	4	7
	225	0	0	0	0	1	7	10
	275	0	0	0	0	3	4	4
	325	0	0	0	0	0	0	1

TABLE 13.D. % Volume change, Pressure 173 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	-3	-4	-5	25	43	47
(mm)	50	0	0	0	0	0	20	40	42
	100	0	0	0	0	3	16	30	31
	150	0	0	0	0	0	9	16	17
	200	0	0	0	0	0	5	9	10
	250	0	0	0	0	0	3	5	5
	300	0	0	0	0	0	0	2	2
	350	0	0	0	0	0	0	0	0

TABLE 14.A. Vertical defs,. Pressure 276 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	-3	-6	0	0
(mm)	50	0	0	0	0	0	-2	0	0
	100	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 14.B. Lateral defs,. Pressure 276 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel (mm)							
		350	300	250	200	150	100	50	0
								Tyre	
Depth	0	0	0	0	0	4	32	40	40
(mm)	50	0	0	0	0	0	14	23	23
	100	0	0	0	0	0	6	10	14
	150	0	0	0	0	0	0	3	5
	200	0	0	0	0	0	0	0	0
	250	0	0	0	0	0	0	0	0
	300	0	0	0	0	0	0	0	0
	350	0	0	0	0	0	0	0	0

TABLE 14.C. Horizontal defs,. Pressure 276 kN/m², @7 kN., @1.4 g/ml.

		Distance from centre line of wheel of the centre of the cube.(mm)						
		325	275	225	175	125	75	25
							Tyre	
Depth	25	0	+3	+7	+6	5	1	8
(mm)	75	0	0	0	+3	3	12	21
	125	0	0	0	3	10	21	28
	175	0	0	0	0	4	11	14
	225	0	0	0	0	2	6	9
	275	0	0	0	0	3	6	6
	325	0	0	0	0	0	2	4

TABLE 14.D. % Volume change, Pressure 276 kN/m², @7 kN., @1.4 g/ml.

APPENDIX 3.1

Numerical Integration Program.

Computer Program.

Line.

```

1      DIMENSION VU(42,42),VV(42,42),VW(42,42),HU(42,42),HIV(42,42),
2      +HW(42,42)
3      READ (5,*) A,N,NN,KKK,POI
4      PIE=3.1415926
5      ZS=0.0
6      XS=(NN-1)*A
7      YS=XS
8      H=A/(N*2)
9      N1=NN+1
10     DO 30 KK=1,KKK
11     Z=ZS+(KK-1)*A
12     DO 20 II=1,NN
13     YO=YS-(II-1)*A
14     DO 20 JJ=1,NN
15     XO=-XS+(JJ-1)*A
16     VU1=0.0
17     VV1=0.0
18     VW1=0.0
19     HU1=0.0
20     HV1=0.0
21     HW1=0.0
22     DO 15 J=1,N
23     YP=(A/2)-((J-1)*H*2)-H
24     Y=(YO-YP)
25     DO 15 I=1,N
26     XP=-A/2)+((I-1)*H*2)+H
27     X=(XO-XP)
28     X2=X*X
29     RR=((X2)+(Y2))**.5
30     R=((X2)+(Y2)+(Z2))**.5)
31     R3=R2*R
32     AA=(1+POI)/(2*PIE)
33     HW1=HW1+AA*X*((Z/R3)+((1-2*POI)/(R*(R+Z))))
34     HV1=HV1+AA*X*Y*((1/R3)-((1-2*POI)/(R*(R+Z)**2))))
35     HU1=HU1+AA*((1/R)+(X2/R3)+(((1-2*POI)/(R*(R+Z)))*
36     +(1-(X2/(R+(R+Z))))))
37     VW1=VW1+AA*((Z*Z/R3)+((2*(1-POI))/R))
38     VV1=VV1+AA*RR*((Z/R3)-((1-2*POI)/(R+Z)))
39     VU1=VU1+AA*RR*((Z/R3)-((1-2*POI)/(R+Z)))
40     15  CONTINUE
41     HW(II,JJ)=HW1
42     HV(II,JJ)=HV1
42     HU(II,JJ)=HU1
44     VW(II,JJ)=VW1
45     VU(II,JJ)=VU1
46     VV(II,JJ)=VV1
47     20  CONTINUE
48     WRITE(2,300)((HU(II,JJ),JJ=1,NN),II=1,NN)
49     WRITE(3,300)((HV(II,JJ),JJ=1,NN),II=1,NN)
50     WRITE(4,300)((HW(II,JJ),JJ=1,NN),II=1,NN)
51     WRITE(7,300)((VU(II,JJ),JJ=1,NN),II=1,NN)
52     WRITE(8,300)((VV(II,JJ),JJ=1,NN),II=1,NN)

```


Line.

53		WRITE(9,300)((VW(II,JJ),JJ=1,NN),II=1,NN)
54	300	FORMAT(1H ,(F16.6))
55	30	CONTINUE
56		ENDFILE 2
57		ENDFILE 3
58		ENDFILE 4
59		ENDFILE 7
60		ENDFILE 8
61		ENDFILE 9
62		STOP
63		END

Explanation**Line 3**

A Dimensions of the area/grid. (0.025 m)

N Number of point loads along area. (8)

NN Number of point solutions required. (41)

KKK Number of point solutions deep. (41)

POI Soil Poisson's ratio. (0.25)

Line 6-8

XS,YS,ZS Distance of first solution point from the centre of the loaded area.

Line 10

Main loop for each layer of solutions.

Line 11

Calculates depth of solution.

Line 12-15

Loops for each point of solution in turn and calculates the distance of the point of solution from the centre of the area.

Line 16-21

Resets running total to zero.

Line 22-27

Loops for each point load in turn and calculates the distance of the load from the centre of the loaded area.
X,Y,Z distance of point load from point of solution.

Line 28-39

Calculates the partial solution at the point of solution for the load on the area and adds it to last value.

Line 41-46

Writes summed solution into a two dimensional array.

Line 48-54

Writes solution to data file.

Line 56-61

Closes data files.

APPENDIX 3.2

Numerical Summation Program.

Computer program

Line.

```

1      COMMON /SUD/AA(62,62)
2      COMMON /SUD/XY(50,41)
3      WRITE (6,100)
4      READ (7,*) WIDE,TLONG
5      WRITE (6,101)
6      READ (7,*) GRID,NOON
7      WRITE (6,102)
8      READ (7,*) YM
9      WRITE (6,103)
10     READ (7,*) ZPRESS
11     WRITE (6,104)
12     READ (7,*) NTIMES,NUM
13     NWIDE=NINT(WIDE/GRID)
14     NLONG=(TLONG/GRID)
15     PRESS=(( (GRID**2)/NOON)/YM)*1000.0*ZPRESS
16     DO 3 LAY=0,NTIMES
17     DO 1 I=16,31
18     DO 1 J=11,40
19         1 XY(J,I)=0.0
20         CALL VLD(NUM)
21         DO 2 JS=1,NLONG
22         DO 2 IS=1,NWIDE
23         DO 2 J=11,40
24         JJ=INT(J-NLONG/2)+JS)
25         DO 2 I=16,31
26         II=INT(I-(NWIDE/2)+IS)
27         XY(J,I)=(XY(J,I)+(AA(JJ,II)*PRESS))
28         2 CONTINUE
29         CALL WRITE
30         3 CONTINUE
31         STOP
32         100 FORMAT(1H , 'THE WIDTH AND LENGTH OF CONTACT AREA (M)',/)
33         101 FORMAT(1H , 'THE GRID SIZE (M) AND NUMBER OF CONTACTS',/)
34         102 FORMAT(1H , 'SOIL YOUNG'S MODULUS',/)
35         103 FORMAT(1H , 'THE VERTICAL PRESSURE (kN/m2)',/)
36         104 FORMAT(1H , 'LAST LAYER AND NUM',/)
37         END

38     SUBROUTINE WRITE
39     COMMON /SUD/XY(50,41)
40     WRITE(9,1) ((XY(J,I),I=16,31),J=11,40)
41         1 FORMAT(1H ,F9.4)
42     RETURN
43     END

44     SUBROUTINE VLD (NUM)
45     DIMENSION B(32)
46     COMMON /SUB/AA(62,62)
47     IF(NUM.EQ.3) GOTO 10
48     READ (8,*) L1,L2,L3,L4
49     NY=61
50     DO 1 J=0,29
51     READ (2,*)(B(I),I=1,31)

```


Line.

```

52      NX=31
53      J1=J+1
54      AA(J1,31)=B(31)
55      NYMJ=NY-J
56      AA(NYMJ,31)=L3*B(31)
57      DO 1 I=1,30
58      NXMI=NX-I
59      AA(J1,NXMI)=L4*B(NXMI)
60      NYMJ=NY-J
61      NXPI=NX+I
62      AA(NYMJ,NXPI)=L2*B(NXMI)
63      AA(J1,NXPI)=L1*B(NXMI)
64      1  AA(NYMJ,NXMI)=L3*B(NXMI)
65      READ (2,*) (B(I),I=1,31)
66      DO 2 I=1,30
67      NXMI=NX-I
68      NXPI=NX+I
69      AA(31,NXPI)=L1*B(NXMI)
70      2  AA(31,NXMI)=L4*B(NXMI)
71      AA(31,31)=B(31)
72      RETURN
73      3  READ (8,*) L1,L2,L3,L4
74      NY=61
75      DO 4 J=0,29
76      READ (2,*)(B(I),I=1,31)
77      NX=31
78      J1=J+1
79      AA(J1,31)=B(31)
80      NYMJ=NY-J
81      AA(31,NYMJ)=L3*B(31)
82      DO 4 I=1,30
83      NXMI=NX-I
84      AA(NXMI,J1)=L4*B(NXMI)
85      NYMJ=NY-J
86      NXPI=NX+I
87      AA(NXPI,NYMJ)=L2*B(NXMI)
88      AA(NXPI,J1)=L1*B(NXMI)
89      4  AA(NXMI,NYMJ)=L3*B(NXMI)
90      READ (2,*) (B(I),I=1,31)
91      DO 5 I=1,30
92      NXMI=NX-I
93      NXPI=NX+I
94      AA(NXPI,31)=L1*B(NXMI)
95      5  AA(NXMI,31)=L4*B(NXMI)
96      AA(31,31)=B(31)
97      RETURN
98      END

```


Explanation

Line 3-12

Input data.

Wide, Contact width (m).

Tlong, Contact length (m).

Grid, Solution grid size (0.025m).

Ncon, Number of point loads/area.

Ym, Young's Modulus (kN/m²).

Zpress, Vertical pressure (kN/m²).

Ntimes, Depth of last layer.

Num, Run number.

1 Vertical deflection.

2 Horizontal deflection.

3 Lateral deflection.

Line 13-14

Calculates contact size to the nearest whole grid size.

Line 15

Calculates P/E and converts solution to mm.

Line 16

Main loop for each layer.

Line 17-19

Sets zero.

Line 20

Calls reflecting routine.

Line 21-28

Main summing routine, adds the effect of each area to each solution.

Line 29

Calls output routine.

Line 38-43

Writes summed solution as a one dimensional array.

Line 47-98

Reflects data from data file around the principle axes.

45-72 num=1,2 for vertical and horizontal loads.

73-98 num=3 rotates horizontal solution through 90°
for a lateral load.

APPENDIX 5.1

Contact Geometry Results.

Load (kN.)	12	Aspect ratio.	3.4	1.57	1	0.63	0.29
		Figure.	5.1:1	5.1:2	5.1:3	5.1:4	5.1:5
18		Aspect ratio.	2.4	1.4	1	0.69	0.411
		Figure.	5.1:6	5.1:7	5.1:8	5.1:9	5.1:10
25		Aspect ratio.	2.1	1.63	1	0.73	0.47
		Figure.	5.1:11	5.1:12	5.1:13	5.1:14	5.1:15

Input variables:-

Moisture content	10 %
Initial soil density	1.3 g/ml
Ground contact pressure	238 kN/m ²
Young's modulus	957.5 kN/m ²
Cut off strain	2.9 %
Poisson's ratio	0.25

Direction of travel.

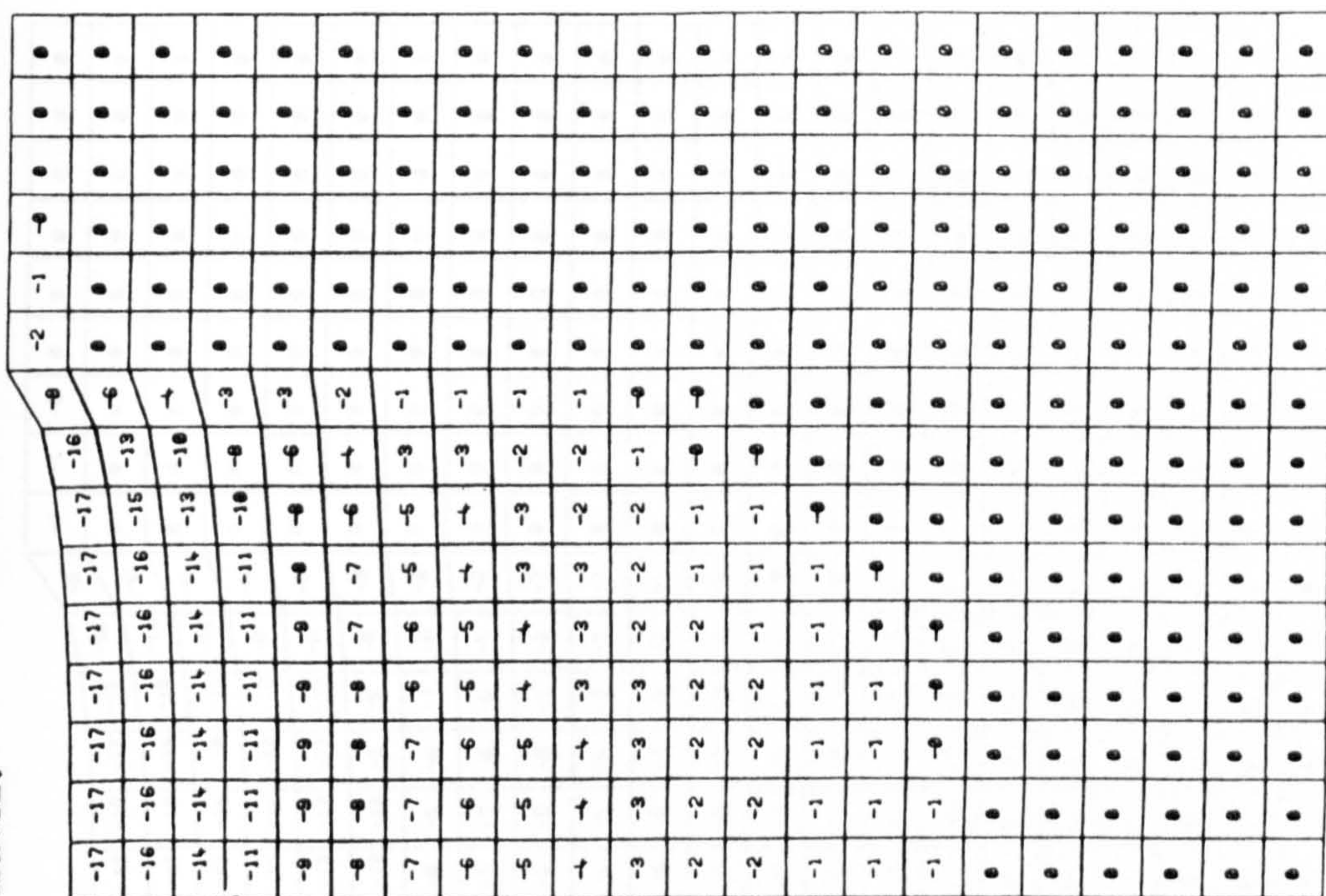
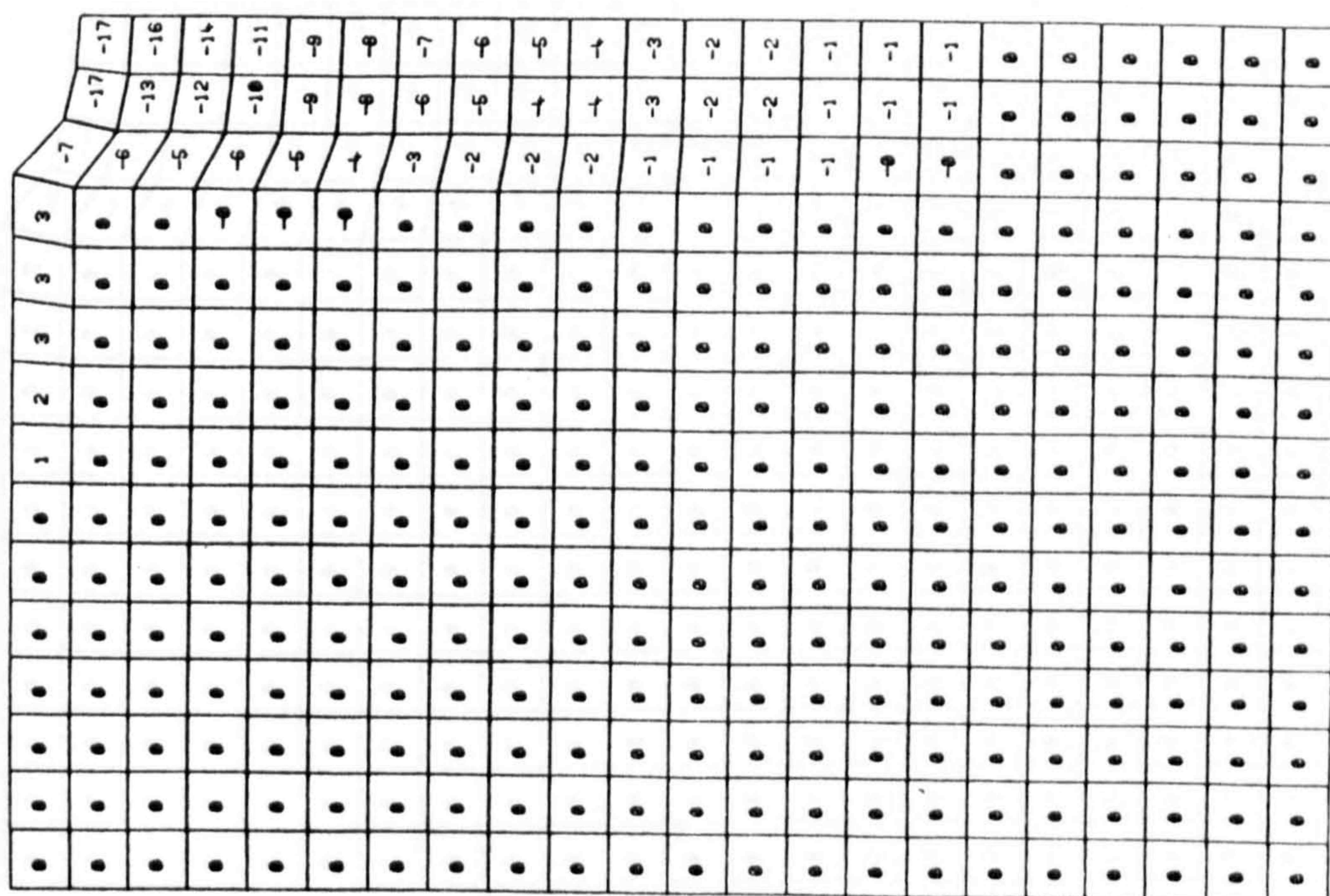


FIGURE 5.1:1.

Direction of travel. 

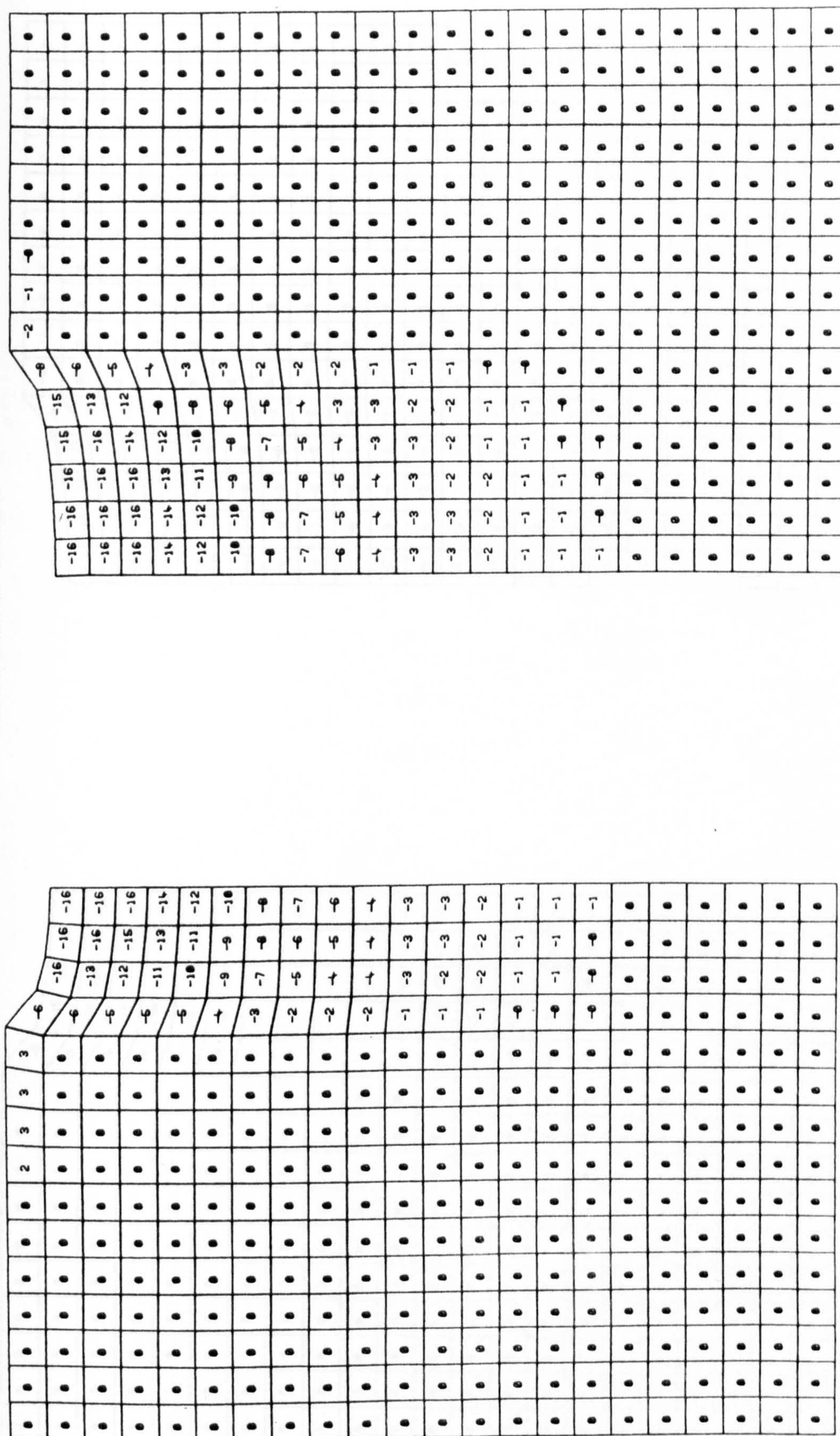


FIGURE 5.1:2.

Direction of travel. 

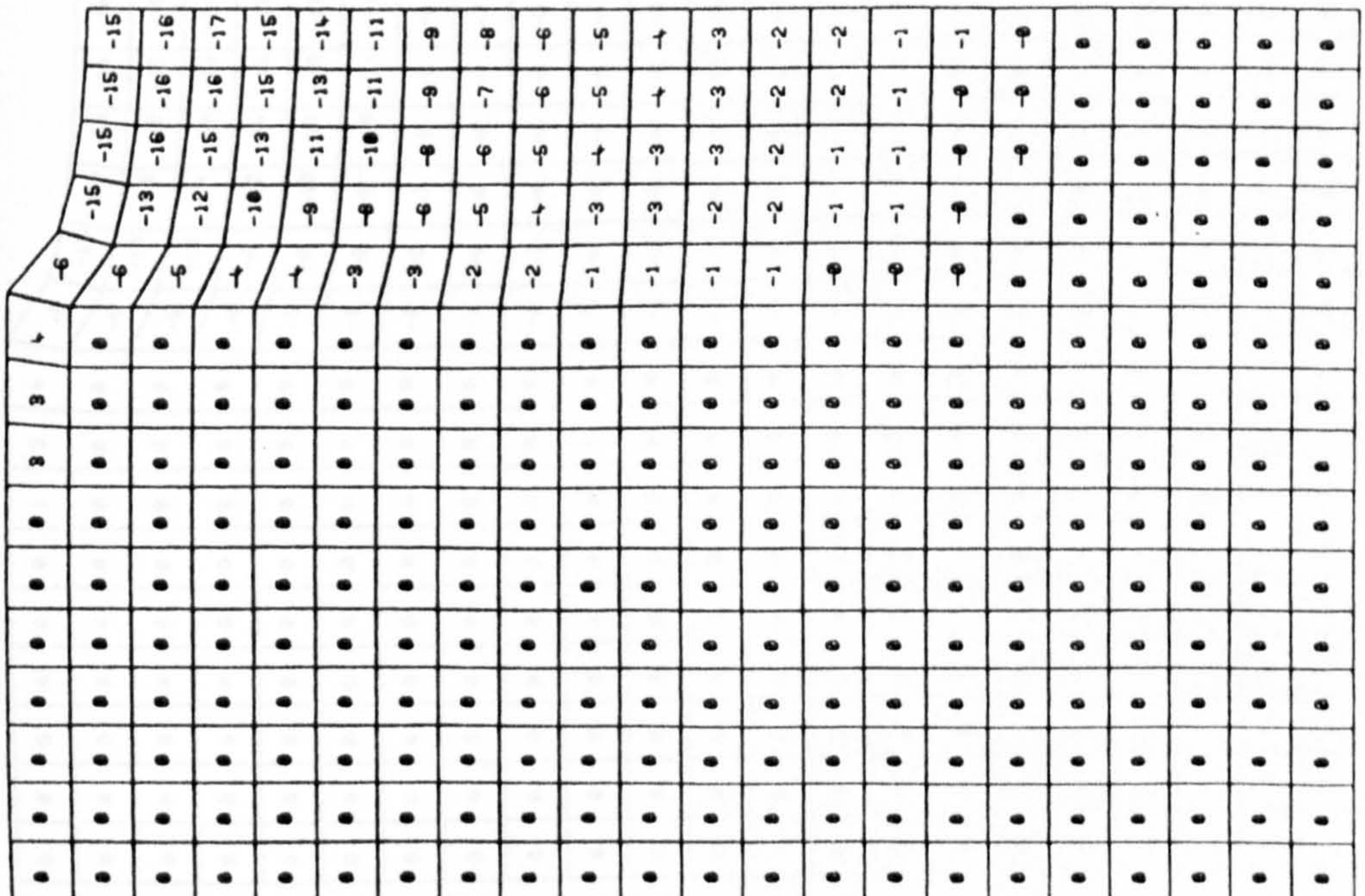
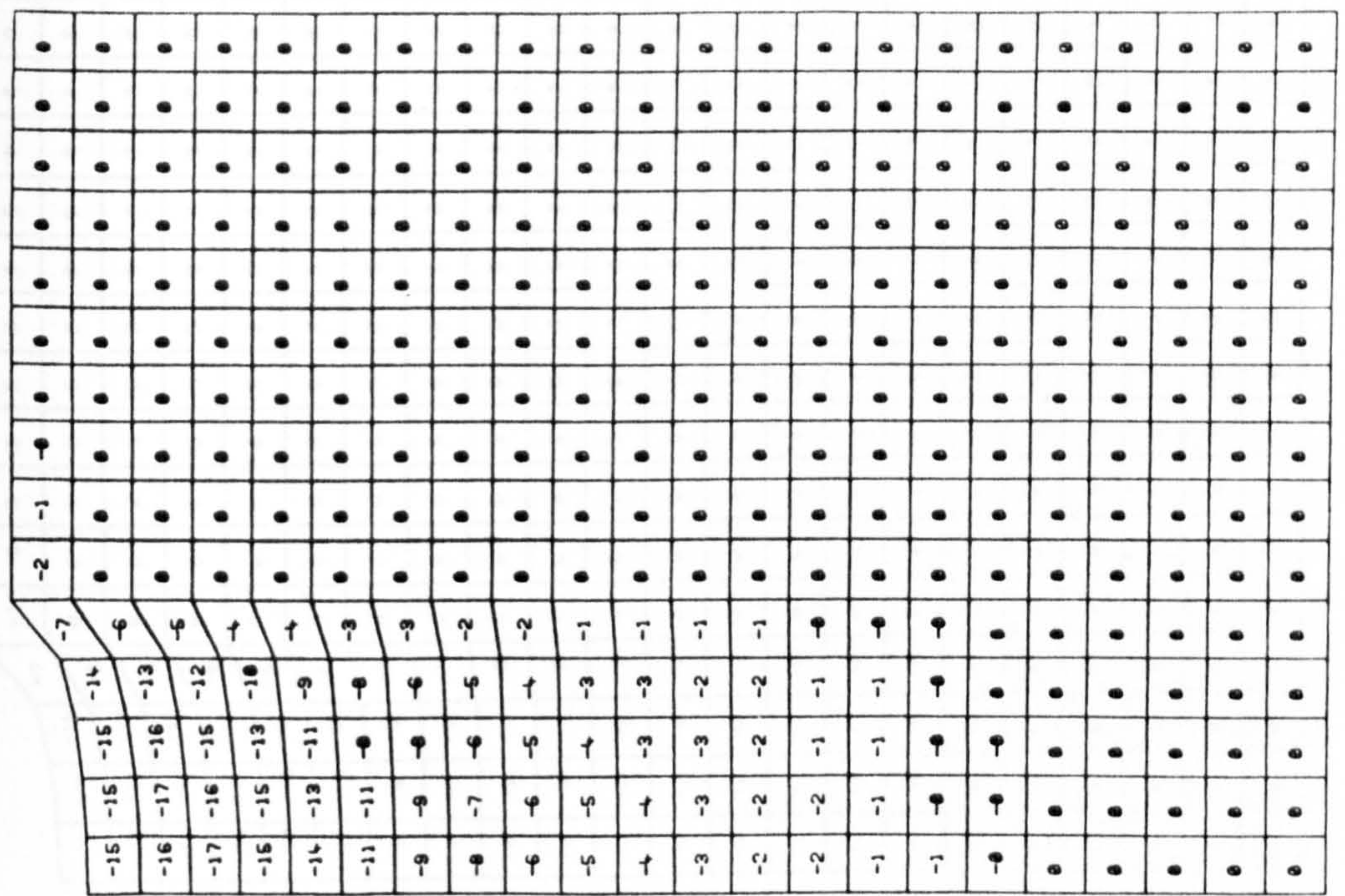
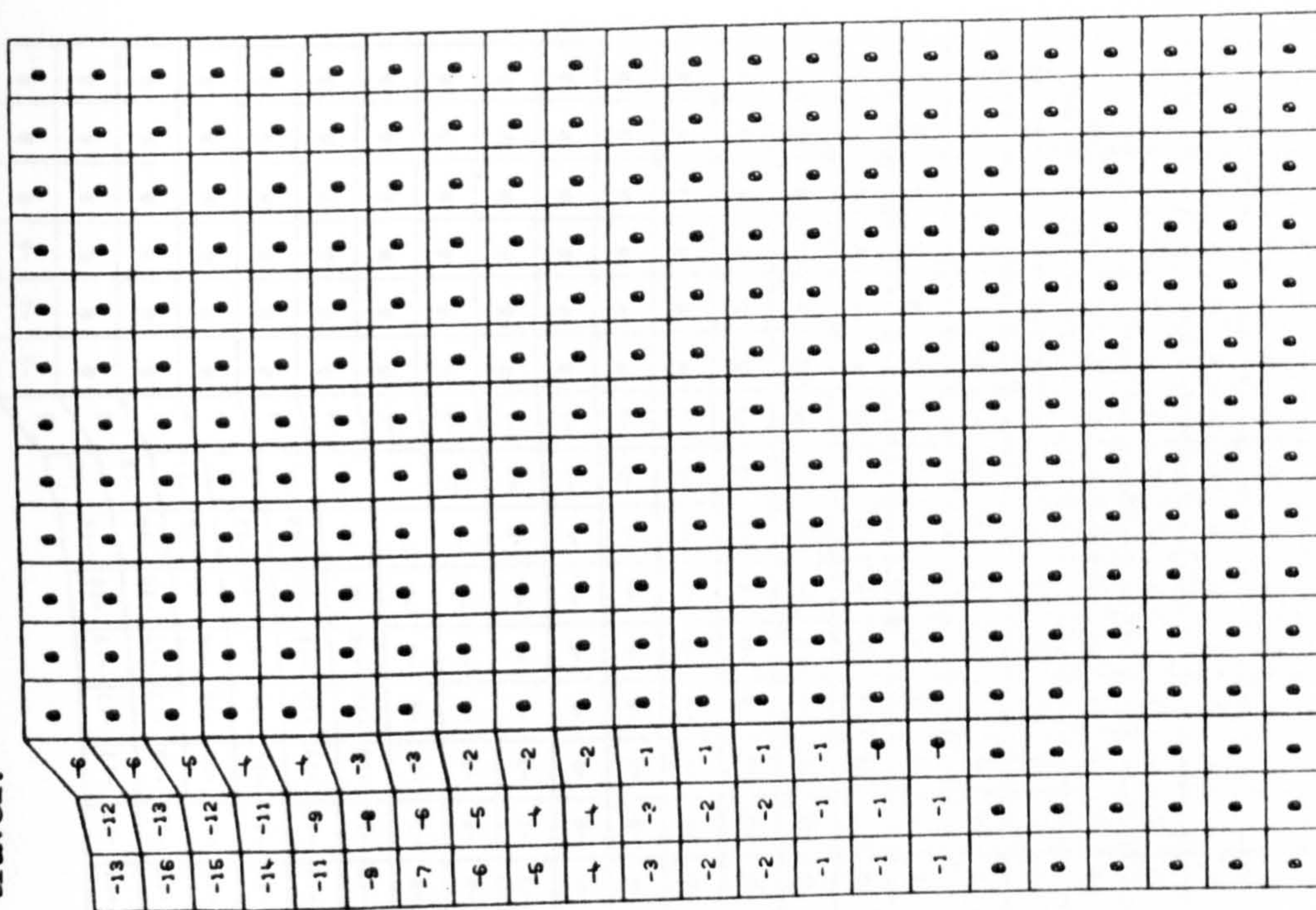
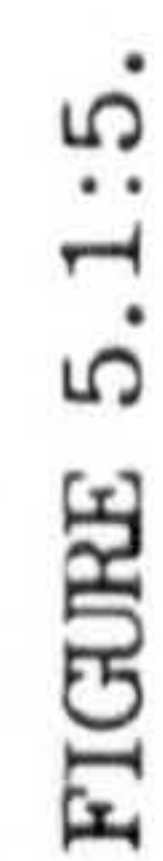


FIGURE 5.1:3.



Direction of travel.

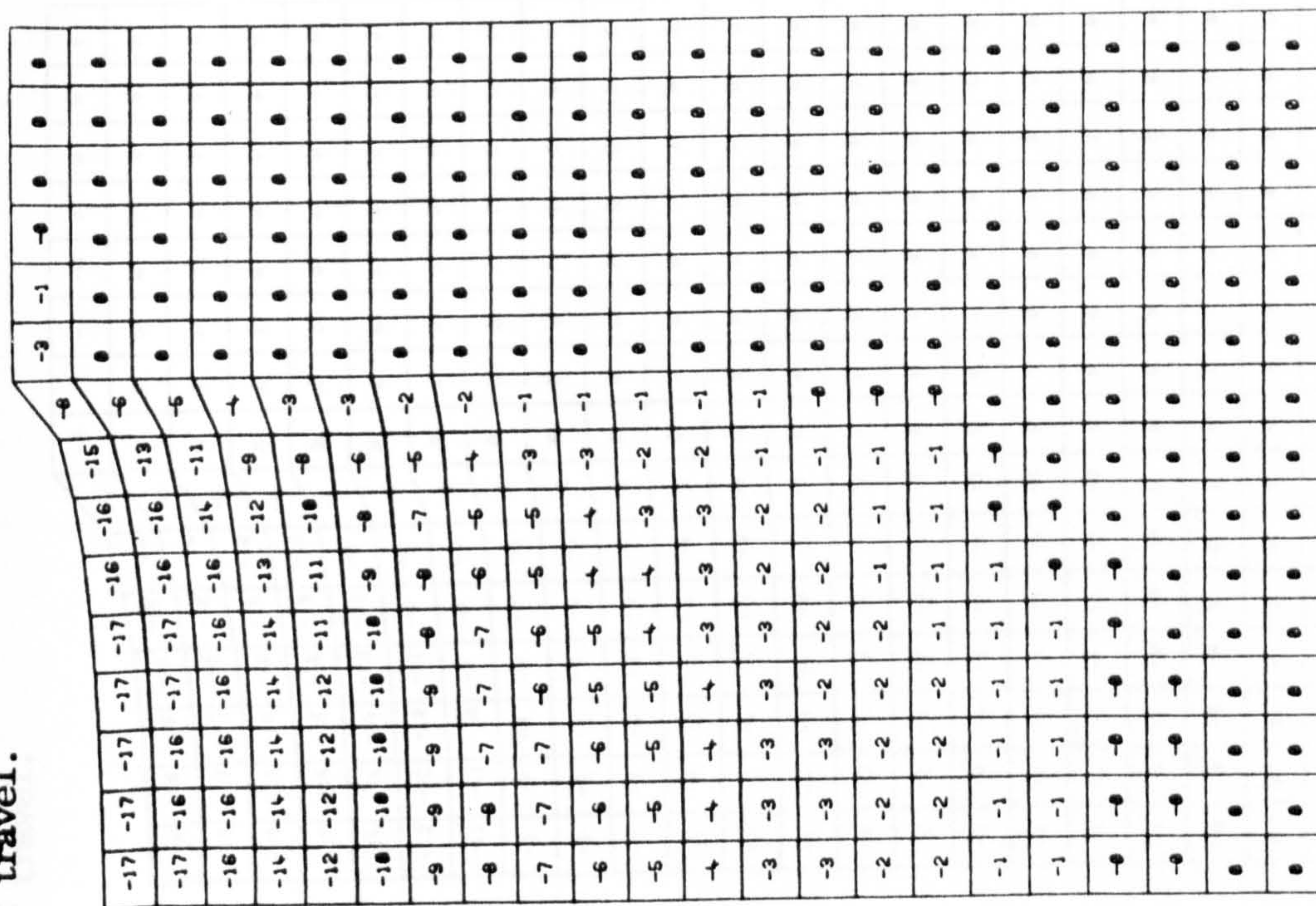
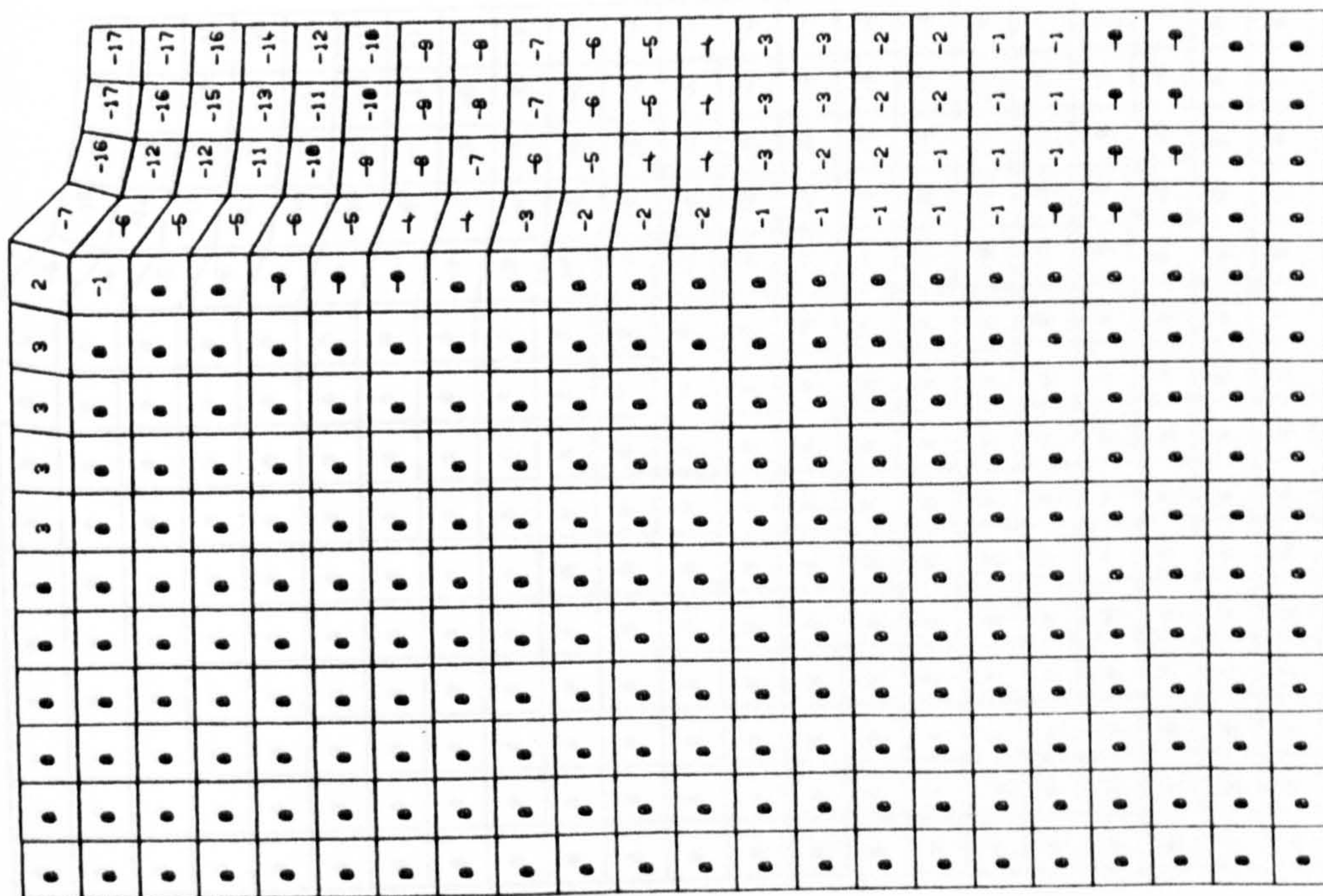


FIGURE 5.1:6.

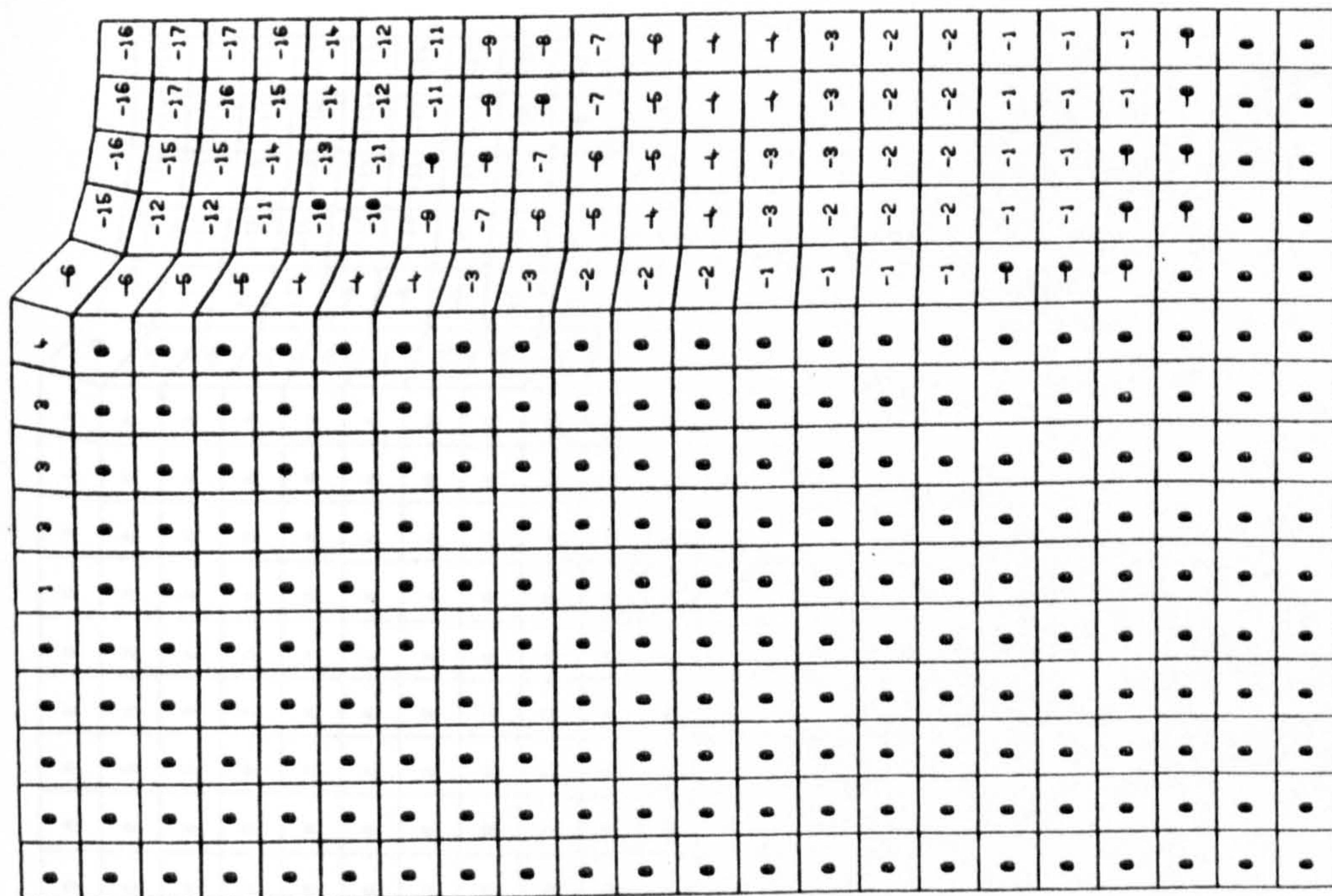
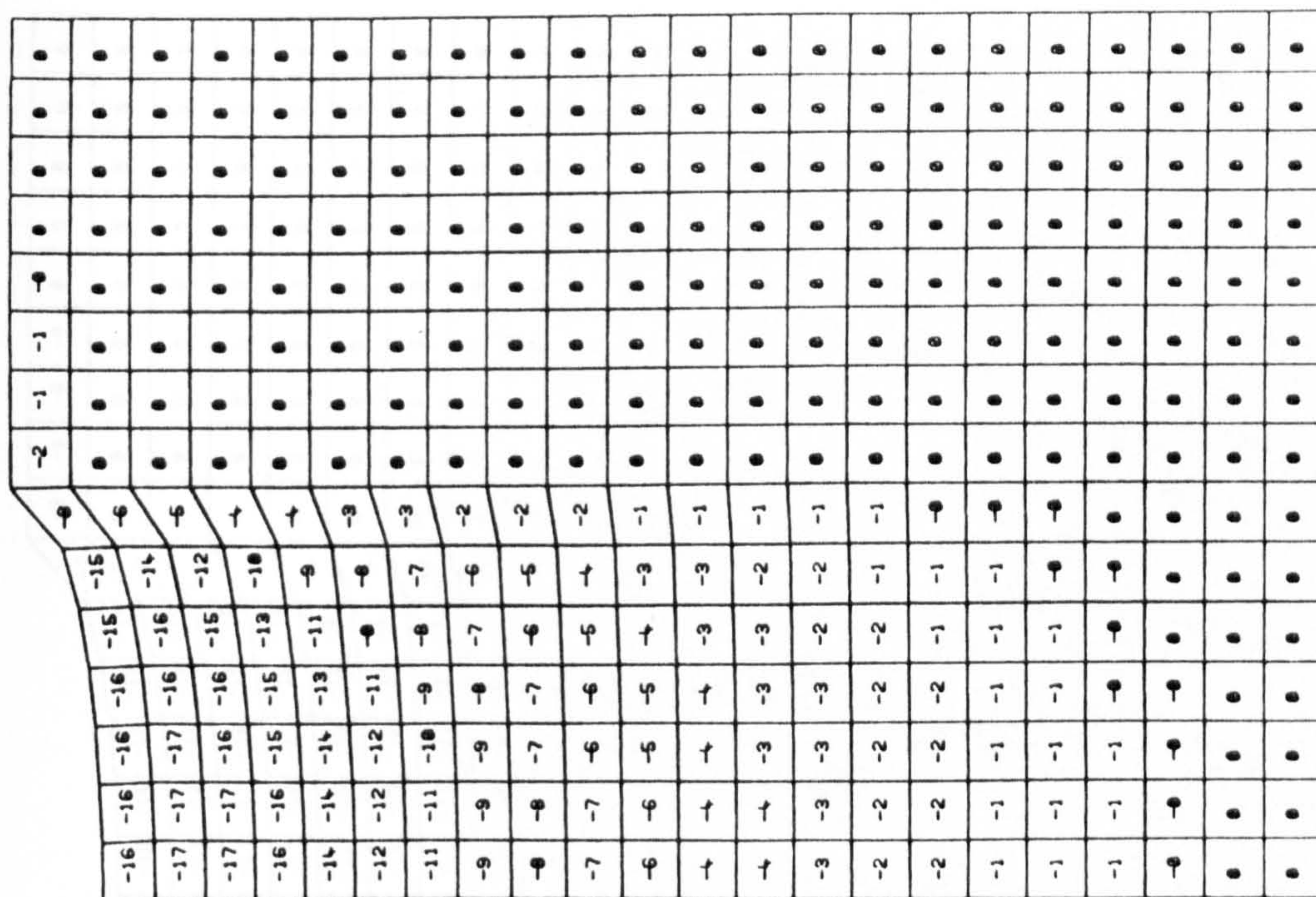


FIGURE 5.1:7.

Direction of travel. $\rightarrow$

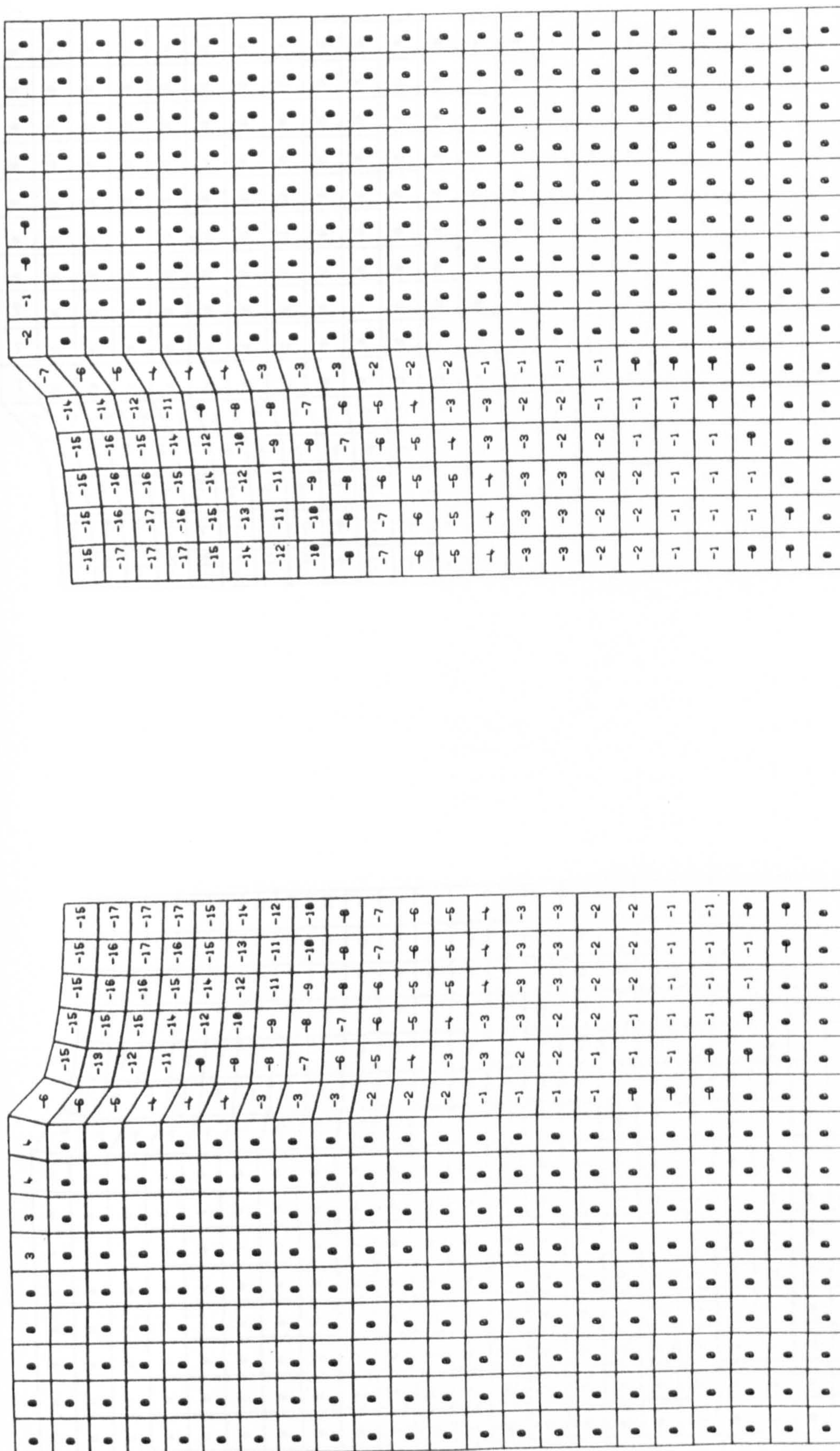
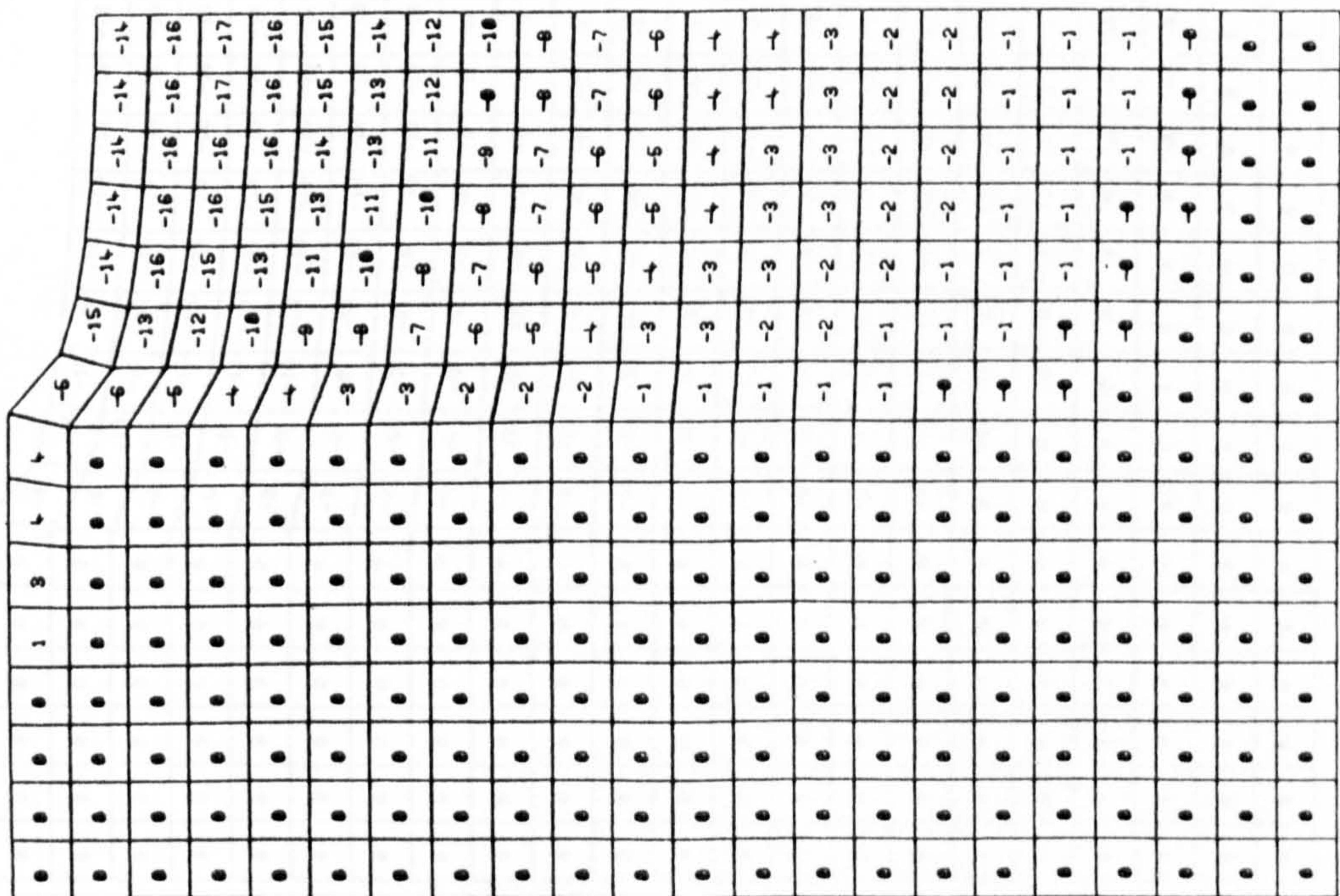
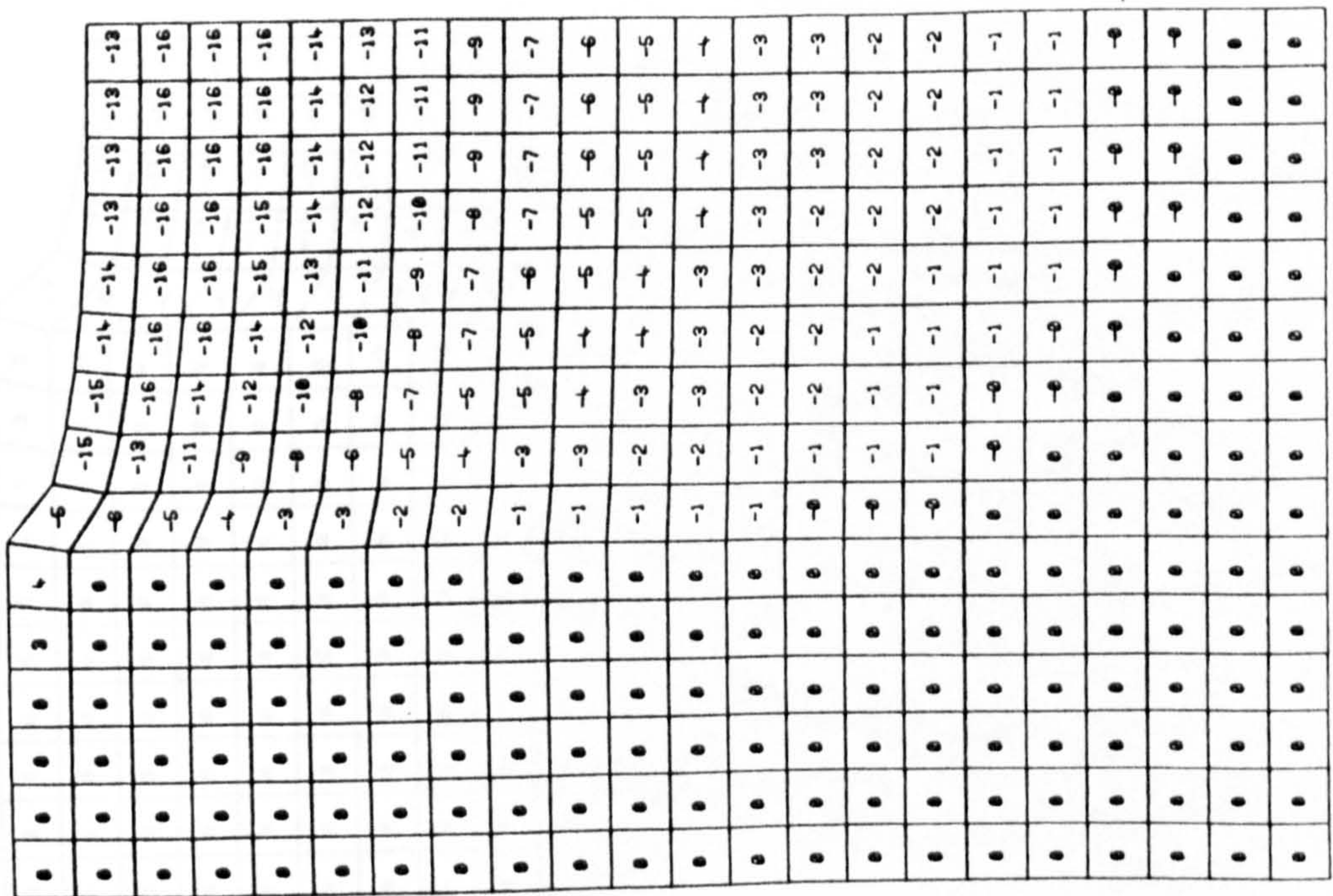


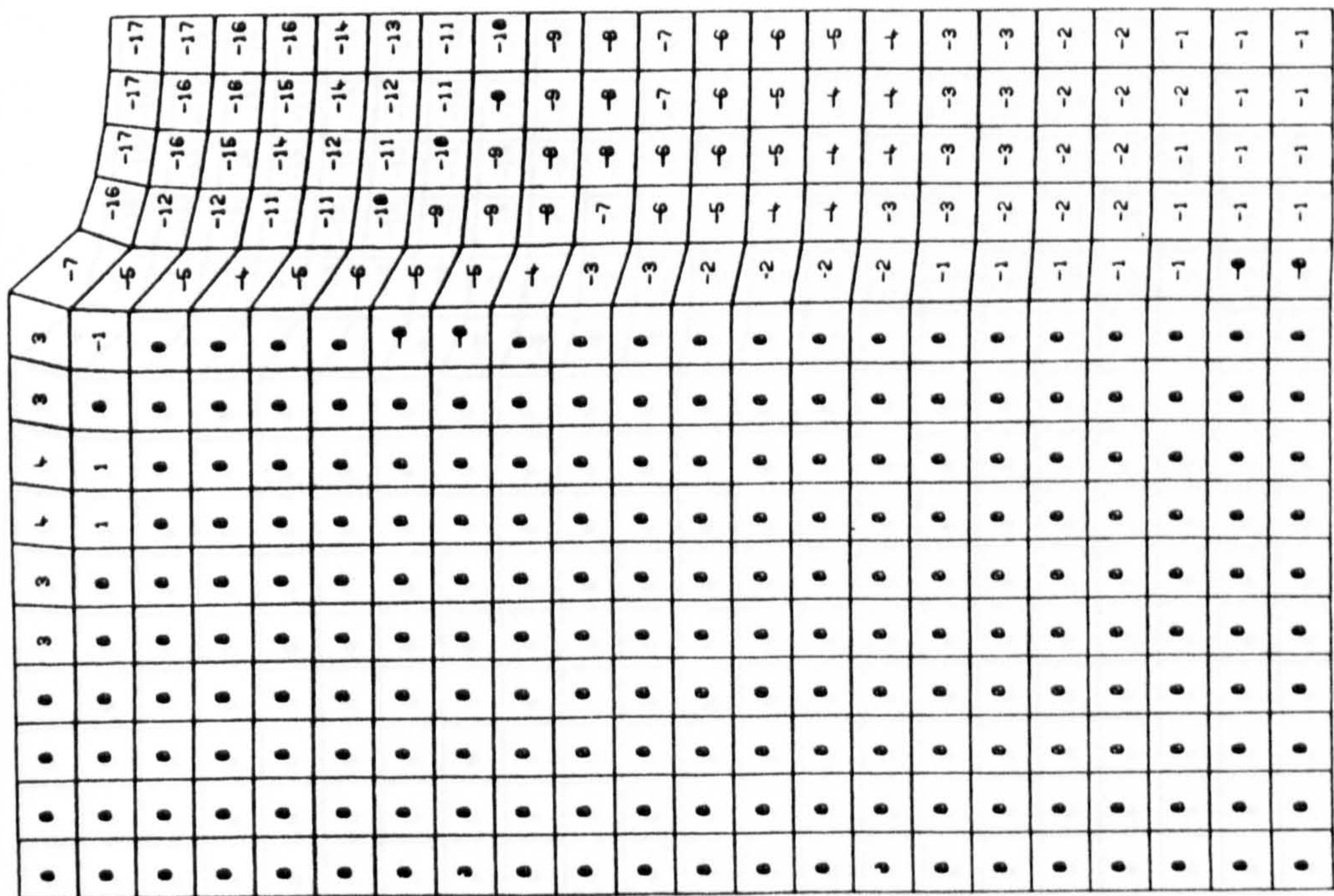
FIGURE 5.1:8.

[illegible]

- 186 -

[illegible]

- 187 -



Direction of travel.

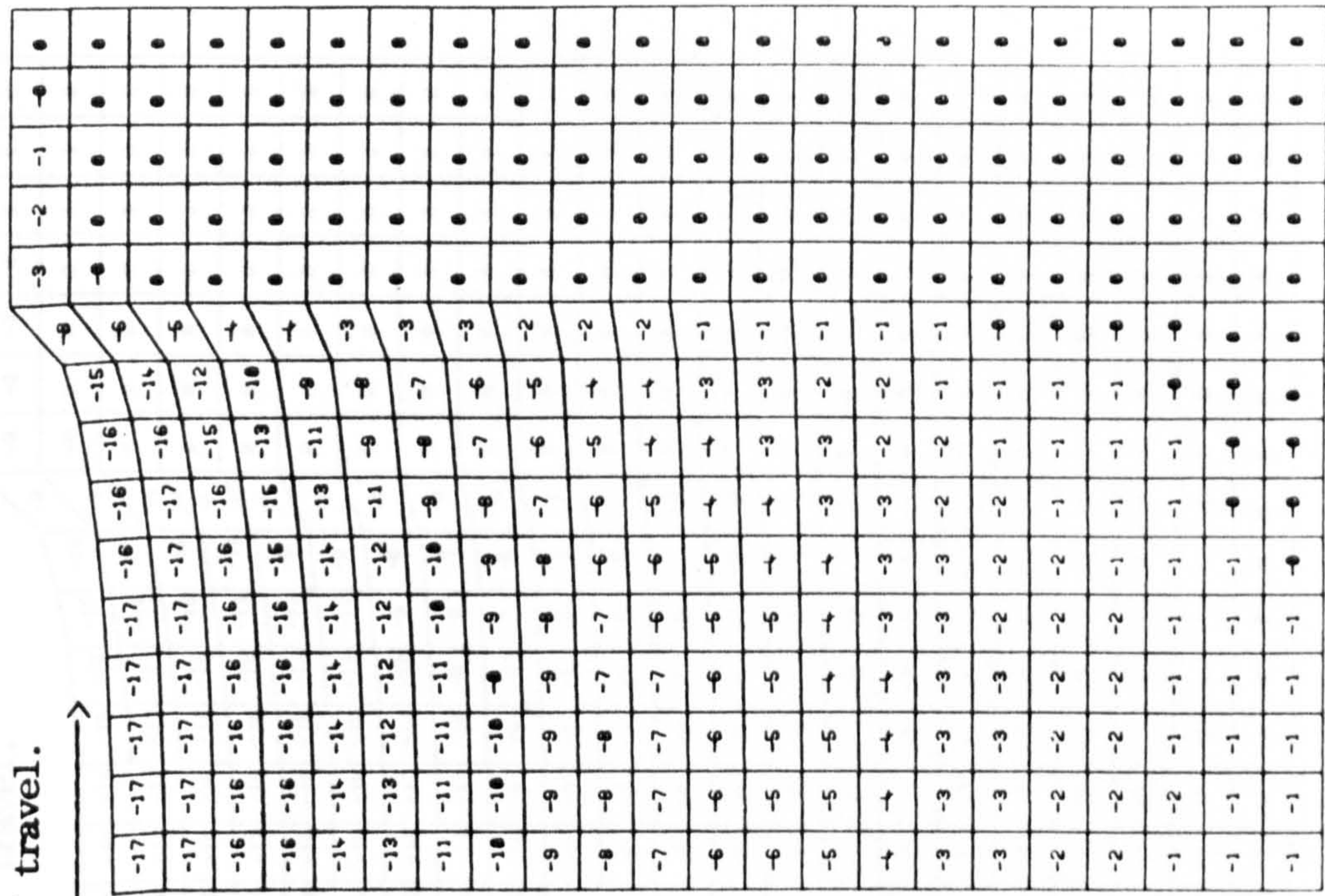


FIGURE 5.1:11.

Direction of travel.

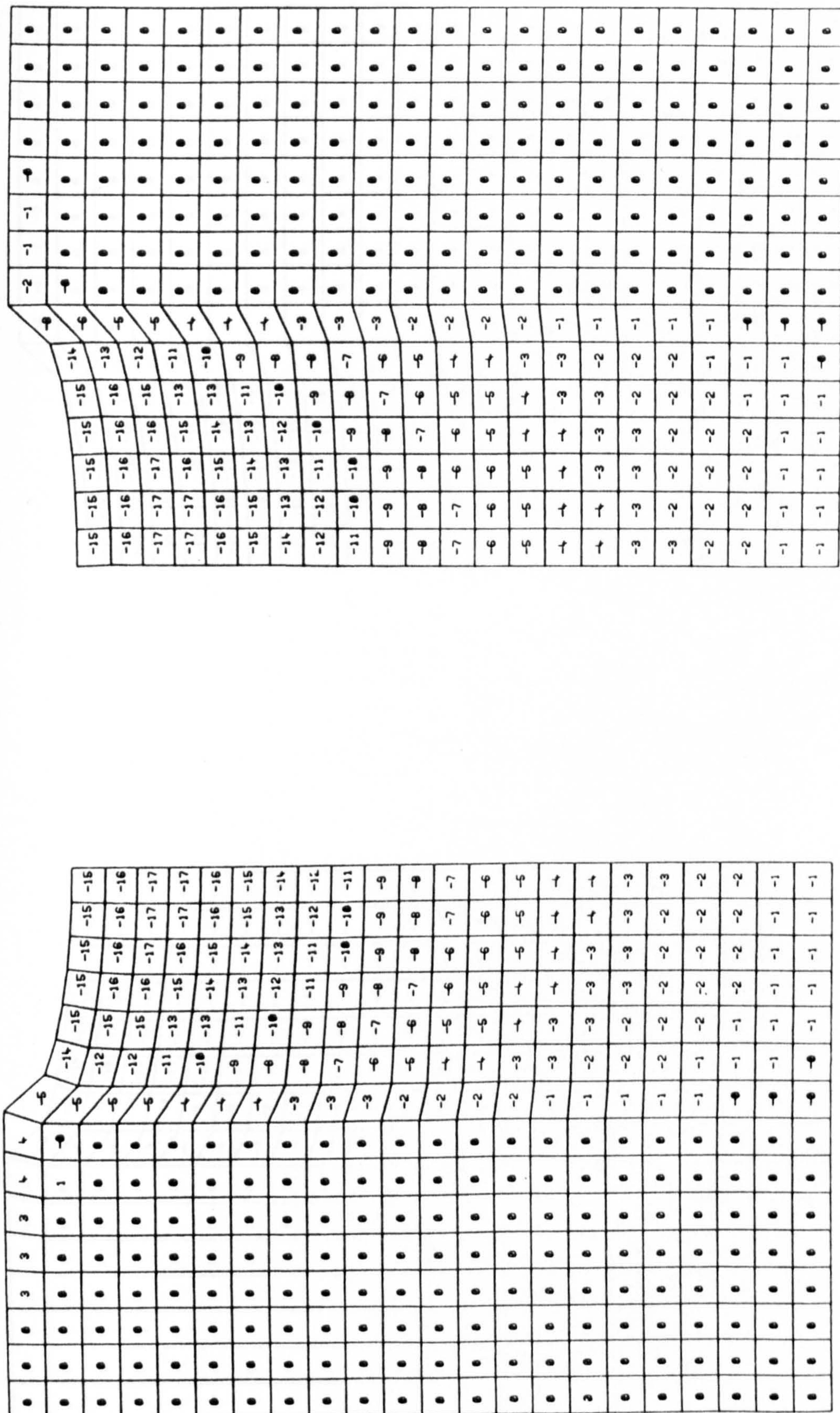


FIGURE 5.1:13.

→
Direction of travel.

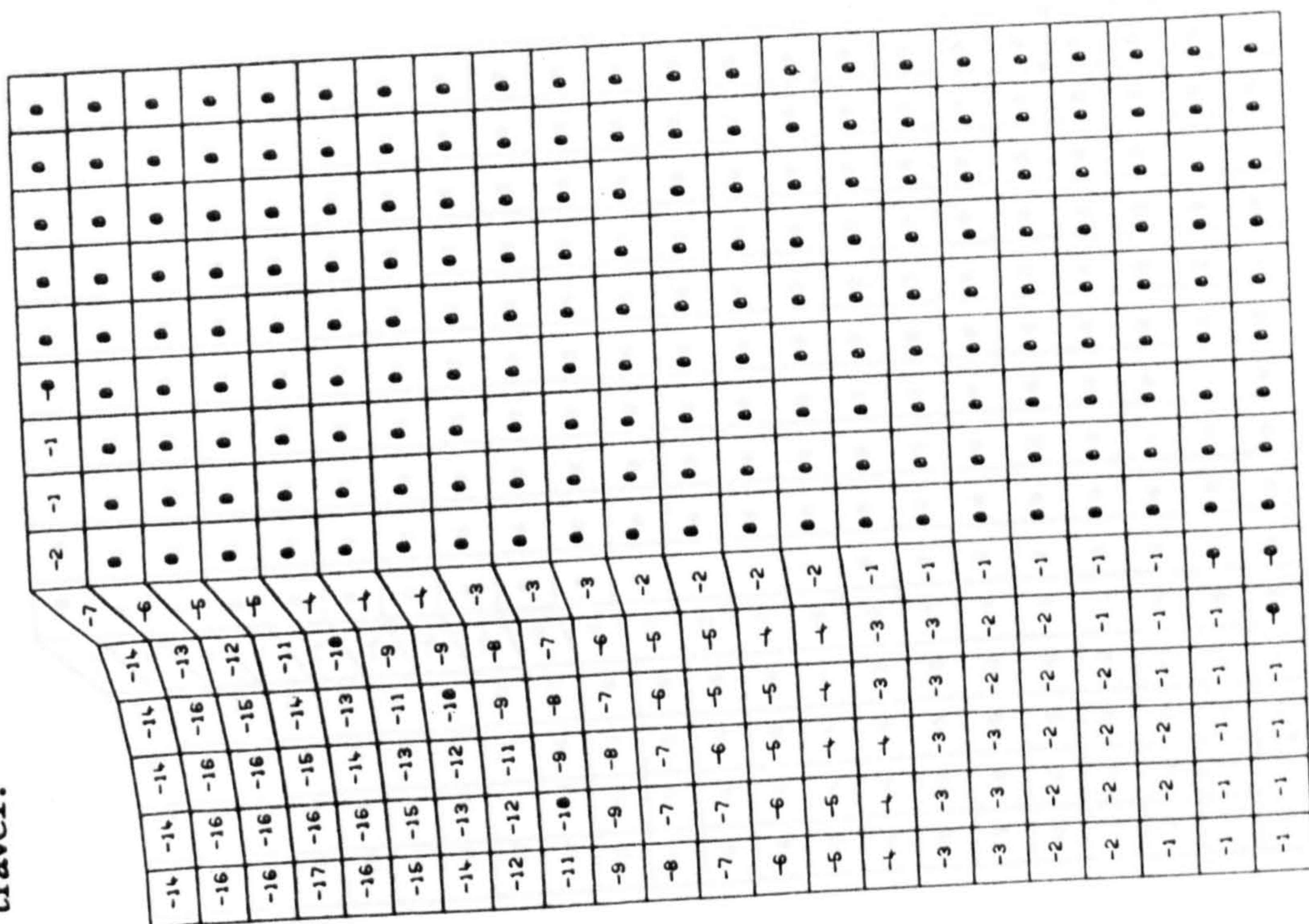
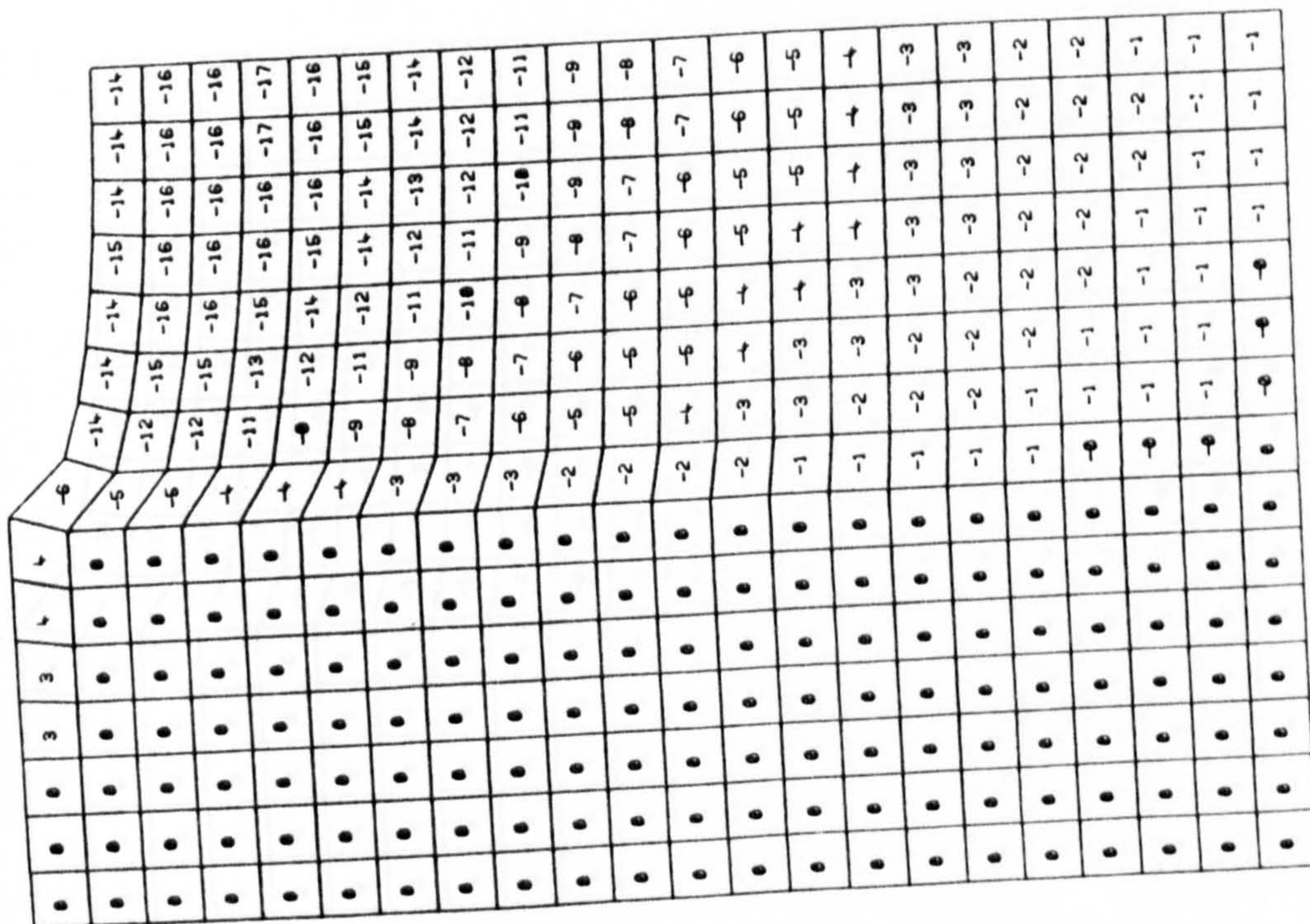


FIGURE 5.1:14.

Direction of travel. 

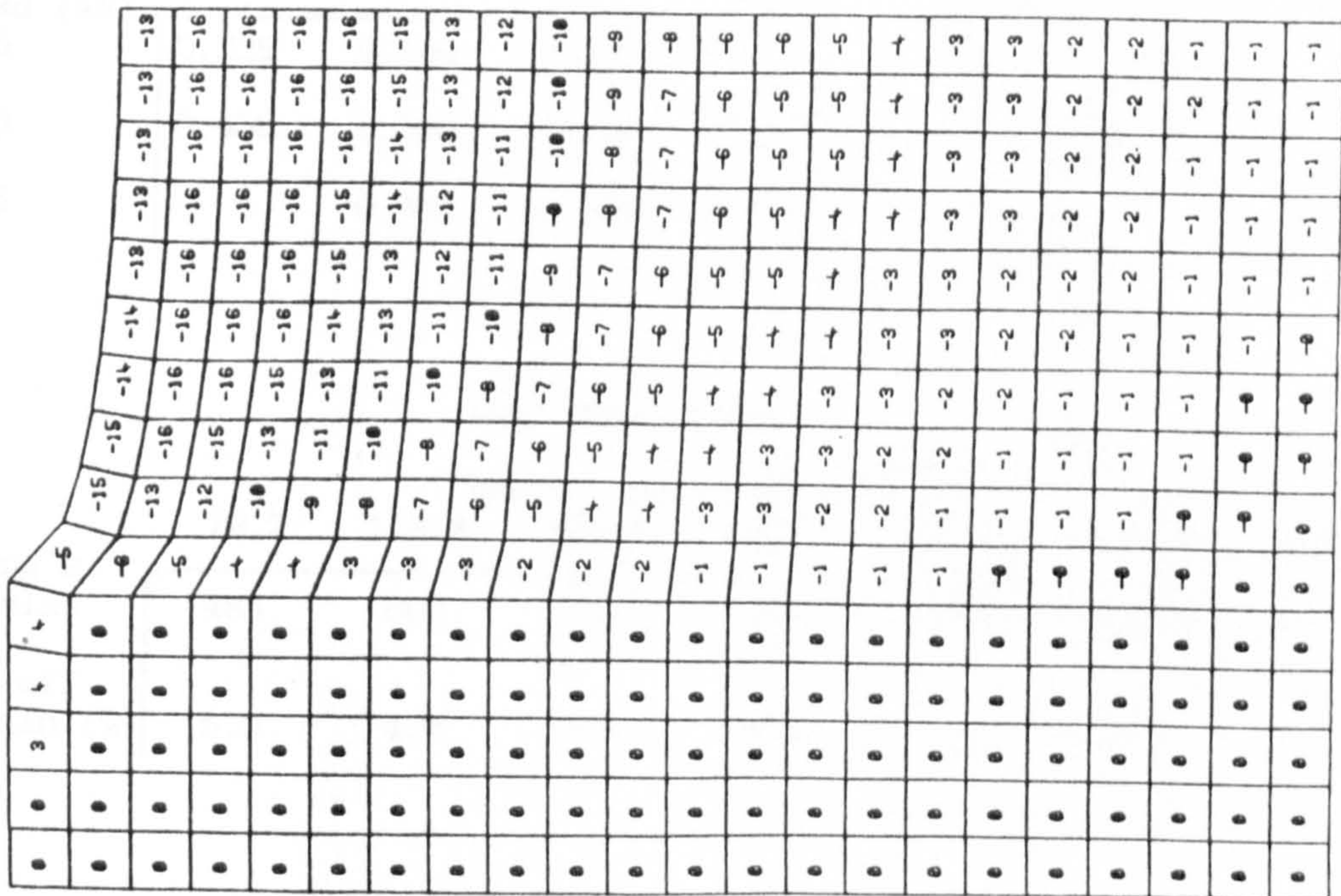
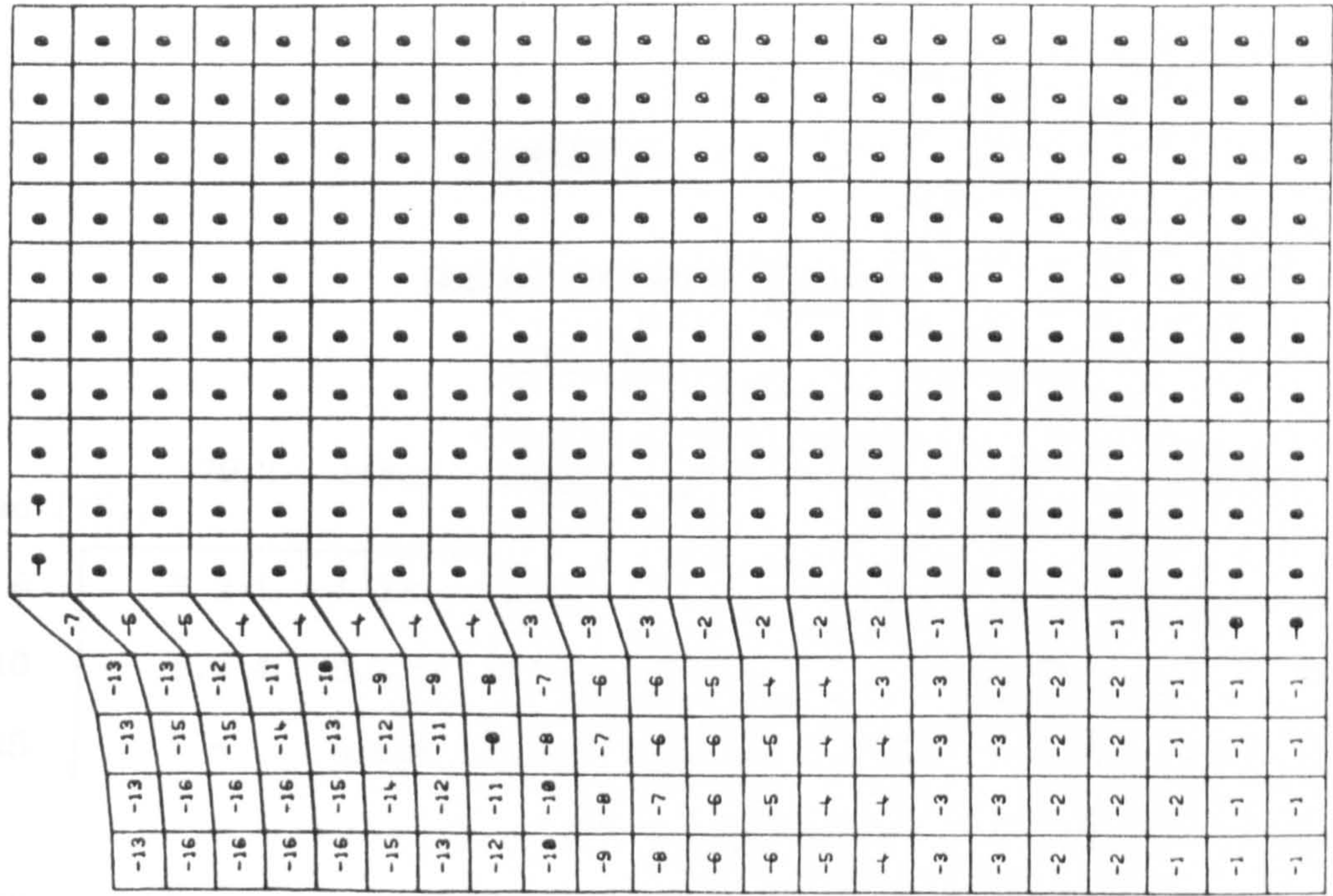


FIGURE 5.1:15.

APPENDIX 5.2

Contact Pressure Results.

Figure number

Load (kN).	Contact pressure kN/m ²						
	79.2	118.8	158.4	198.0	237.6	277.2	316.8
5	5.2:1	5.2:2	5.2:3	-	-	-	-
10	5.2:4	5.2:5	5.2:6	5.2:7	-	5.2:8	-
15	-	5.2:9	5.2:10	5.2:11	5.2:12	-	5.2:13

Input variables:-

Moisture content	10%
Initial soil density	1.3 g/ml
Contact patch width	0.275 m
Poisson's Ratio	0.25

Contact length (m).

Load (kN)	Contact pressure kN/m ² .						
	79.2	118.8	158.4	198.0	237.6	277.2	316.8
5	0.229	0.154	0.115	-	-	-	-
10	0.459	0.308	0.230	0.183	-	0.131	-
15	-	0.462	0.345	0.275	0.230	-	0.172

Soil properties

	Contact pressure kN/m ² .						
	79.2	118.8	158.4	198.0	237.6	277.2	316.8
Young's Modulus	485	606	711	843	920	1039	1142
Cut off strain (%)	5.9	4.5	3.8	3.5	3.2	2.9	2.5

Direction of travel. $\rightarrow$

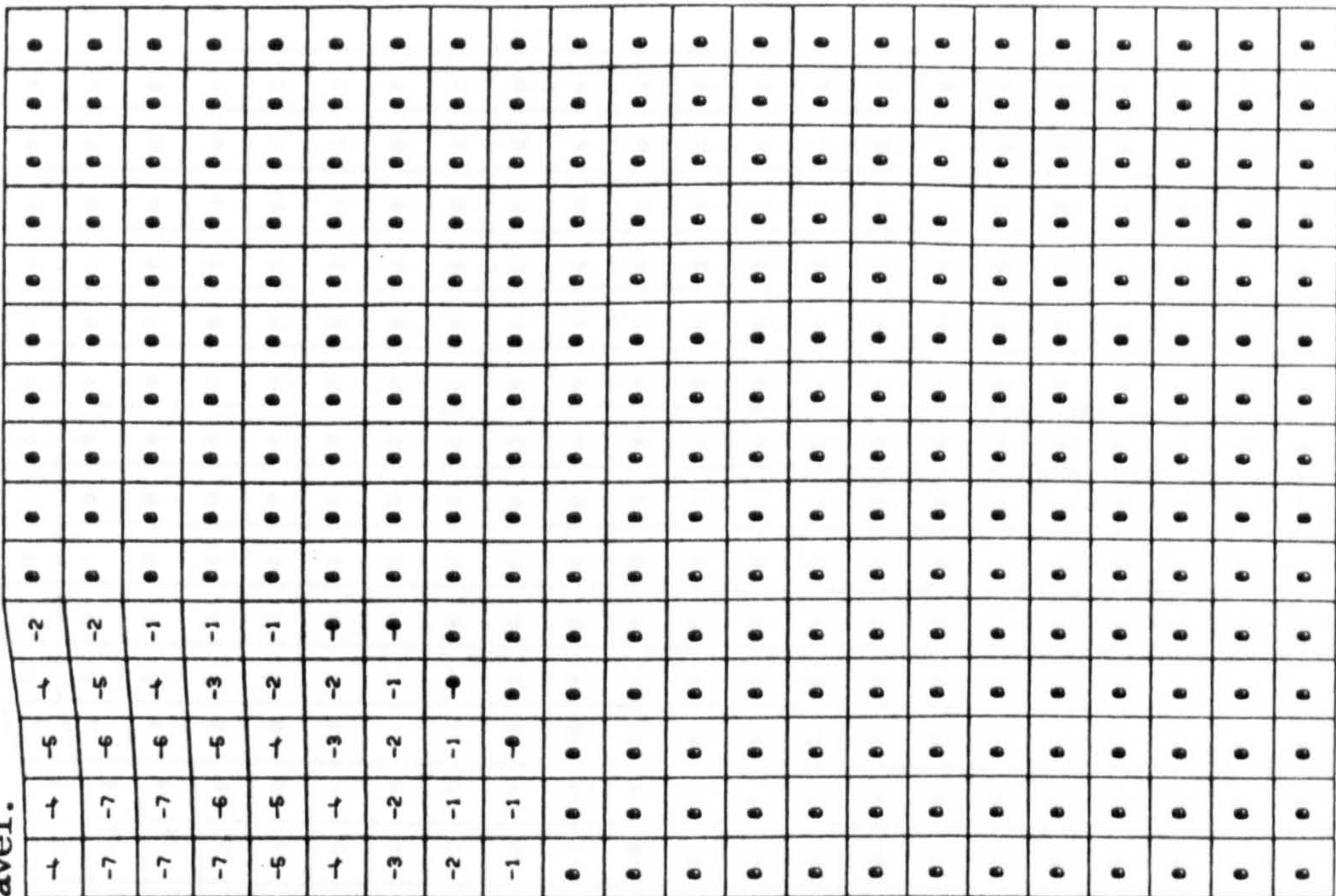
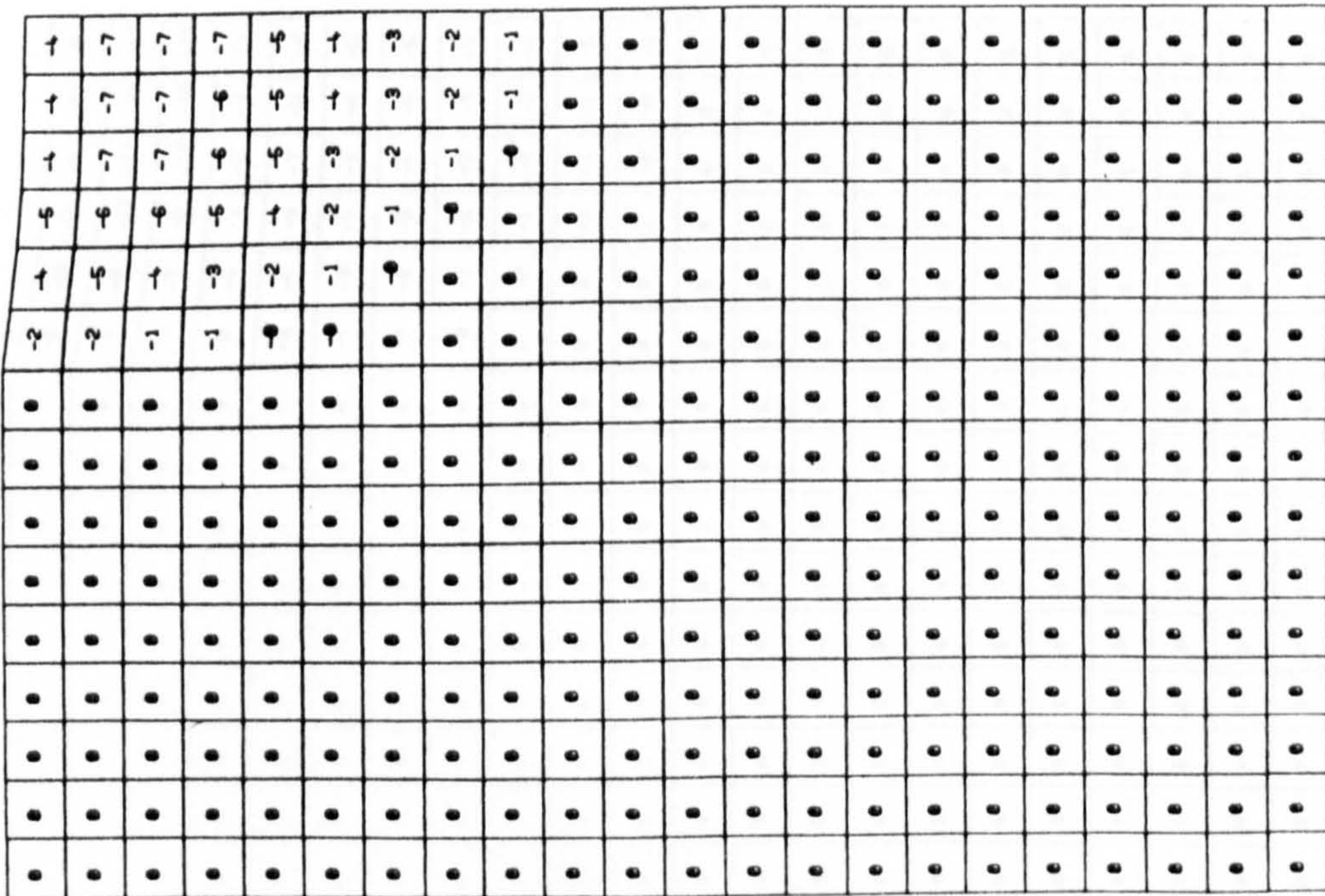


FIGURE 5.2:1.

Direction of travel. $\rightarrow$

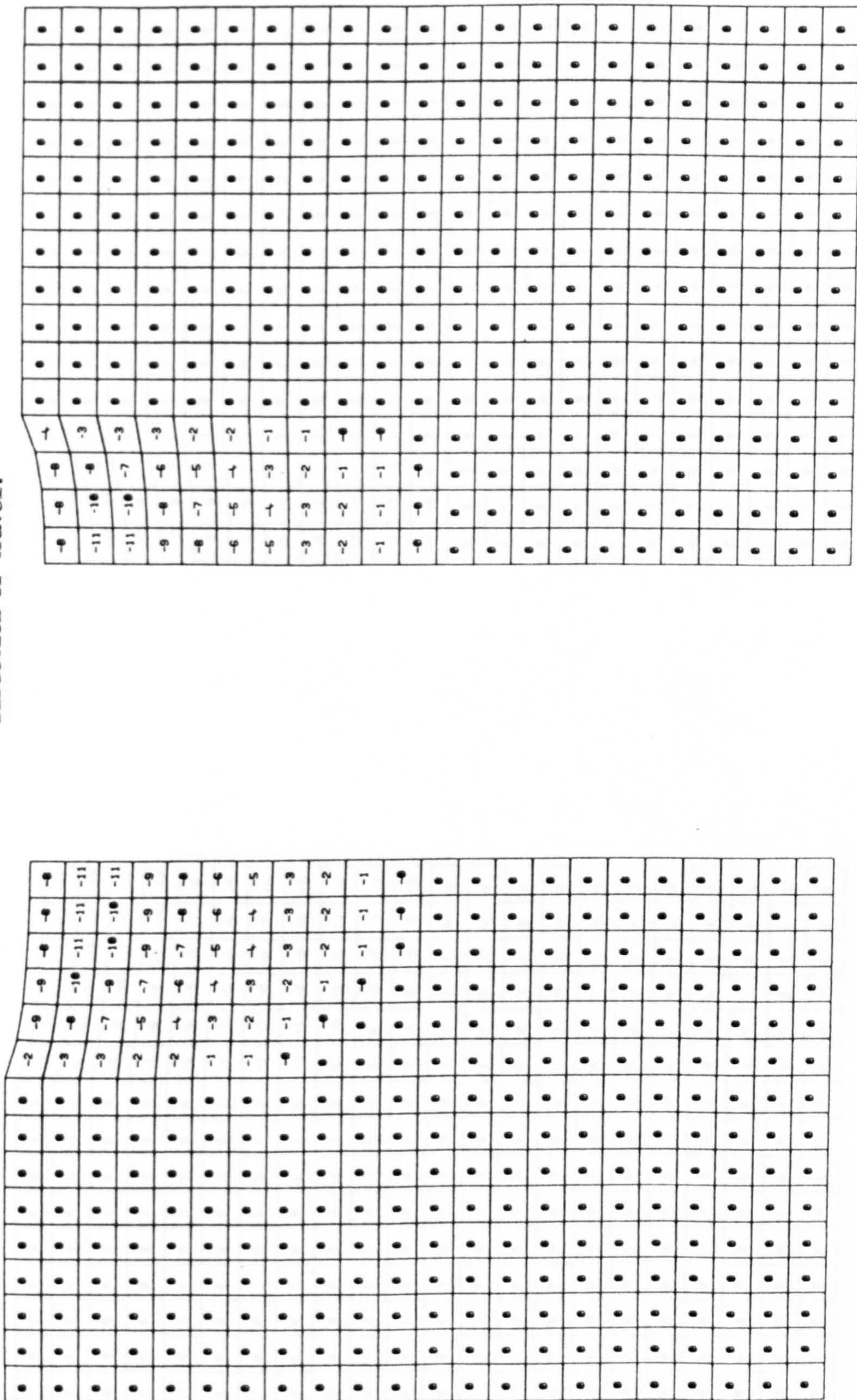


FIGURE 5.2:2.

↑
 Direction of travel.

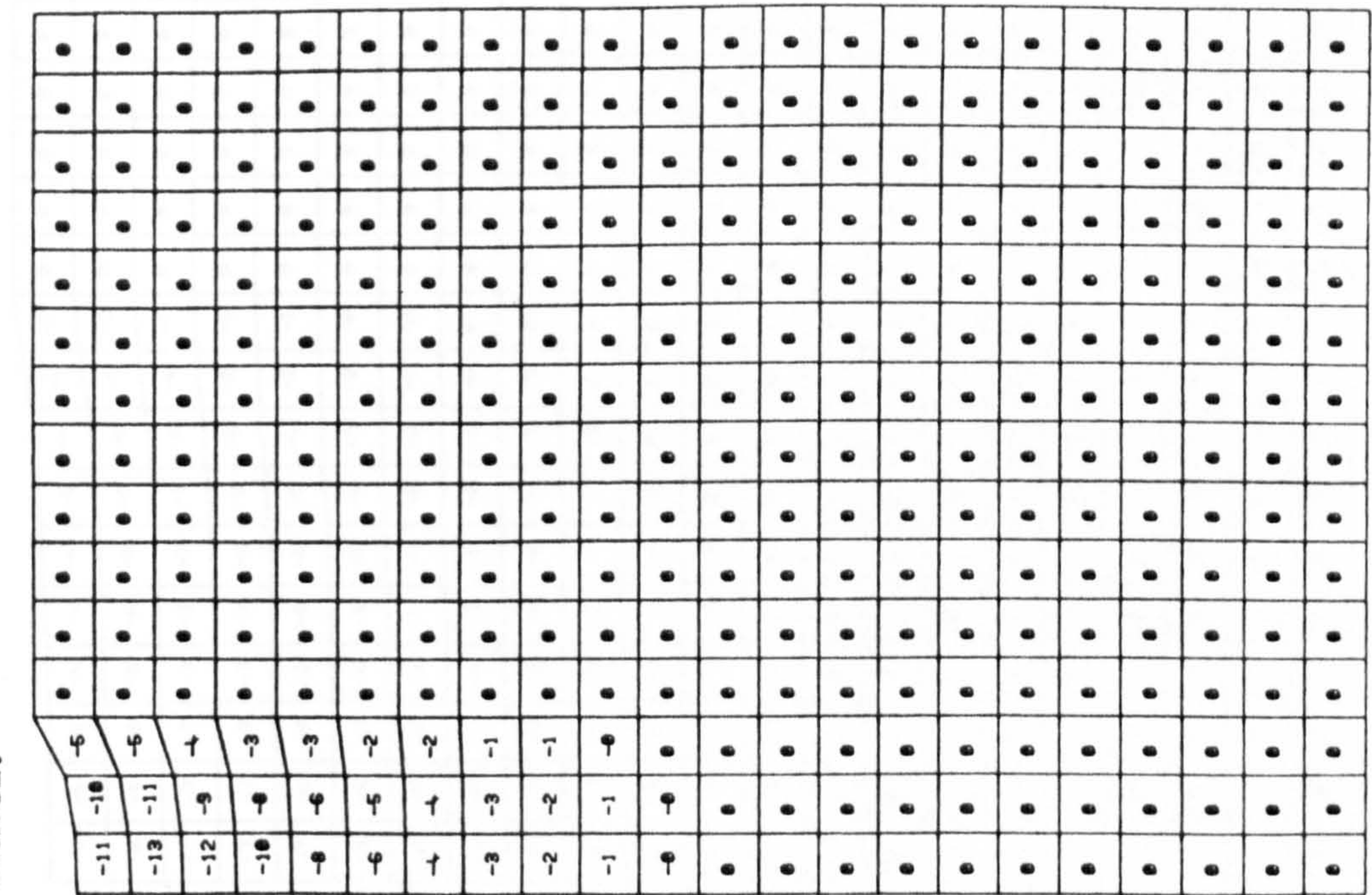
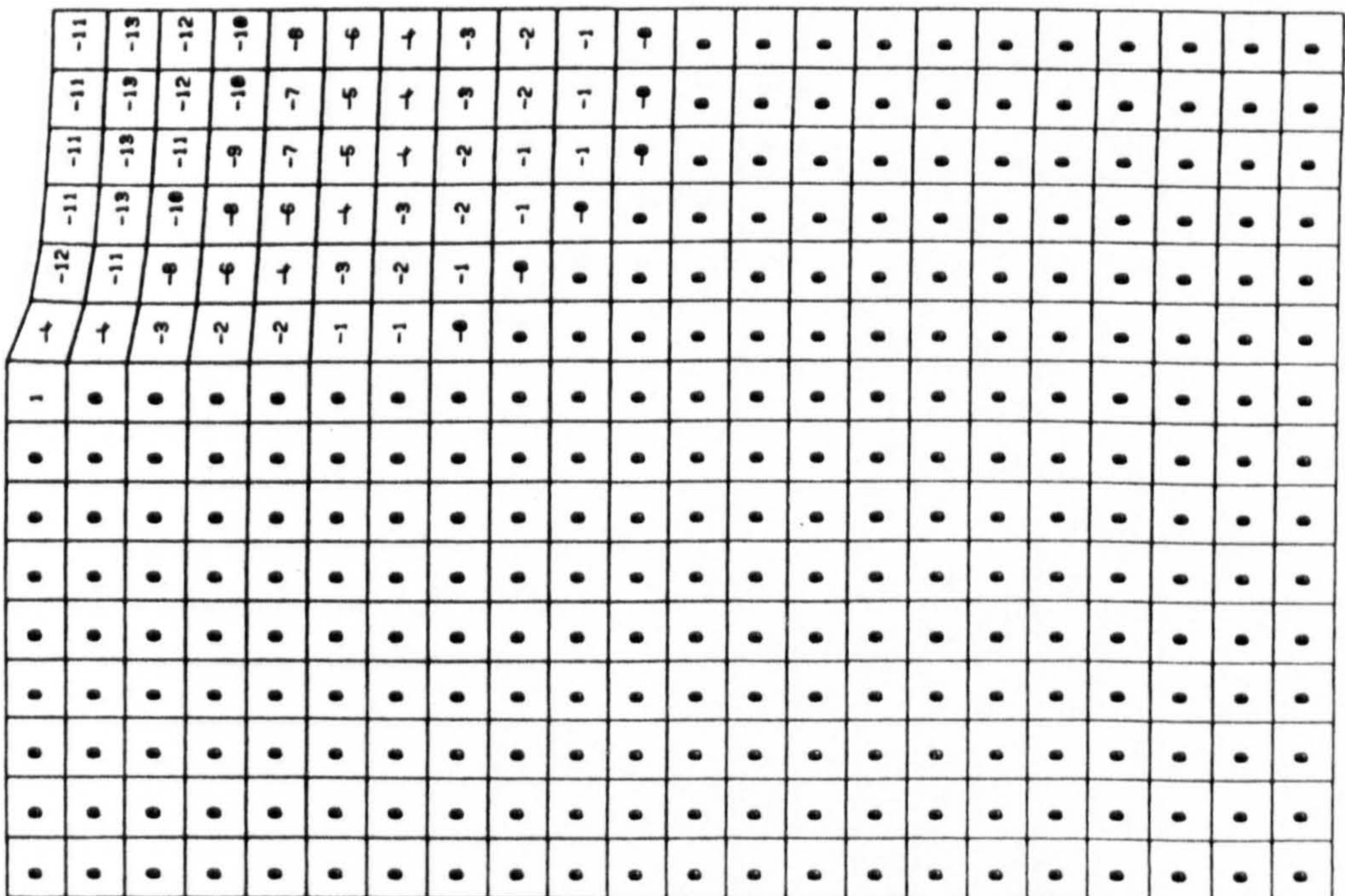


FIGURE 5.2:3.

Direction of travel. $\rightarrow$

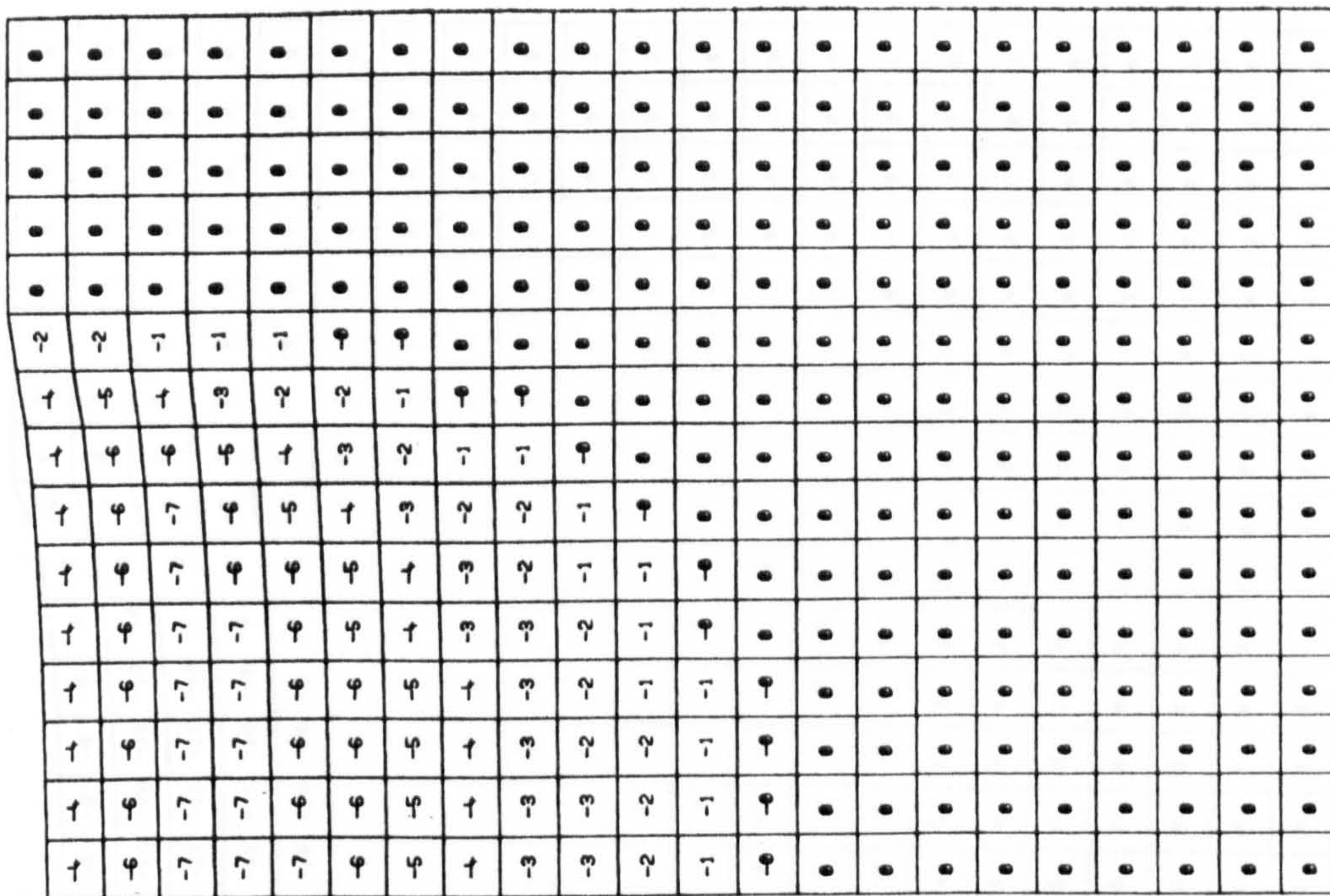
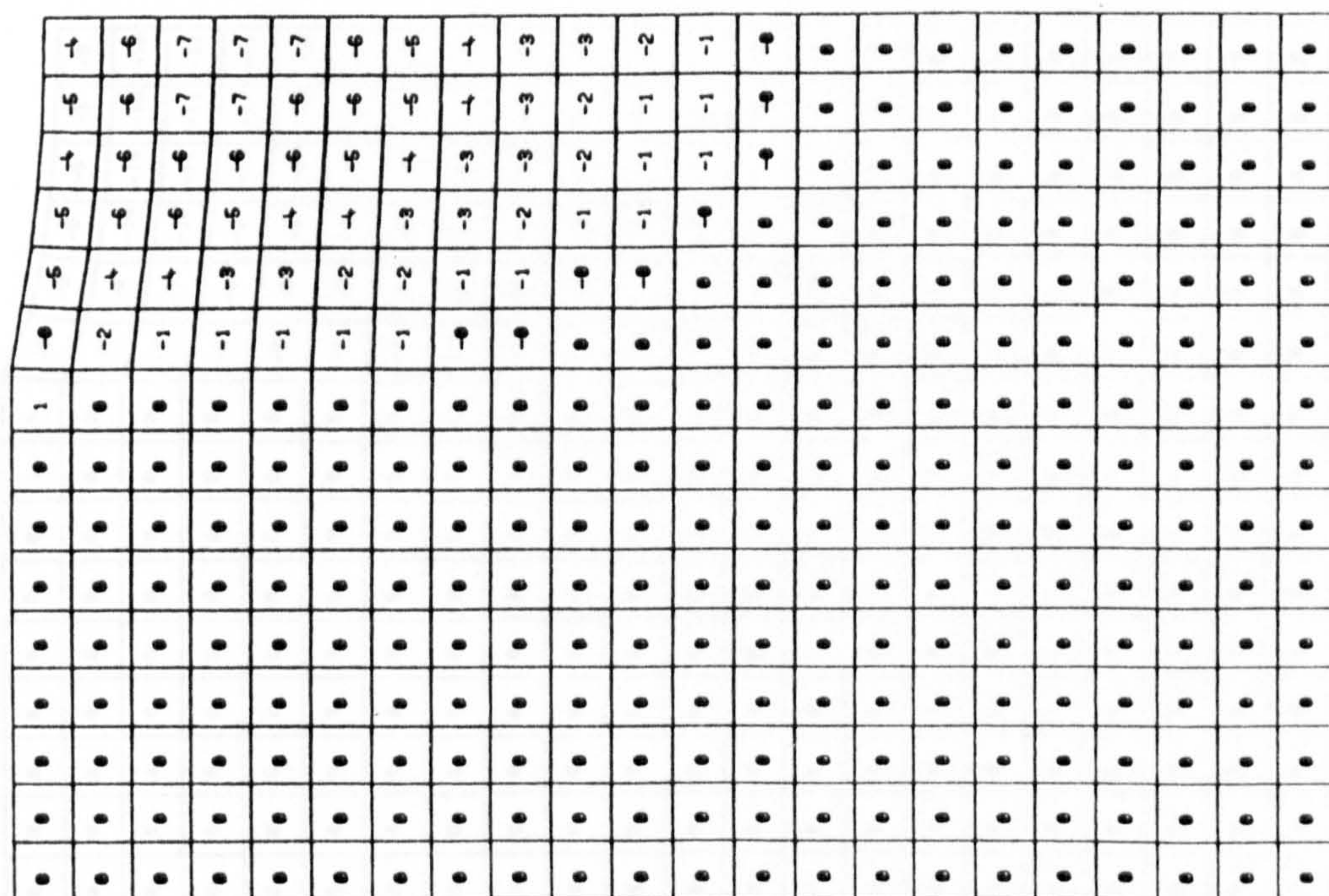


FIGURE 5.2:4.

Direction of travel. $\rightarrow$

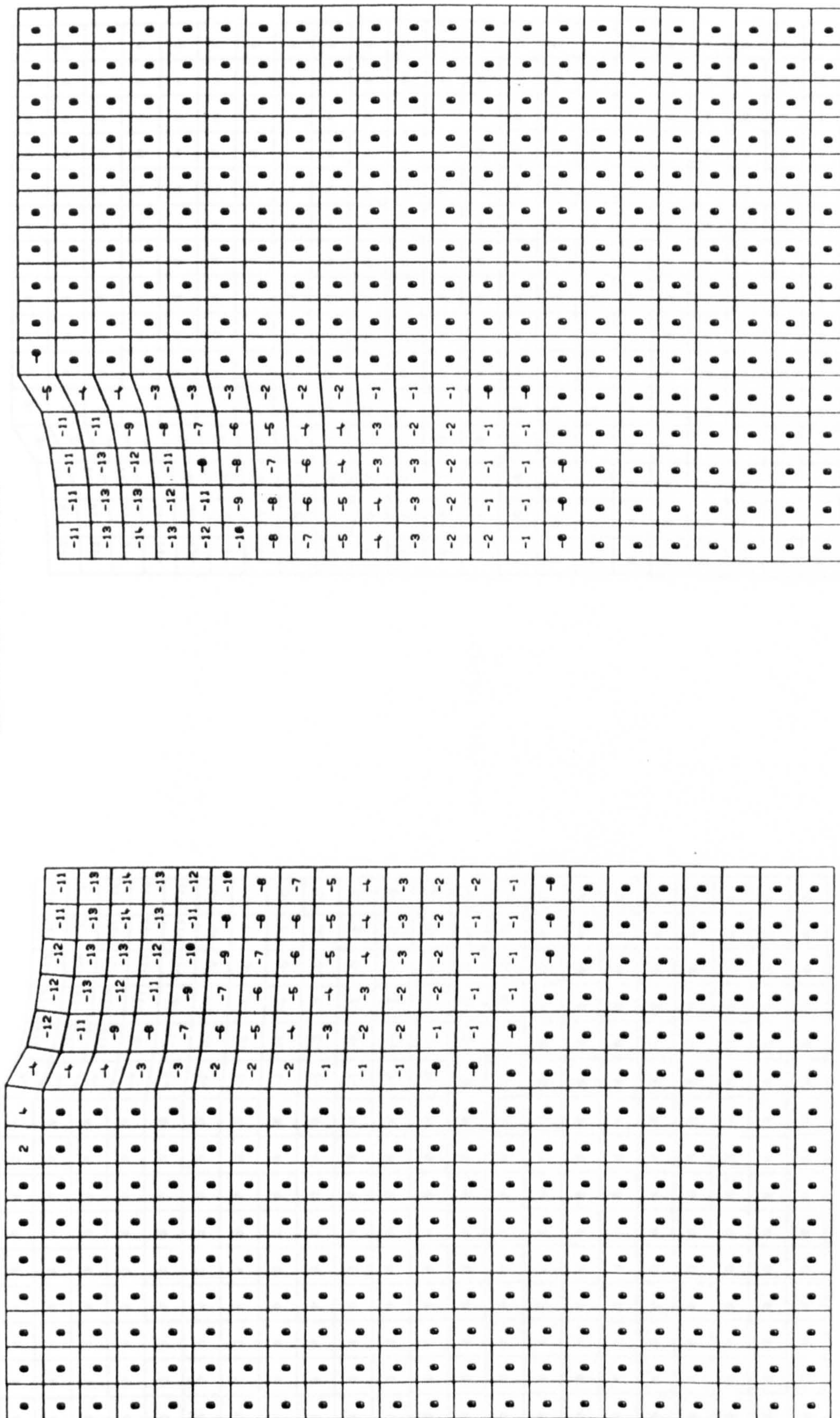


FIGURE 5.2:6.

Direction of travel. 

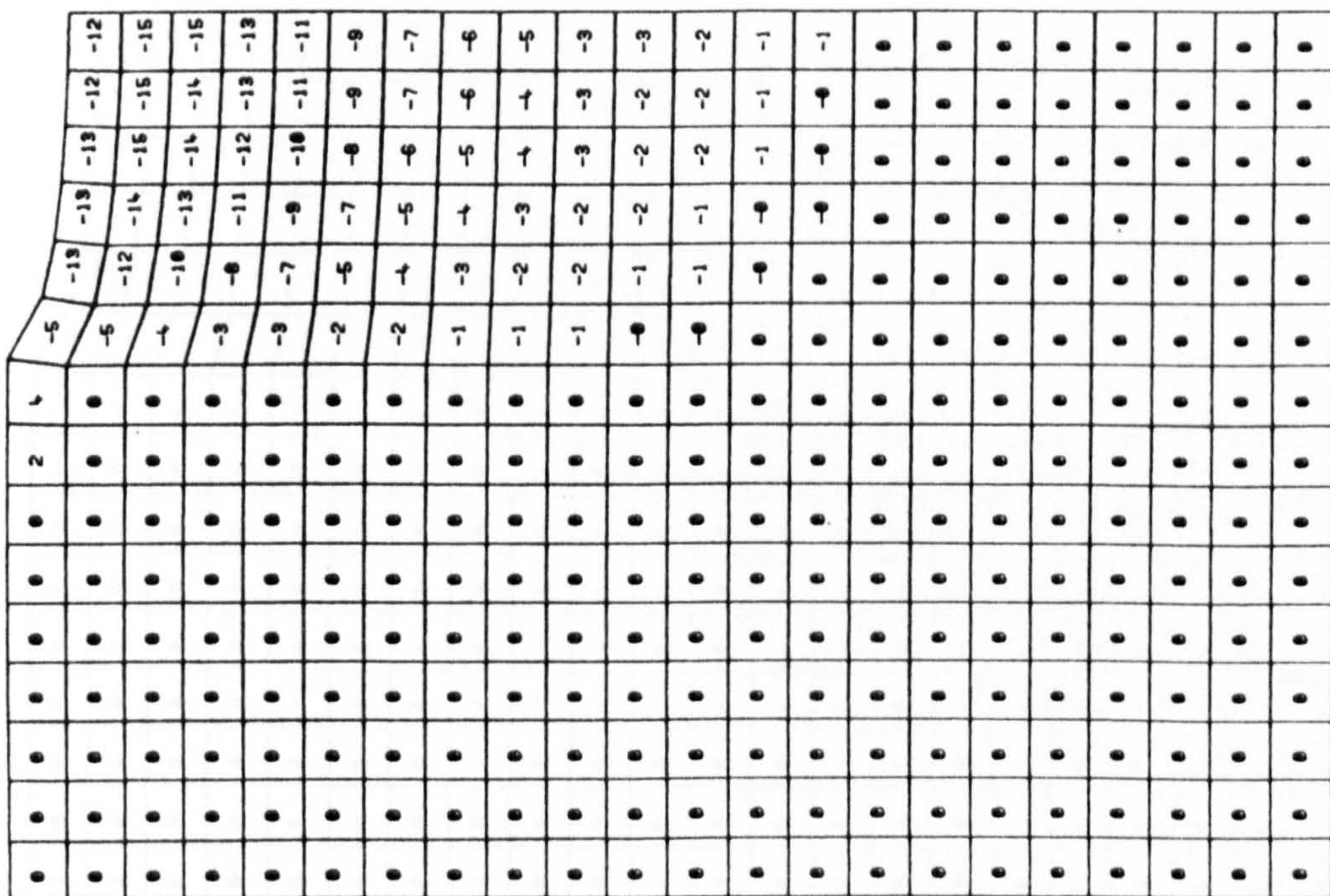
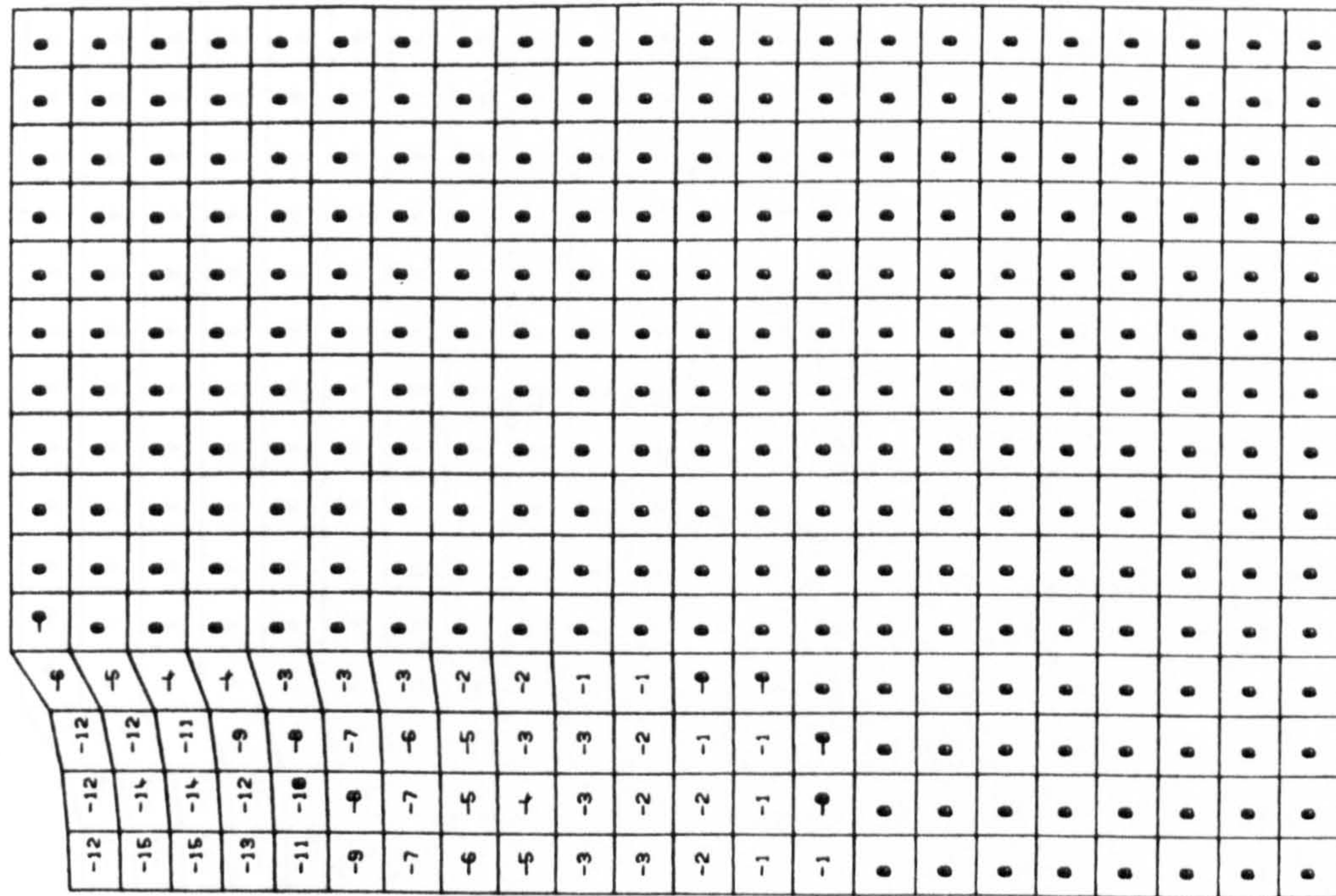


FIGURE 5.2:7.

Direction of travel. $\rightarrow$

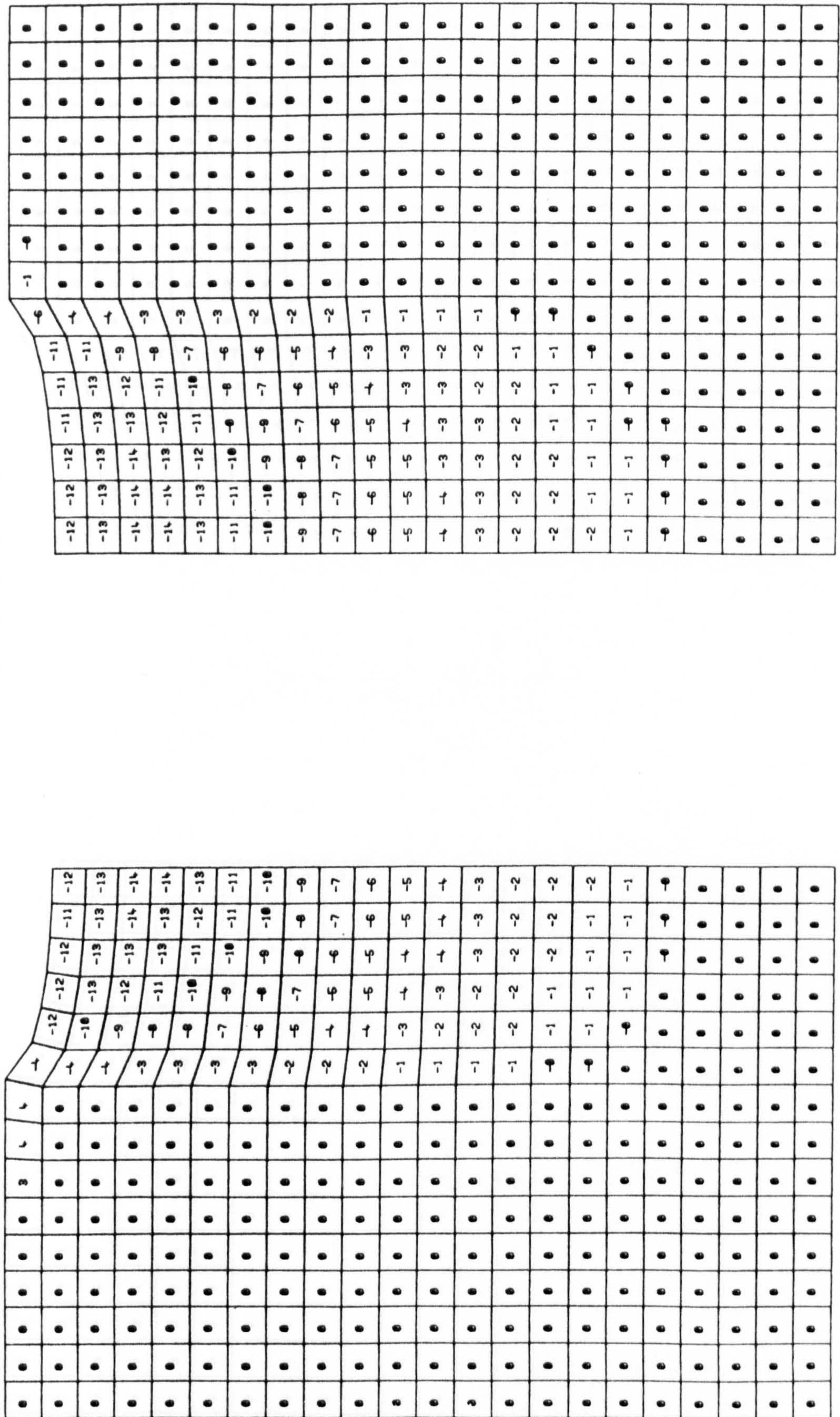


FIGURE 5.2:10.

Direction of travel. $\rightarrow$

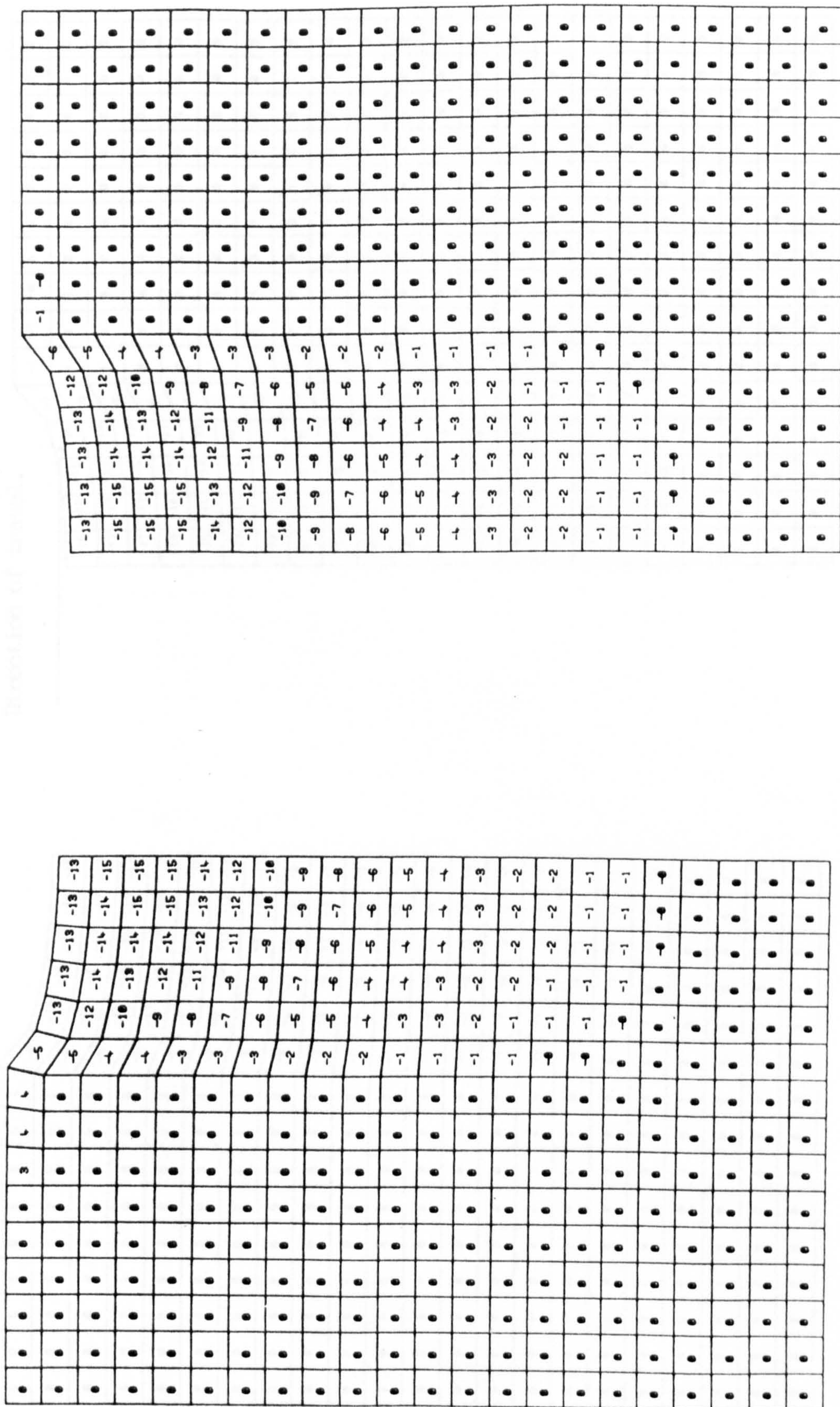


FIGURE 5.2:11.

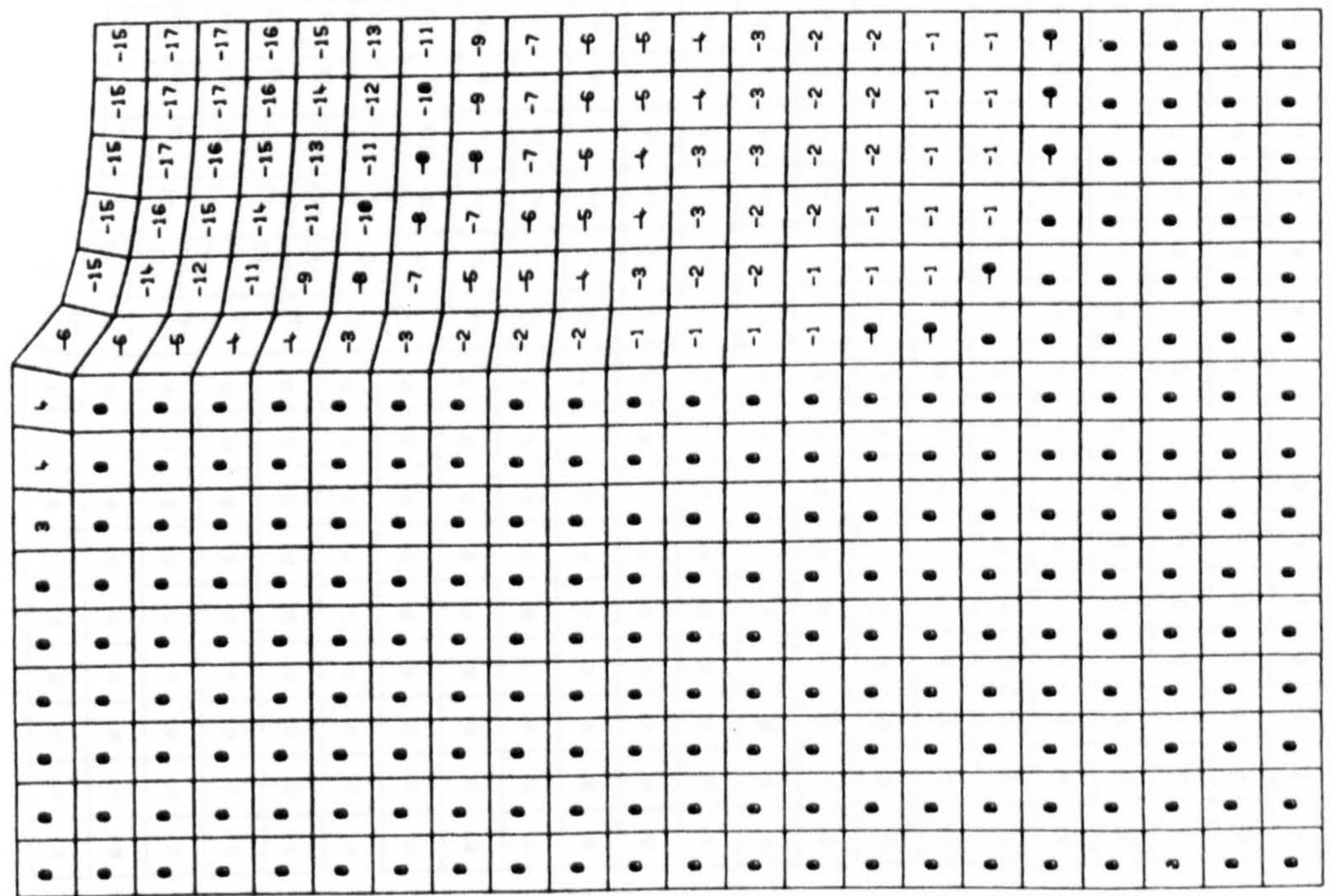
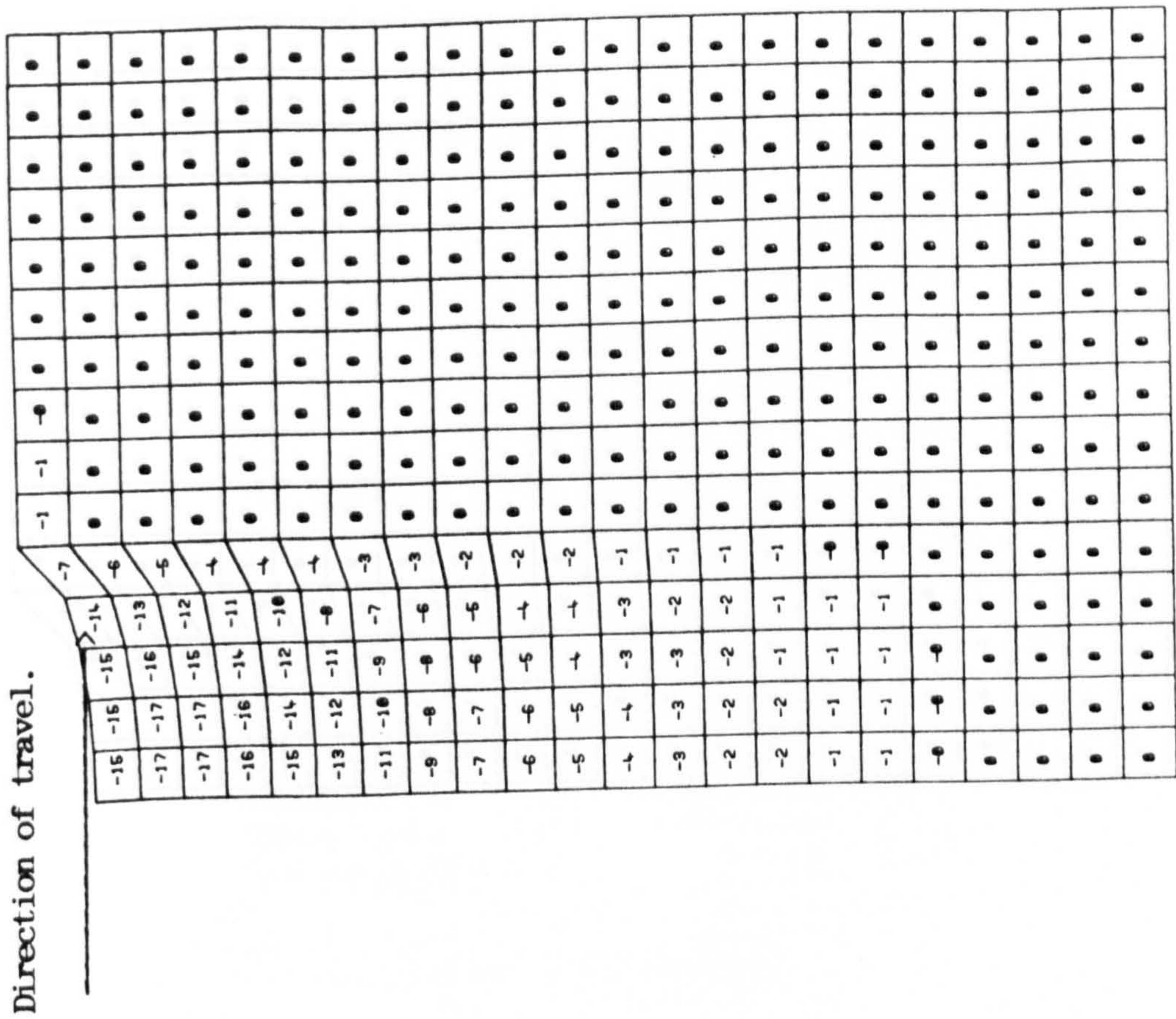
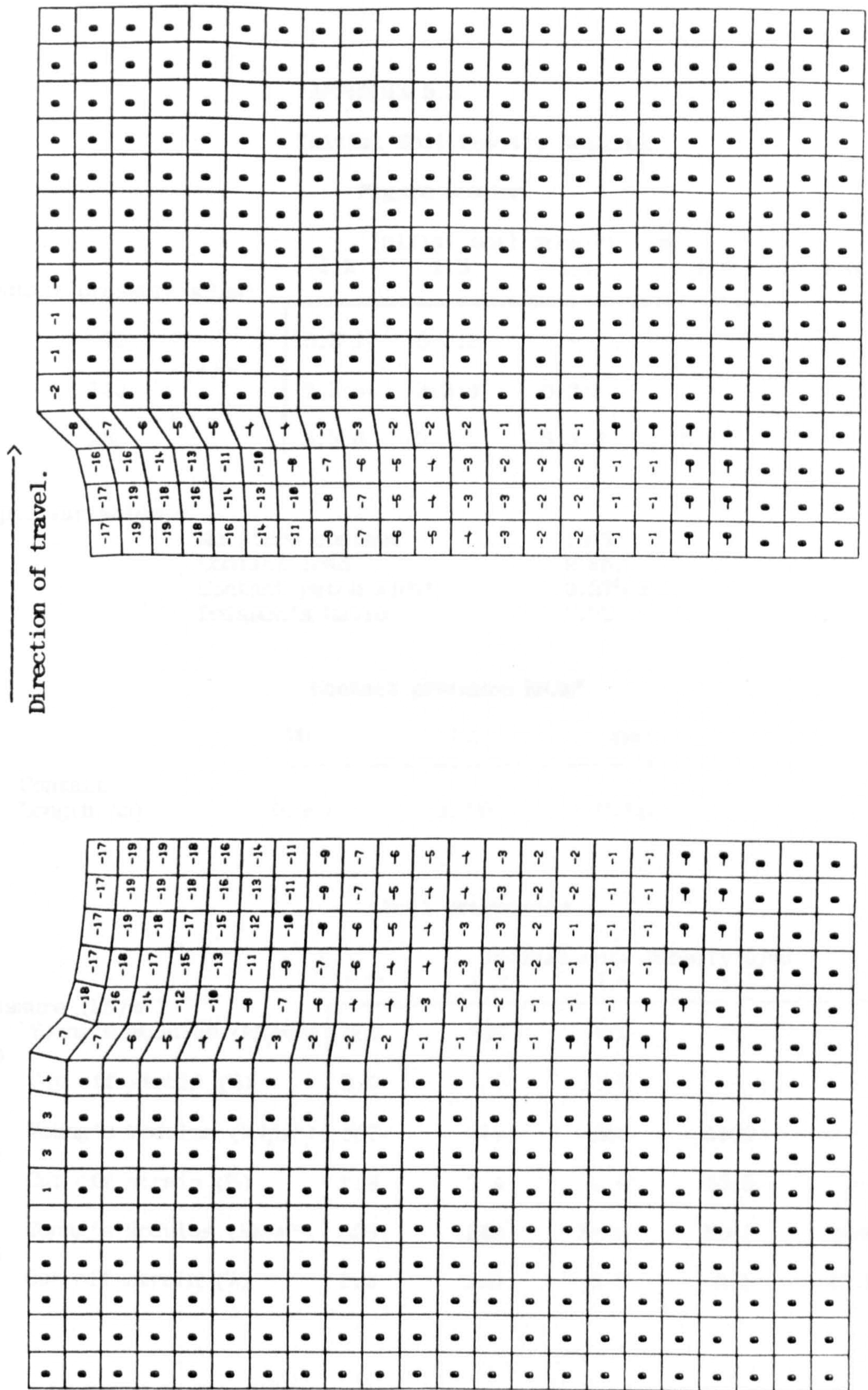


FIGURE 5.2:12.



APPENDIX 5.3

Initial Soil Density Results.

Figure number

Contact pressure kN/m ²	Initial soil density g/ml.				
	1.2	1.3	1.4	1.5	1.6
70	5.3:1	5.3:2	-	-	-
140	5.3:3	5.3:4	5.3:5	-	-
280	5.3:6	5.3:7	5.3:8	5.3:9	-

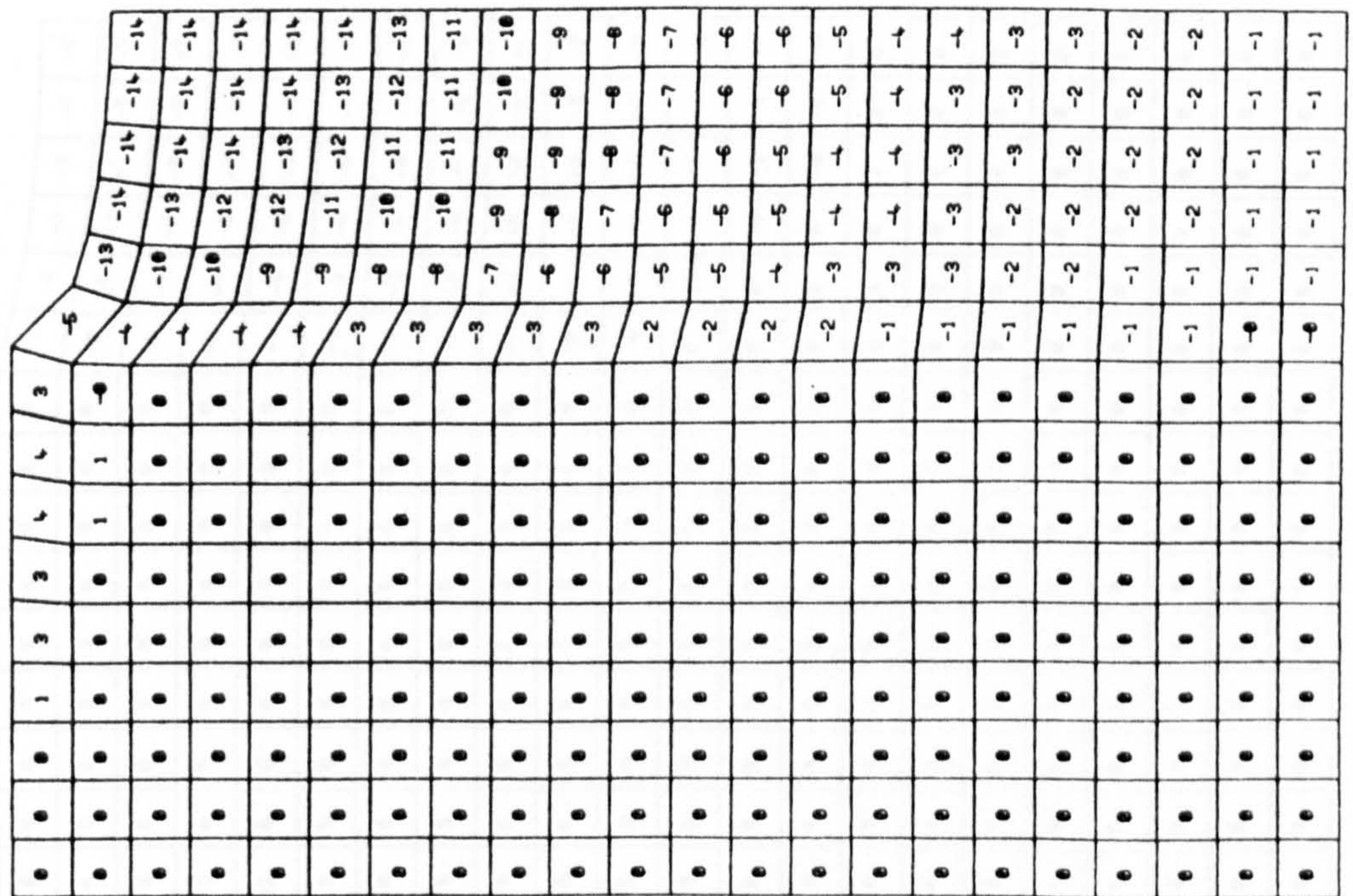
Input variables:-

Moisture content	10 %
Contact load	9 kN.
Contact patch width	0.275 m
Poisson's Ratio	0.25

Contact Length. (m)	Contact pressure kN/m ²		
	70	140	280
	0.467	0.233	0.116

Soil properties

Pressure (kN/m ²)		Initial soil density g/ml				
		1.2	1.3	1.4	1.5	1.6
70	Young's modulus (kN/m ²)	361	447	475	-	-
	Cut off strain (%)	3.0	5.8	12.0	-	-
140	Young's Modulus (kN/m ²)	567	711	965	1109	-
	Cut off strain (%)	1.8	3.8	7.0	10.5	-
280	Young's Modulus (kN/m ²)	898	1142	1468	1941	2488
	Cut off strain (%)	1.2	2.5	5.6	8.1	11.2



Direction of travel.

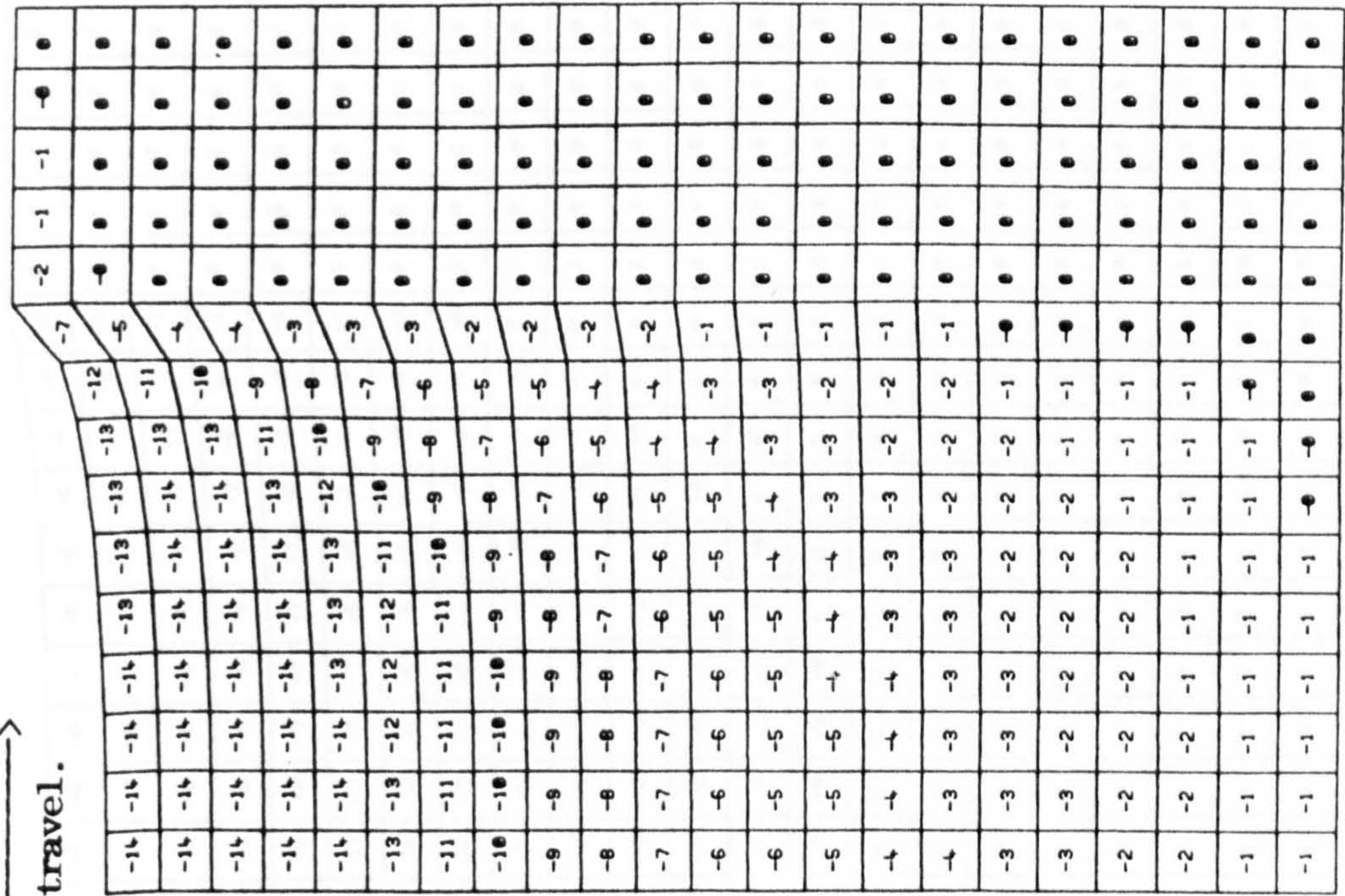


FIGURE 5 3.1

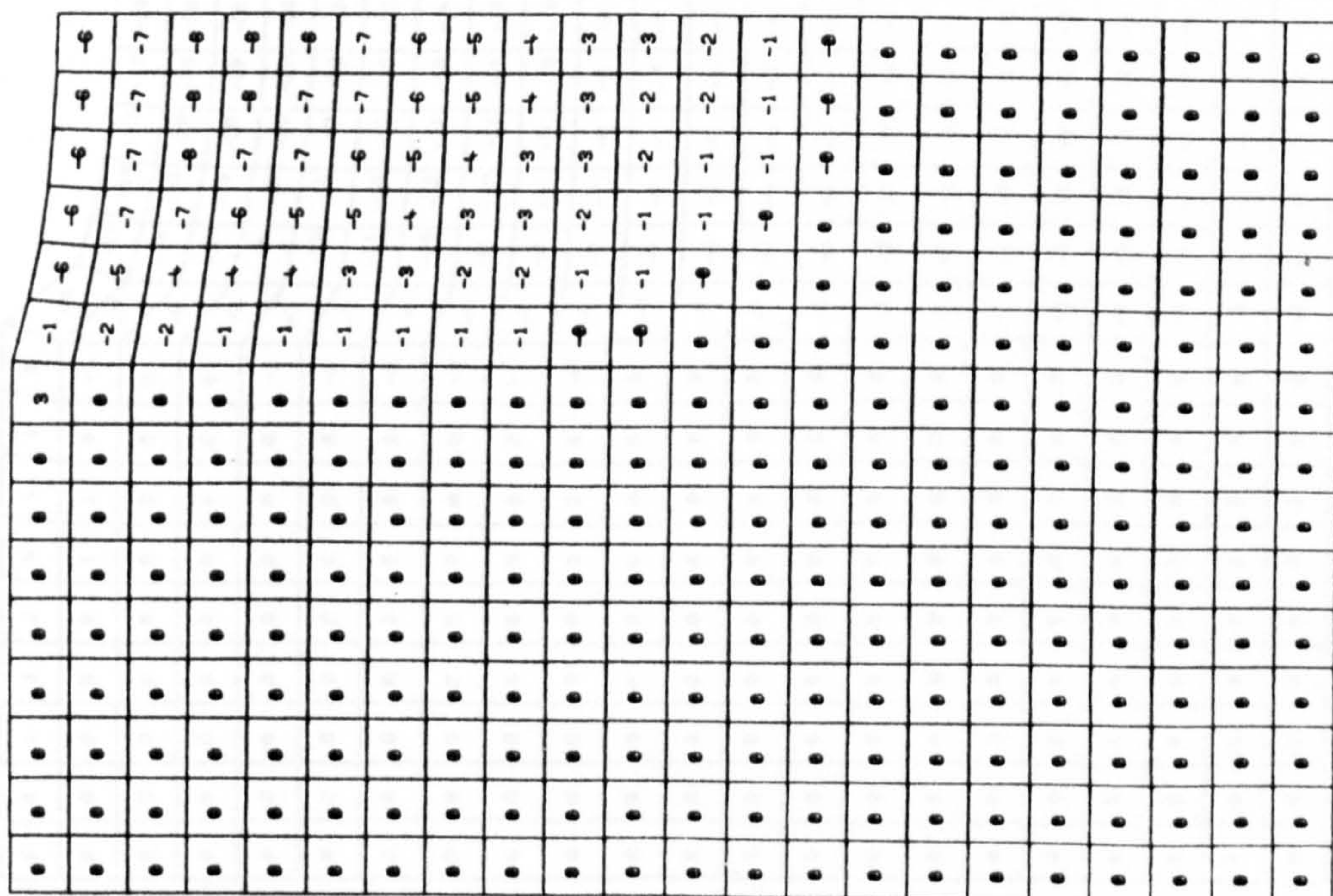
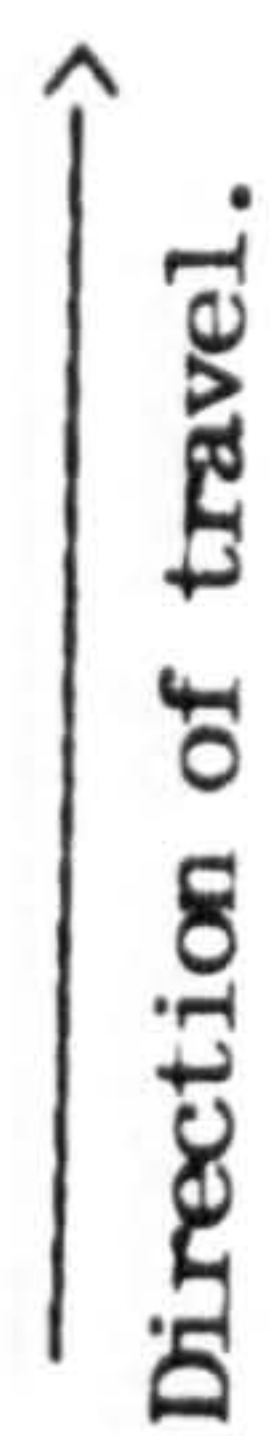


FIGURE 5.3:2.

Direction of travel. $\rightarrow$

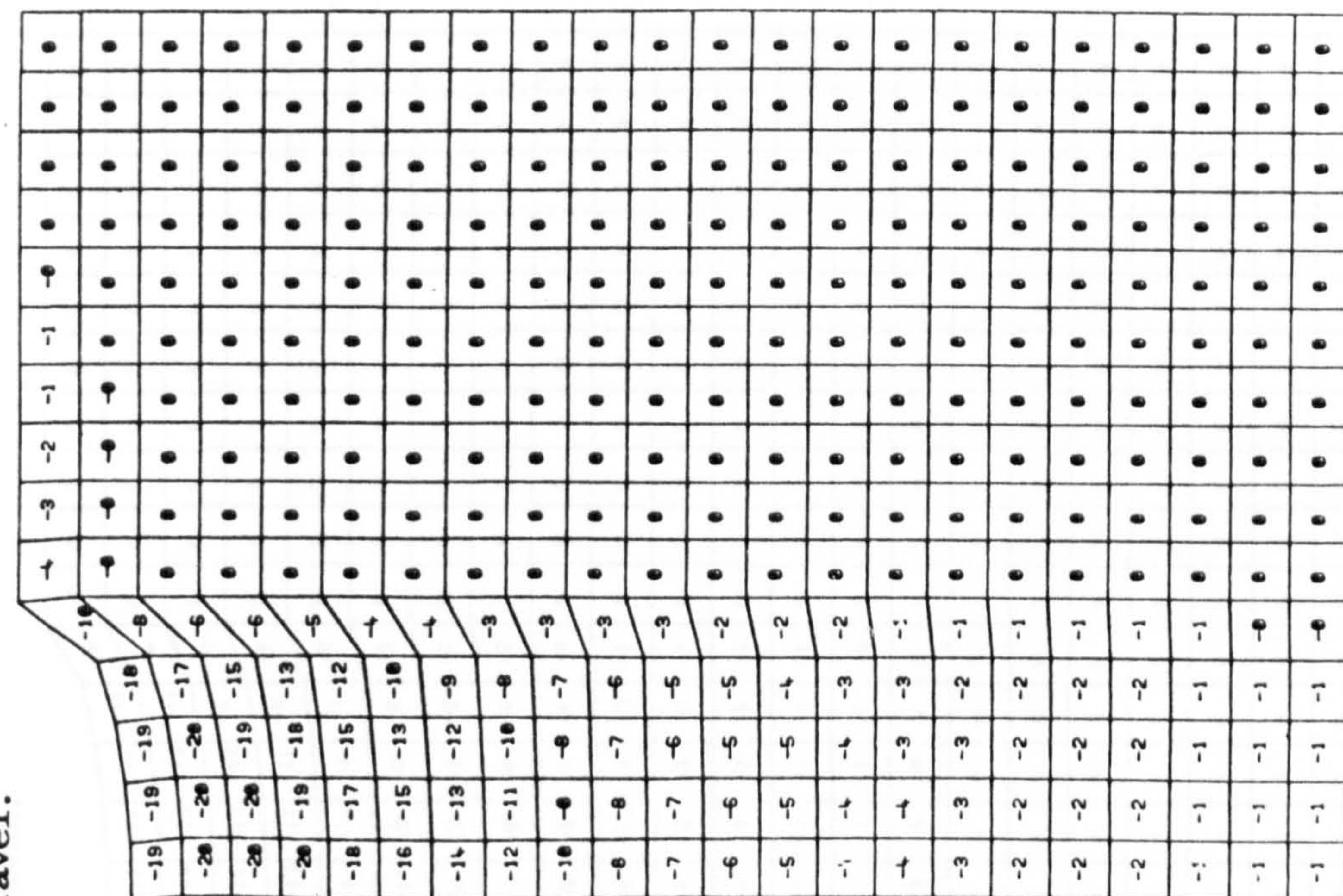
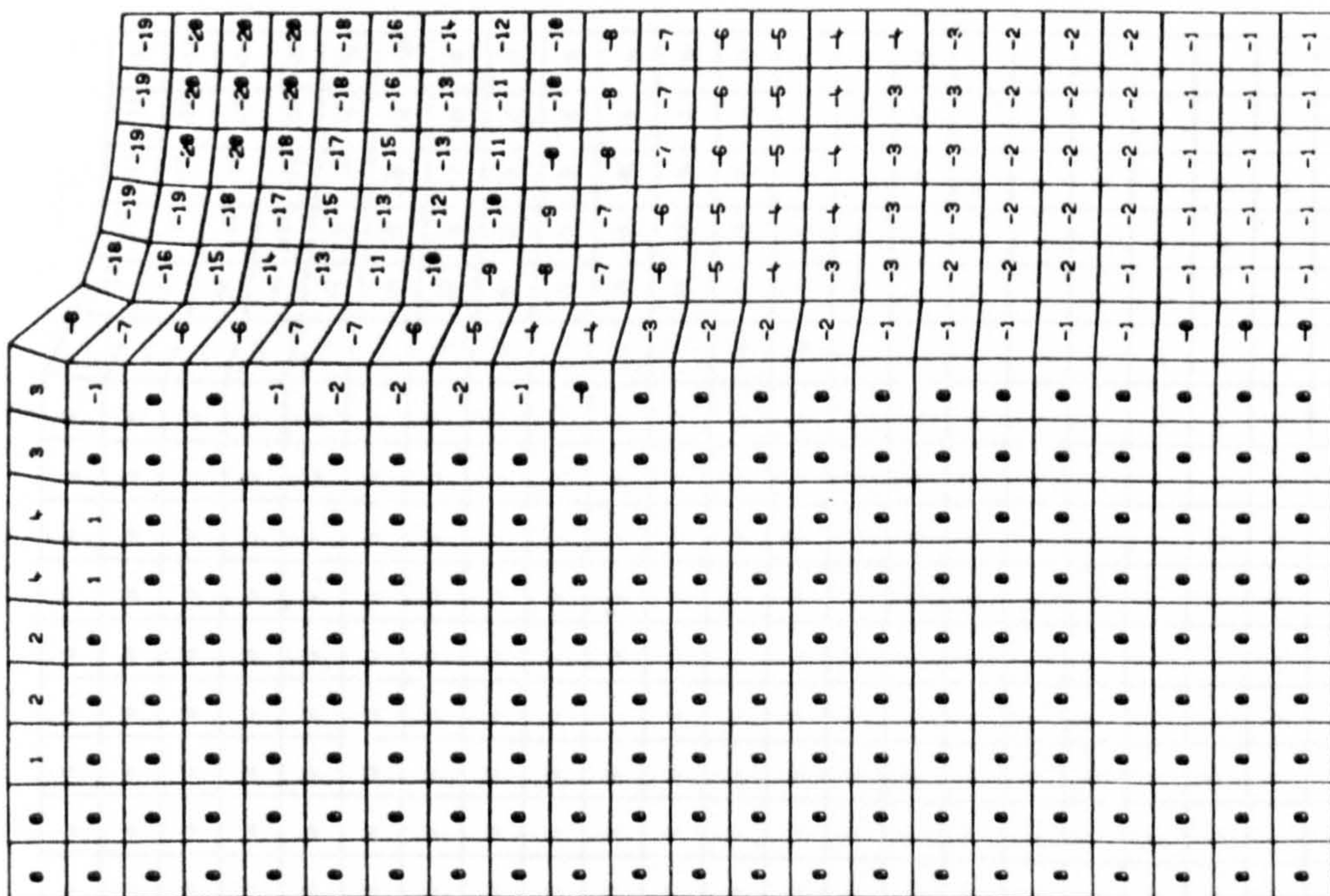


FIGURE 5.3:3.

Direction of travel. $\rightarrow$

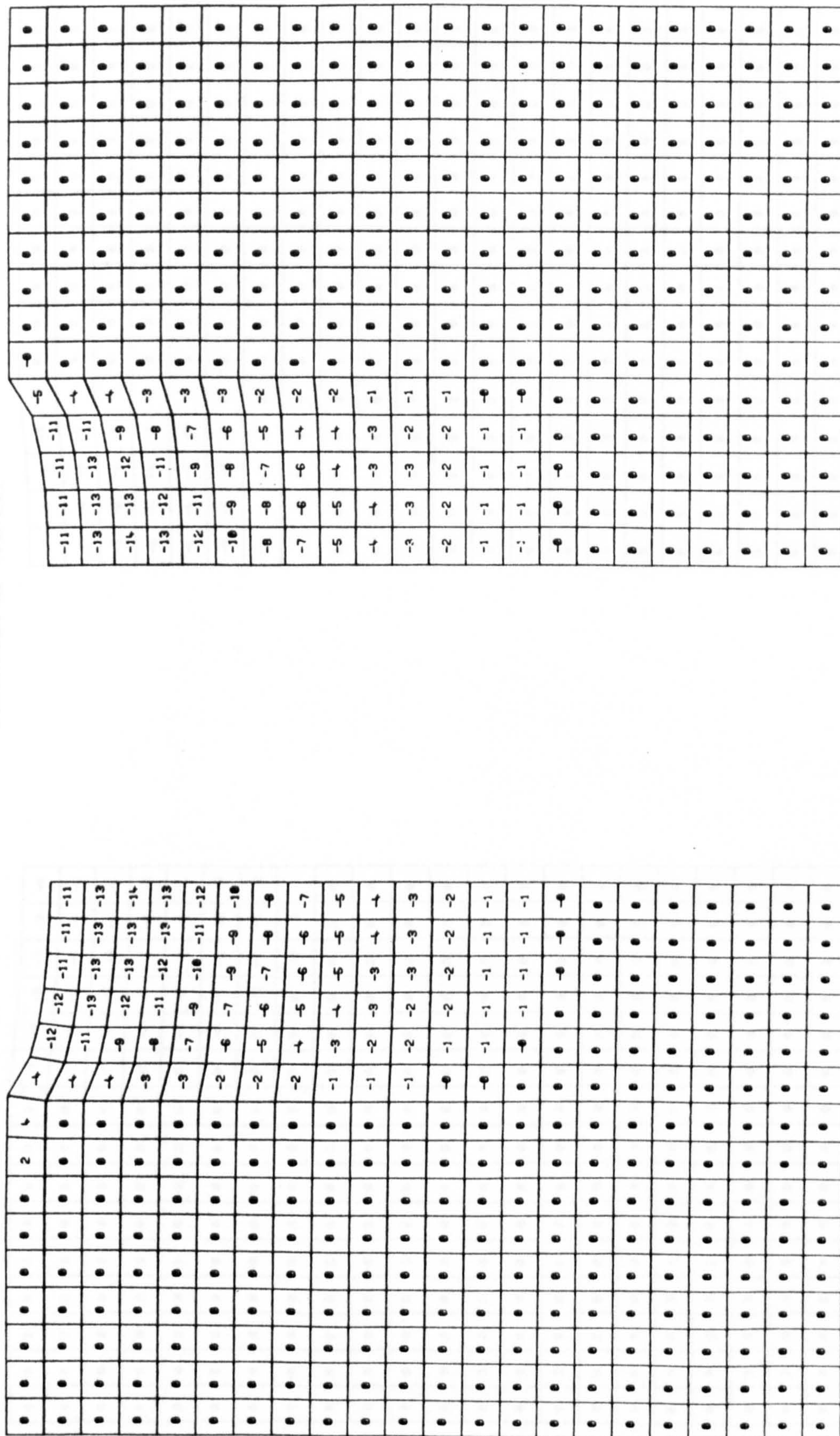


FIGURE 5.3:4.

↑
 Direction of travel.

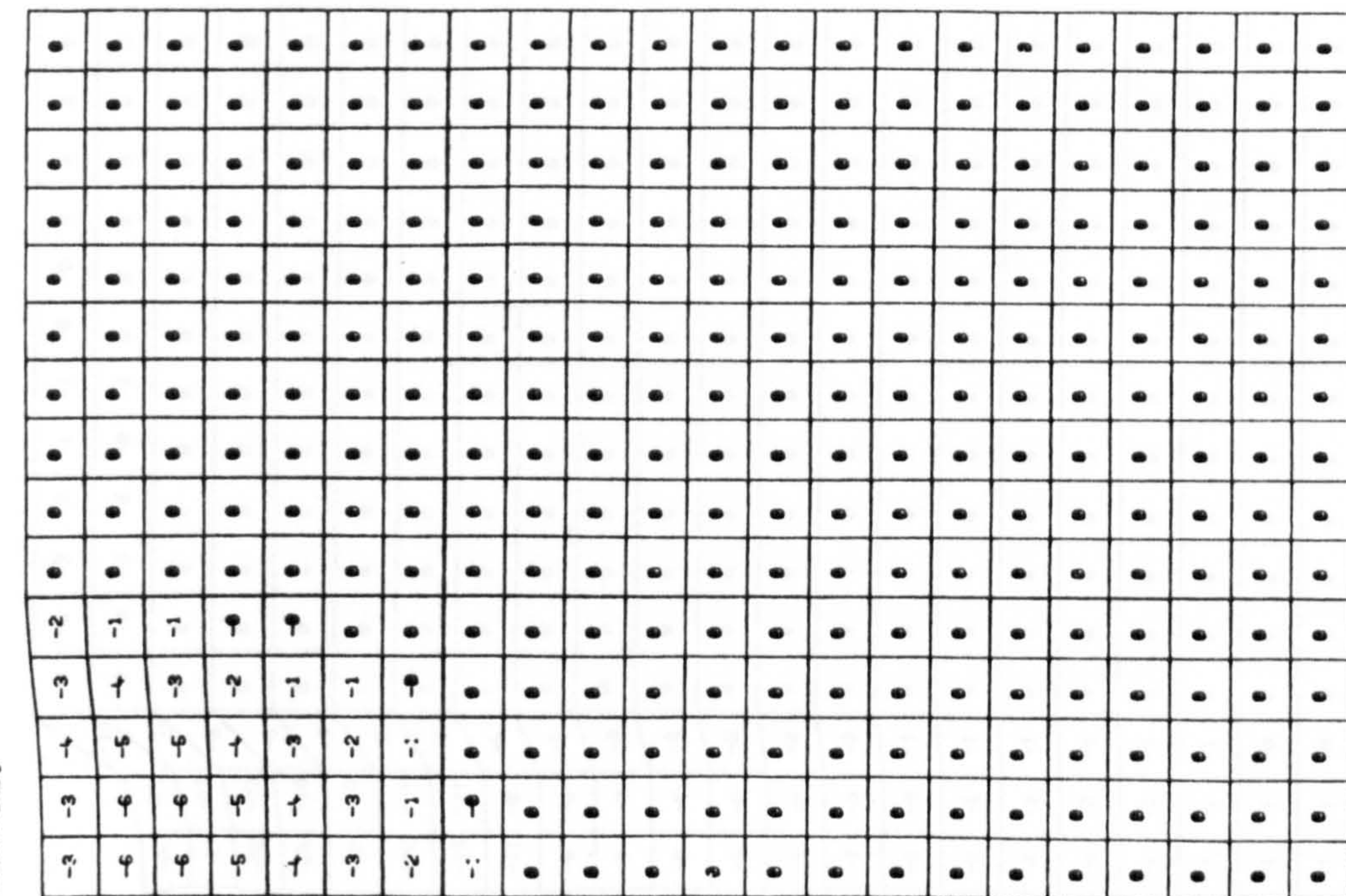
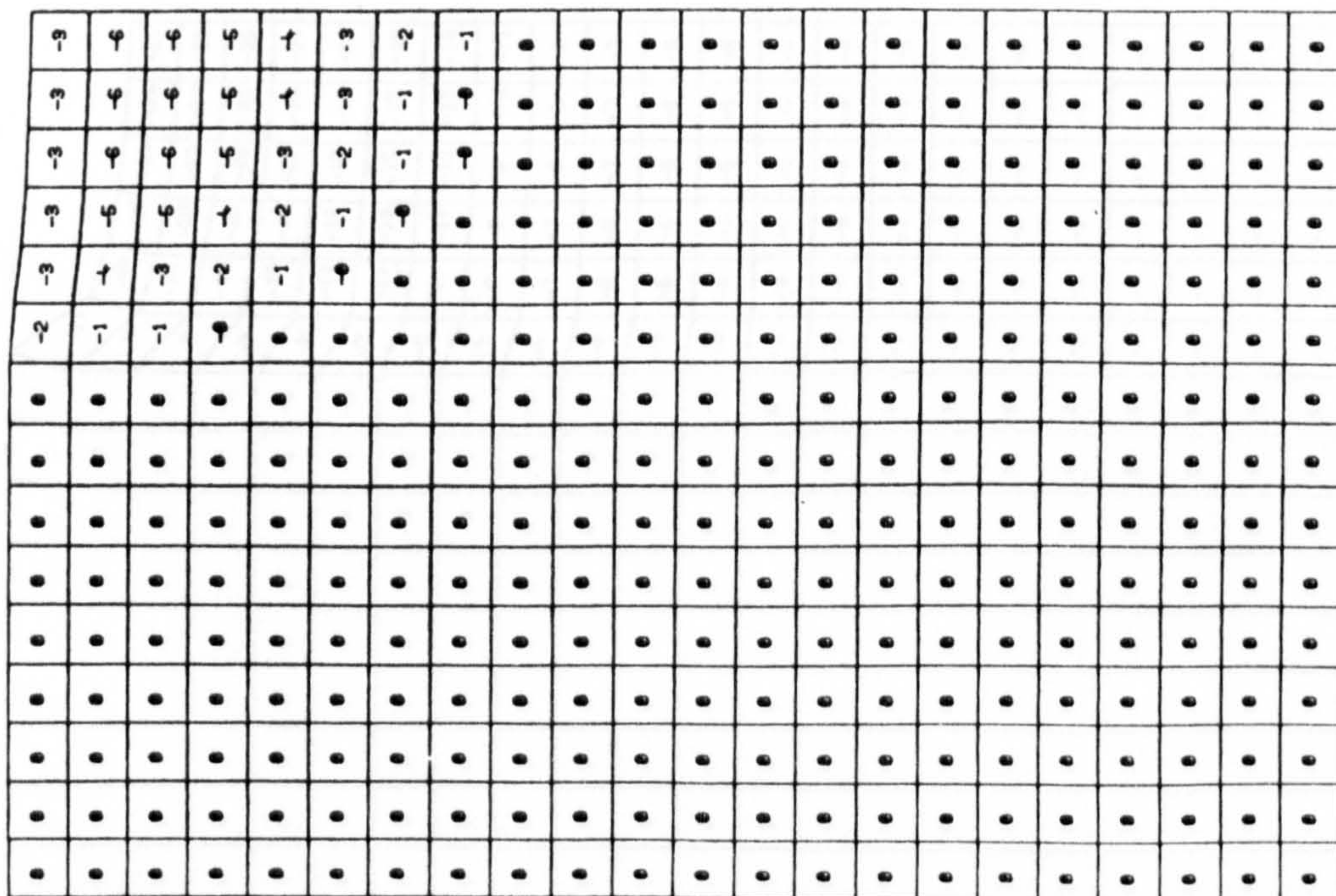


FIGURE 5.3:5.

Direction of travel. $\rightarrow$

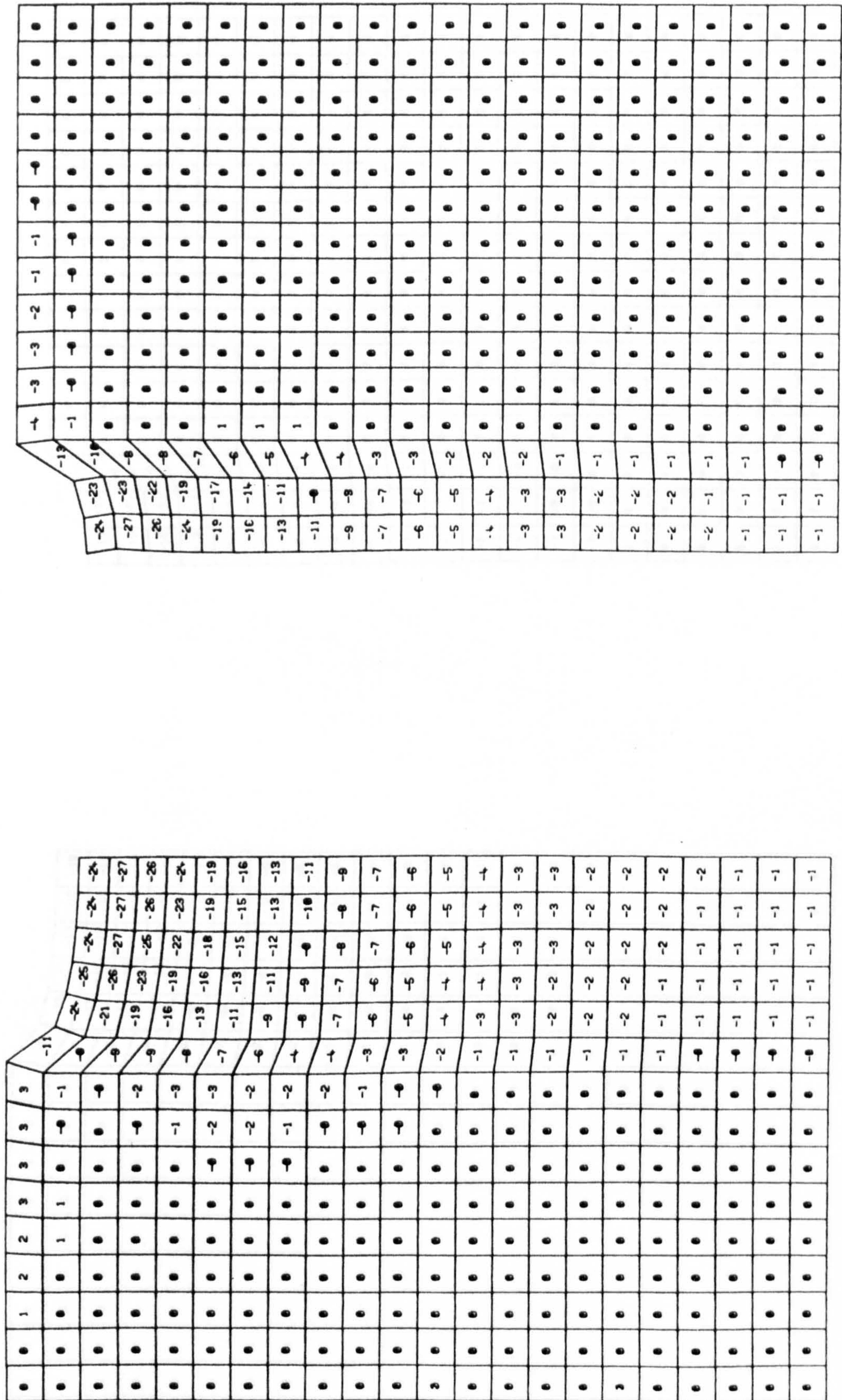


FIGURE 5.3:6.

Direction of travel. $\rightarrow$

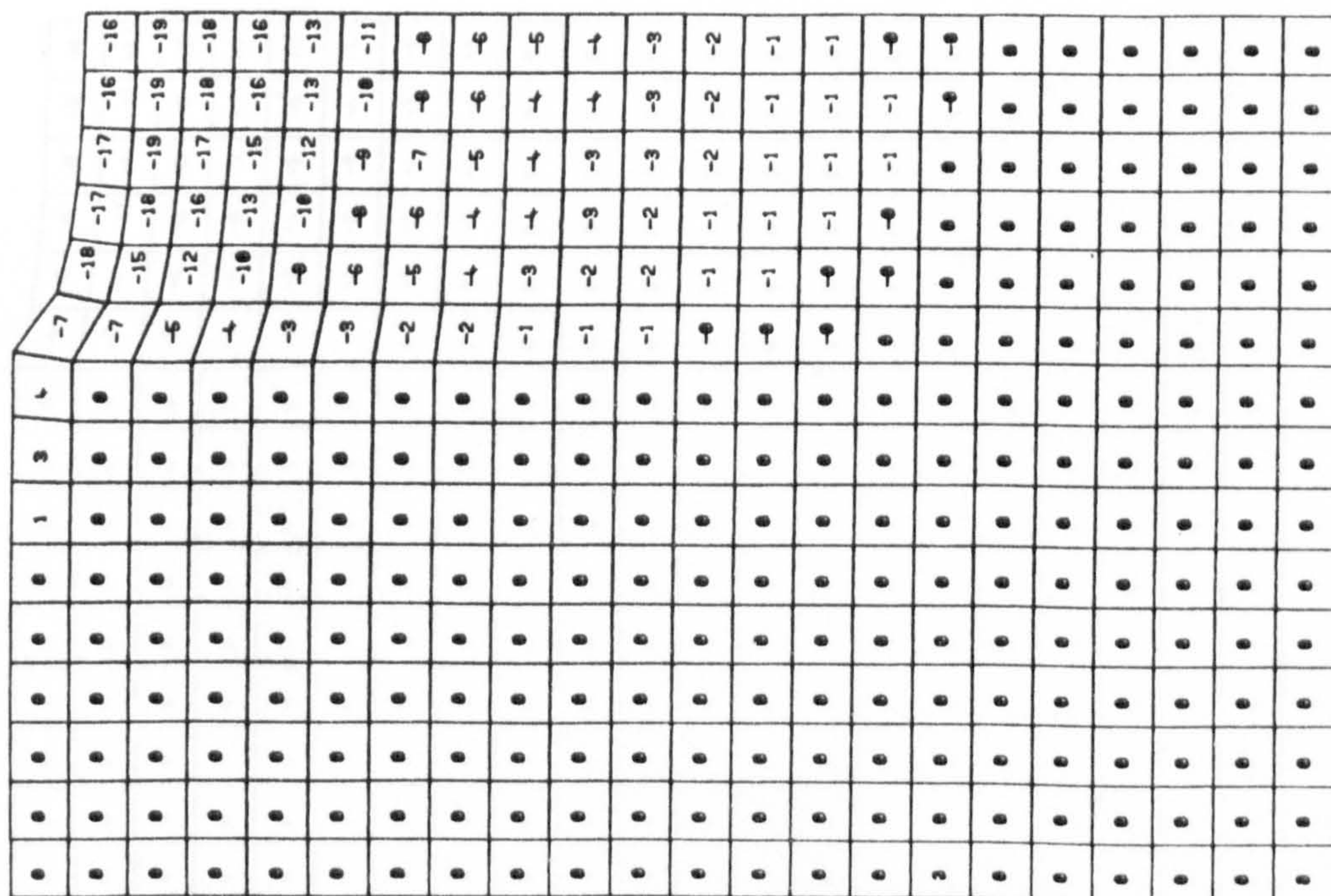
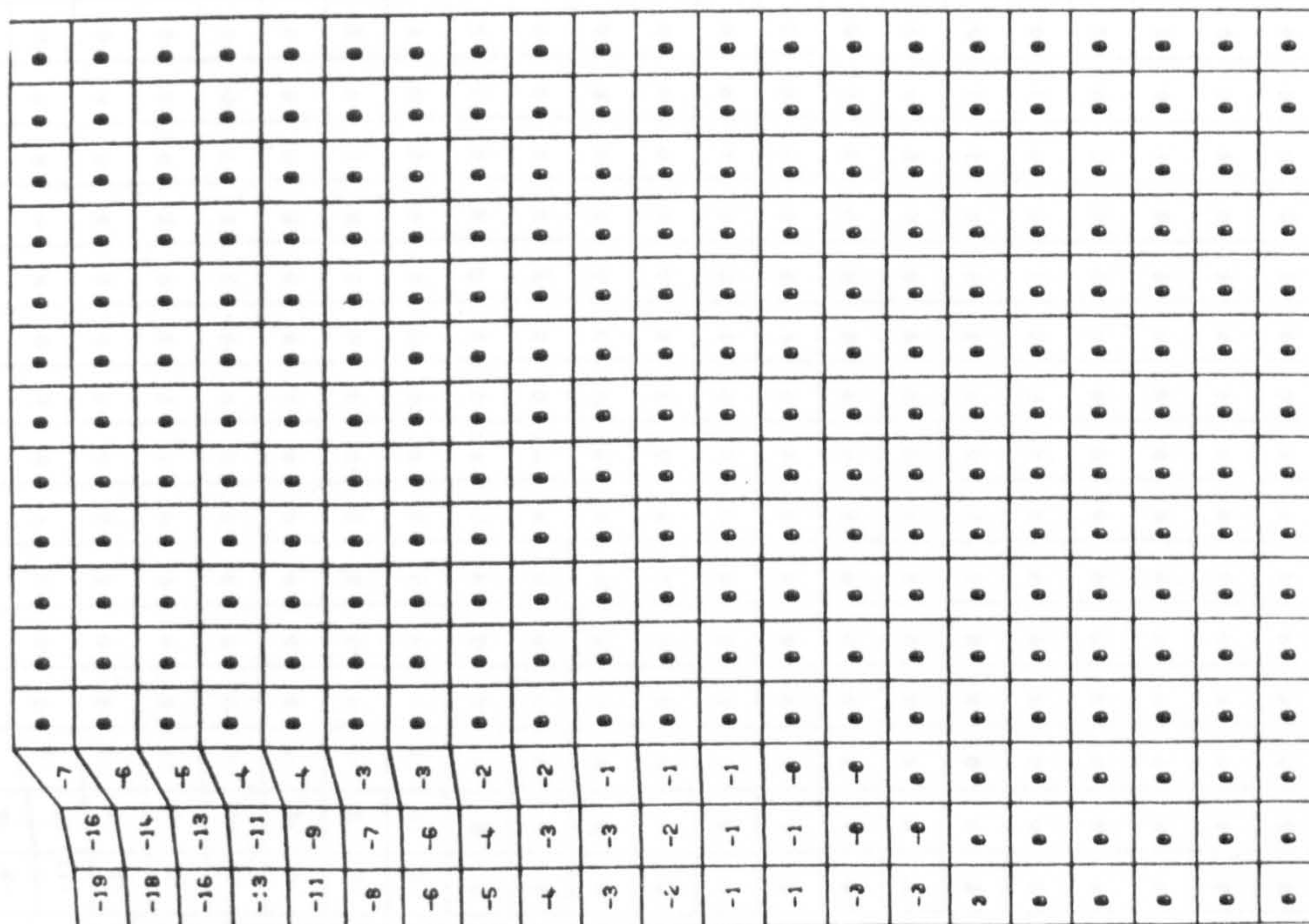


FIGURE 5.3:7.

Direction of travel. 

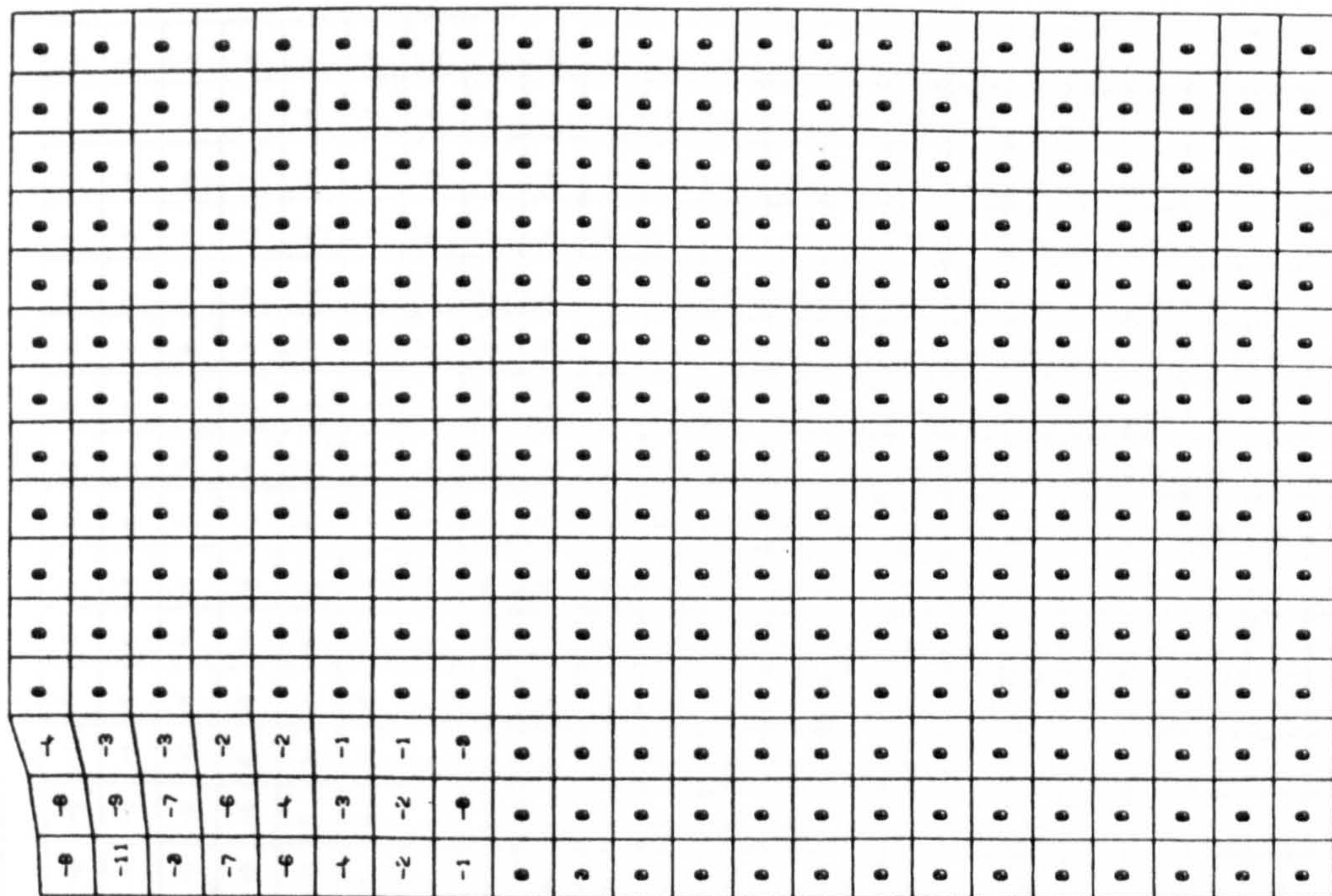
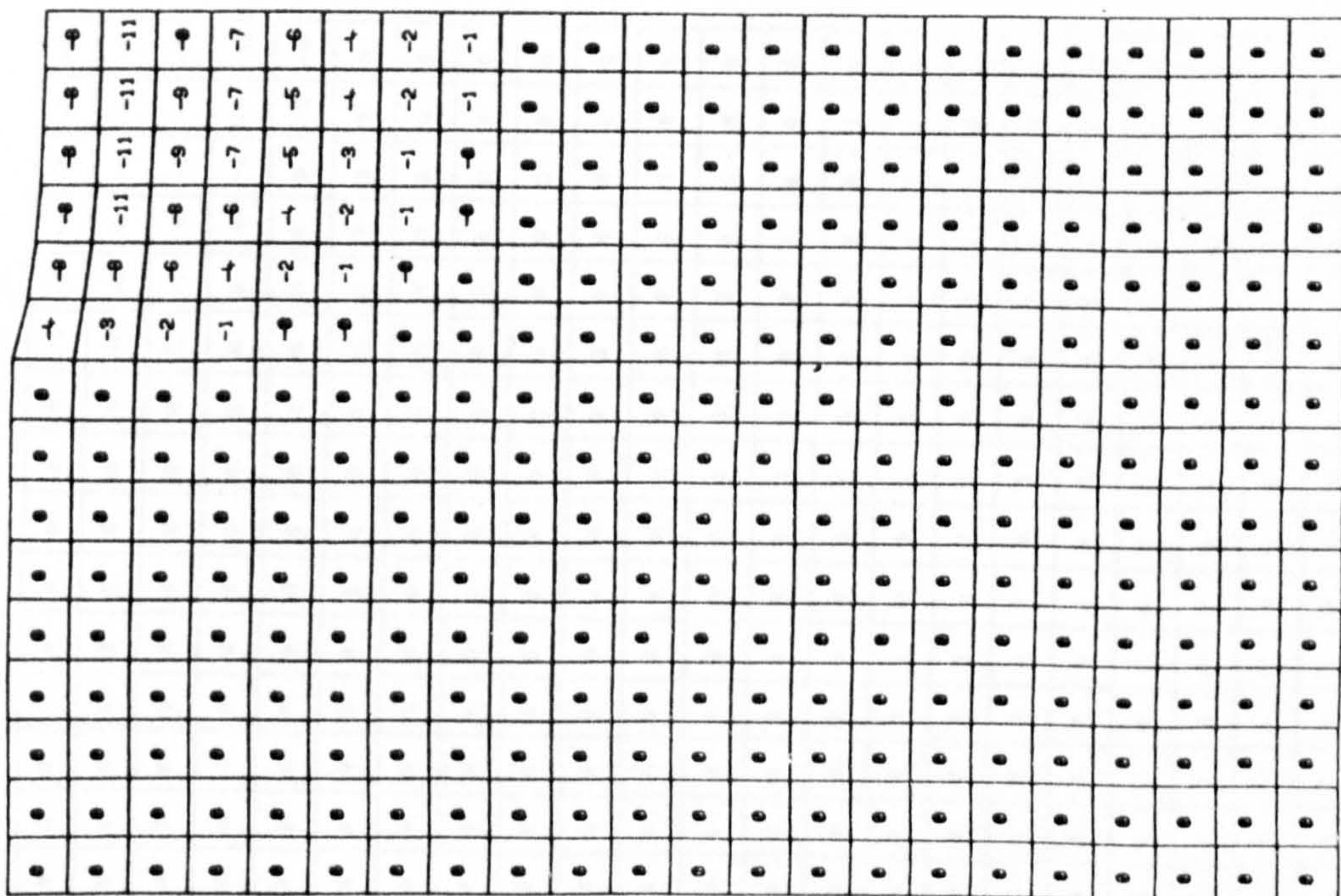


FIGURE 5.3:8.

Direction of travel. $\rightarrow$

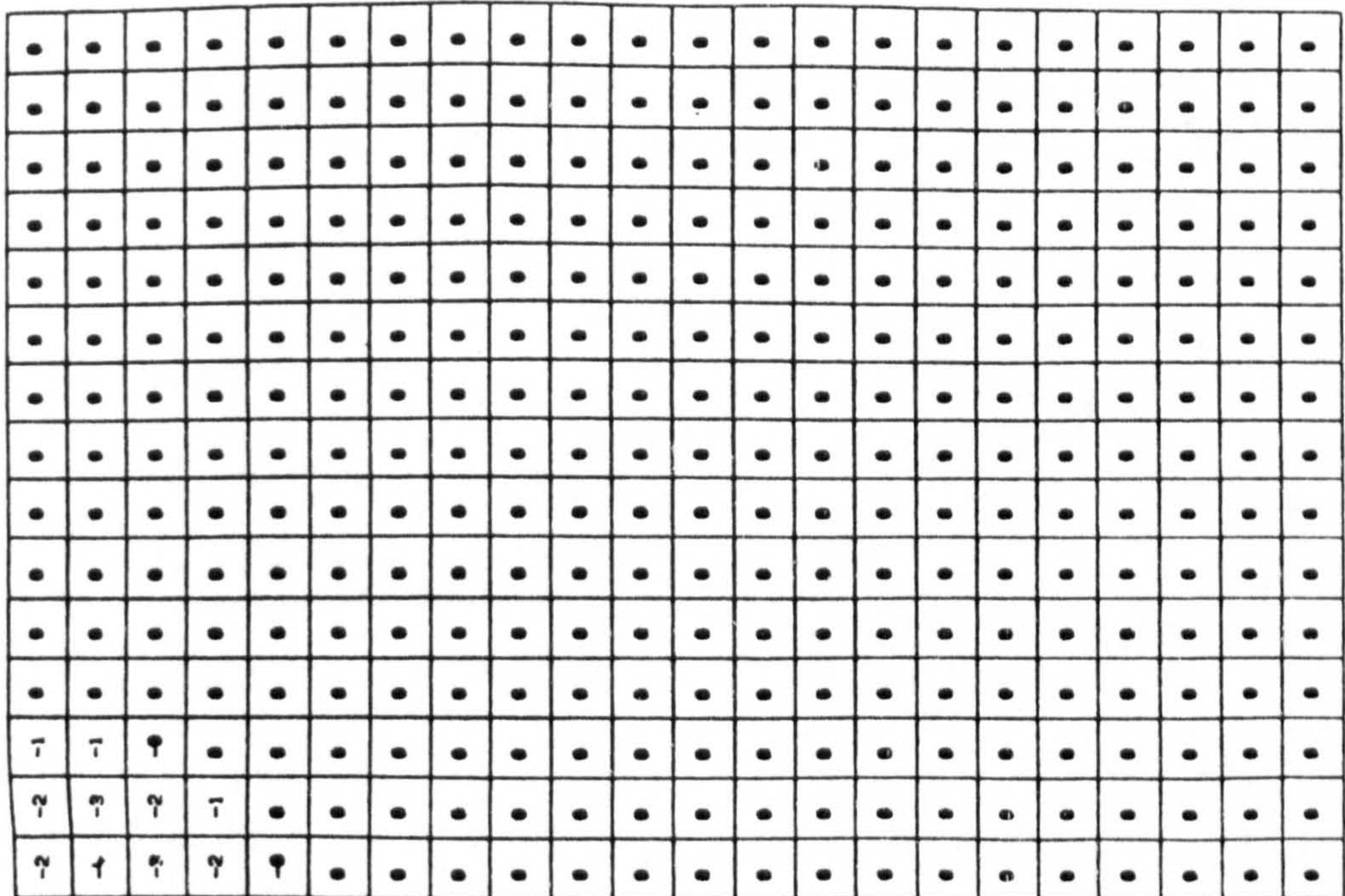
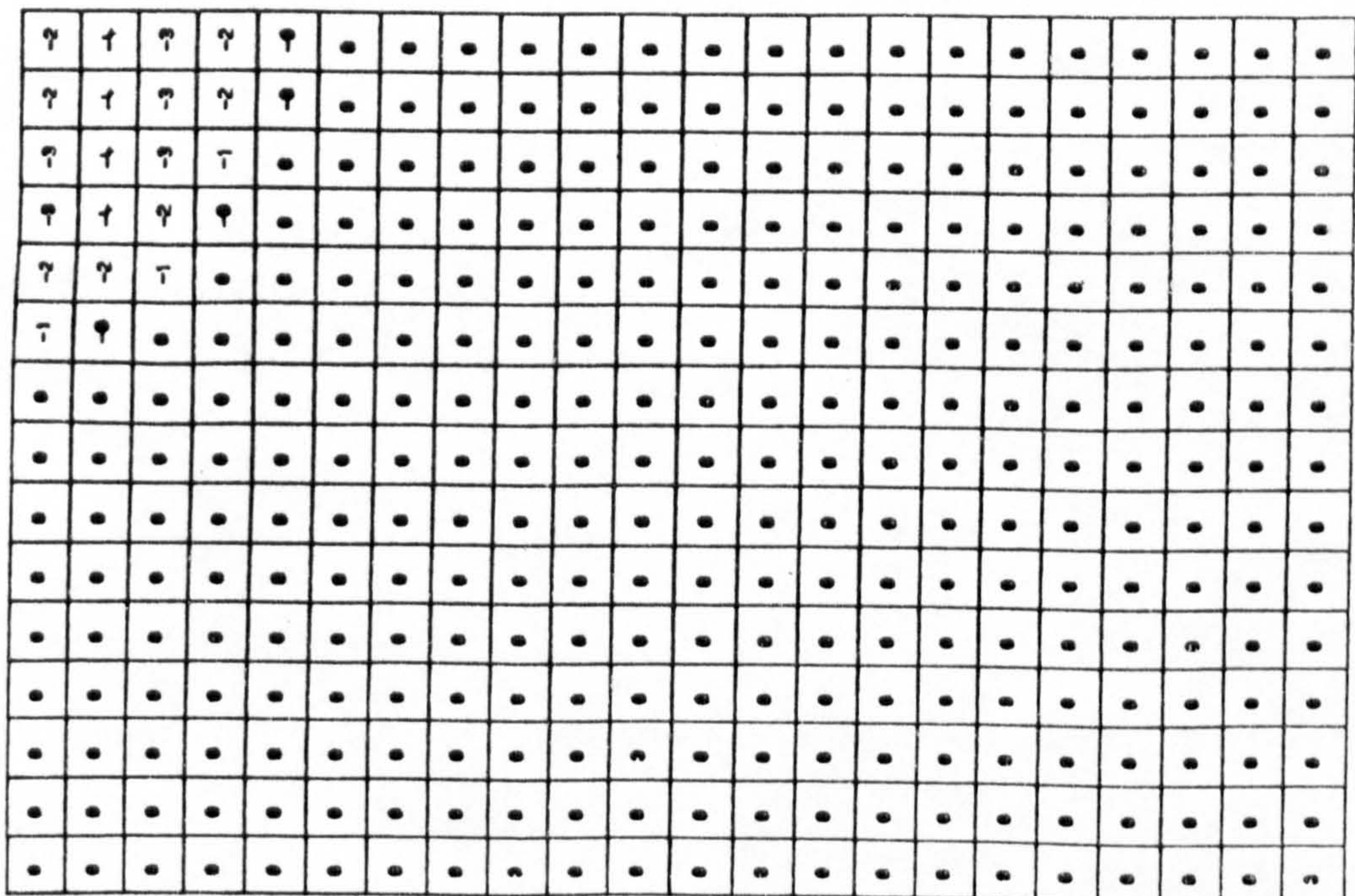


FIGURE 5.3:9.