THESIS SUMMARY

THE RIPPABILITY OF ROCK

1. INTRODUCTION

Ripping is a method of loosening rock during excavation using steel tynes attached to the rear of bulldozers. The tynes are lowered into the ground as the bulldozer moves forward and soil or blocks of rock are displaced by the tynes.

Ripping with bulldozers was first introduced during the late 1950's and has become a popular method of excavating soil and rock. For many years ripping was used to loosen soils and weak rocks while any stronger material was blasted. In recent years, however, regulatory authorities have tightened the restrictions on blasting in cities and residential areas, and contractors have had to try to rip rock which would have been previously blasted. It has become critical to define better the limits of rippability and the potential ranges of productivities for any given bulldozer on a particular site.

Over the years techniques for preparing construction programmes and estimating the costs of excavation have also improved and it is important in preparing these estimates to know the type of equipment required to excavate a particular site. In most cases ripping with a bulldozer is cheaper than drilling and blasting, however, as the ripping becomes harder, the wear and tear on the bulldozer increases and the productivity decreases until drilling and blasting becomes a more economical solution.

Methods for predicting whether bulldozers can rip a particular rock have been available since the late 1950's. Many of these are based on using the refracted seismic velocity of the rock to predict rippability but some of the methods proposed since the 1970's have included a range of other geological factors. Field experience using these prediction methods has shown that most of the methods are not very accurate and that there is room for improvement. A common problem with many of these prediction methods is that they have been based on few data points and are often useful in a particular rock type only.

2 OBJECTIVES AND SCOPE OF STUDY

The main objective of this research project was to develop a method of predicting the productivity of bulldozers ripping in different rock types. The research comprised collection of detailed ripping data in various rock types, examination of the fundamental mechanisms involved in the ripping process and attempts to numerically model these mechanisms.

Initially a review was undertaken of the existing literature on ripping techniques, prediction methods and any rock cutting or penetration theories which might be applicable to the research.

Collection of detailed ripping data was carried out on various sites in New South Wales (Australia). Geological factors were observed, as well as bulldozer variables, and block samples were taken for laboratory testing. Detailed seismic refraction surveys were undertaken on some sites with the aim of improving existing seismic investigation techniques.

During the collection of field data the manner in which the ripper tynes loosened the ground was observed closely to determine the breaking mechanisms involved in the ripping process. Several numerical techniques were used to attempt to model these mechanisms and to examine the ripping process in a fundamental manner.

Laboratory scale modelling of ripping, particularly the penetration process, was performed to test the influence of various factors and to provide a means of verifying the numerical models. A full-scale bulldozer was then instrumented to measure the forces in its tyne during ripping. This trial was used to check the results of the laboratory modelling and to provide a link with the detailed geological and ripping data collected in the field.

The results of the research were then analysed and compared with existing methods of predicting rippability. A new method of predicting the productivity of ripping was proposed and compared with existing methods.

3 LITERATURE REVIEW

Available literature on ripping and related topics was reviewed as part of the research project. The literature which was reviewed included details of bulldozer characteristics and techniques recommended for use by operators; assessments of geotechnical factors which most affect the ripping process and systems proposed for the prediction of rippability; and theoretical and experimental work on cutting and penetration mechanisms in rock, particularly for drag picks on underground mining machines.

4 FIELD DATA COLLECTION AND LABORATORY TESTING

A major objective of the research project was to build up a database of detailed ripping, geological and laboratory test data from different rock types. This database could then be used to develop predictions of bulldozer productivity and to assess methods of predicting rippability as well as testing numerical and laboratory models of ripping.

The method of data collection was designed to obtain detailed geological data and laboratory samples from the same areas of construction sites in which ripping had been observed. Typically a bulldozer ripping a particular area would be observed and its operations recorded, then during a break in operations a representative sample of the ripped material would be taken for laboratory testing and any exposed surfaces geologically mapped.

An aim of the project was to obtain from ripping in as many different rock types as possible and from observing a range of bulldozer sizes. Unfortunately most of the construction in NSW during the study was within 200 km of Sydney where there is a preponderance of sandstones and most excavation companies use the larger size bulldozers. This dominance is reflected in the data collected although information was obtained from ripping in a range of rock types. Most of the sites were road or highway construction sites although some data was also collected from Sydney city building sites, open-cut coal mines in the Hunter Valley and waste disposal sites. There were some differences between the operations on the different types of sites, however it was considered that generally the ripping techniques and factors affecting rippability were independent of the type of site.

The field data was collected from excavation of a total of 19 rock types on 15 sites in New South Wales. Ripping was observed in a total of 242 distinct areas, and after the data had been divided into different orientations, operators, bulldozers and initial or cross ripping, there were 527 sets of ripping data for analysis. The data also included some areas where the contractor had assessed that either the physical or economic limit of rippability had been reached and had opted for drilling and blasting of the rock.

In order to quantify the rippability for each area a form of productivity was calculated from field observations which allowed comparison between areas where different types of earthmoving operations occurred. Analysis of operations found that, even when a bulldozer was dedicated only to ripping, the percentage of time the tyne was in the ground ranged from 30% to 93%. This was largely due to time spent reversing or turning the bulldozer between ripping runs. When the bulldozer was also involved in other operations, such as pushing scrapers, the percentage of time the tyne was in the ground ranged from 3% to 58%.

The calculated productivity is a measure of the volume of material loosened in each hour of ripping, assuming that the ripper tyne is continuously in the ground ripping. To obtain more conventional measures of productivity the time the bulldozer spends reversing or turning between runs, the time spent dozing or pushing scrapers, and the time spent on maintenance or meal breaks need to be estimated for each area.

All the data was entered into a spreadsheet and correlations between individual variables were examined as well as the effect of each variable on the ripping productivity. Good correlations were obtained between the results of different laboratory tests with point load tests and Brazilian tests having the highest correlation with unconfined compressive strength (UCS) tests and a very good correlation obtained between Young's modulus and sonic velocity.

The variables which had the best correlations with productivity were UCS and seismic velocity, however the range of productivity for each value of either UCS or seismic velocity was large indicating that a combination of factors is likely to give a more accurate prediction. The correlation between UCS and measured productivity is shown on Figure 1. As a result, multiple variable regression statistical analysis was undertaken to assess the effect of a combination of variables.

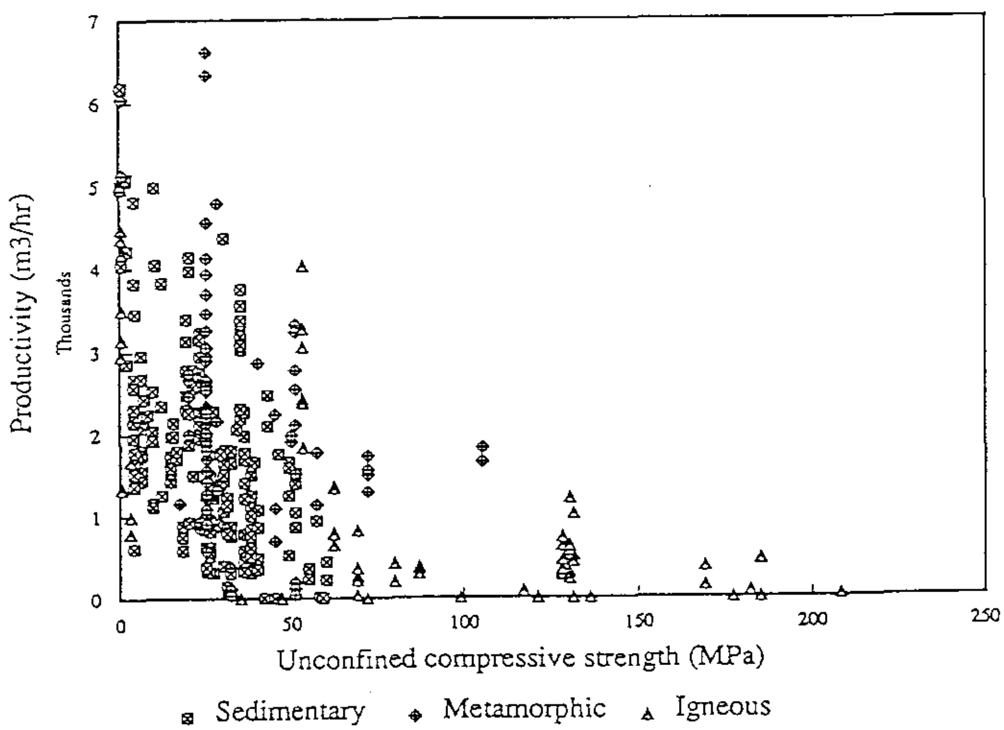

Fig 1: Measured productivity compared to UCS values.

There was a considerable scatter in the ripping data which is probably caused by either errors in measuring and estimating the various field and laboratory parameters, natural variability in the geological parameters on any site, or variations in the operations of the bulldozer. Despite this scatter it was possible, using statistical analysis techniques, to obtain reasonable estimations of the productivity of an area using only a few key parameters. Factors describing dozer equipment and operations were shown to have a significant effect on the productivity but these factors cannot usually be predicted prior to the excavation of a site. If only factors which can be measured or estimated prior to excavation are considered, reasonable estimates of productivity can be obtained from combinations of UCS, degree of weathering, refracted seismic velocity, grainsize of the rock, geological structure of an area, number of defect sets, roughness of the defects and the weight of the bulldozer. An equation predicting productivity from a combination of the above factors is given below and the correlation between the measured productivities and those estimated from the equation are illustrated in Figure 2.

Equation 4:

$$\sqrt{\frac{\text{Productivity}}{\text{Bulldozer mass }(+)}} = 0.469 - 0.00321\ \text{UCS (MPa)} + 0.0230\ \text{weathering rating} - 0.0205\ \text{Grain size rating} - 0.000111\ \text{Seismic velocity (m/s)} + 0.0535\ \text{Roughess rating} + 0.0524\ \text{No of defect sets} + 0.0114\ \text{Structure rating}$$

Rating systems for each of the variables are given in detail in the full thesis. The first three variables combine to define the rock material properties such as rock type, fabric and strength. The last three variables define the type, frequency and nature of the defects in the rock and the seismic velocity is influenced by both the rock material and the defects.

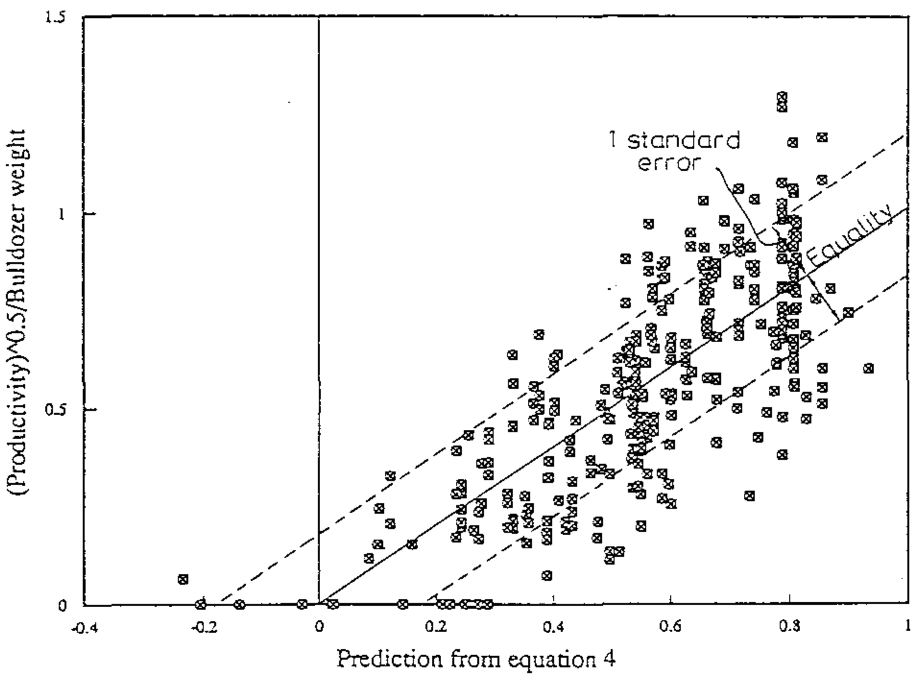

Fig 2: Measured (productivity) $^{0.5}$/bulldozer weight compared to estimated productivity from regression equation.

5 SEISMIC REFRACTION INVESTIGATIONS

Although seismic refraction is often criticised as inaccurate it is still probably the most economical method of scanning large sections of the subsurface during the investigation stages of a project. As part of this project the seismic refraction techniques used currently in site investigations were examined to see whether improvements could be made.

Both circular arrays and linear arrays with closer geophone spacing than normally used were examined. The results of the seismic investigations suggest that circular arrays are often a useful tool for determining anisotropy in rock, whether it be caused by the rock fabric or by defects. Circular arrays over phyllites and metamorphosed siltstones showed markedly high velocity directions parallel to the cleavage direction of the rock. If the site investigation traverses had been oriented parallel to the cleavage direction then the rock may have been assessed as being unrippable, however, in practice the bulldozers readily ripped the rock in the direction of the lowest velocity. A comparison between seismic velocity, defect orientation and ripping productivity is shown on Figure 3.

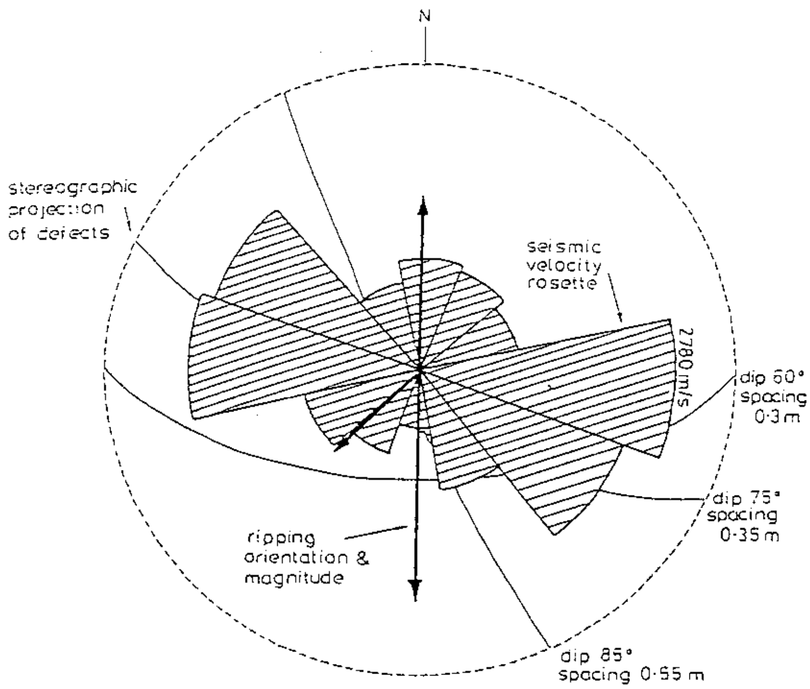

Fig 3: Comparison of seismic velocity, defect orientation and ripping productivity.

In addition some circular arrays appear to have detected stress relief fracturing caused by an adjacent vertical excavation through massive sandstone beds.

It is suggested that during site investigations, after routine traverses have been analysed, more detailed seismic arrays, possibly including circular arrays, be performed in areas where the rippability appears to be marginal or in areas where there are difficulties in determining a reasonable geological model from the analysis.

6 RIPPING MECHANISMS

The ripping process is a complex combination of different mechanisms which alter depending on the geological environment. In order to better understand and model the ripping process the manner in which the ripper tyne broke and loosened the rock was observed and described during the collection of data.

Most of the ripping observed in the field seemed to be a combination of two or more basic mechanisms. Which of these basic mechanisms occurred at a site seemed to be influenced mostly by the strength of the rock and the pattern and spacing of the defects.

The initial penetration of the tyne into the rock occurred either through the rock mass, along defect planes or a combination of both, as illustrated in Figure 4. The primary factor influencing which mechanism occurs is the strength of the rock mass. The difficulty of penetration is also affected by the shape and orientation of the ripper boot and the force which can be applied to the boot.

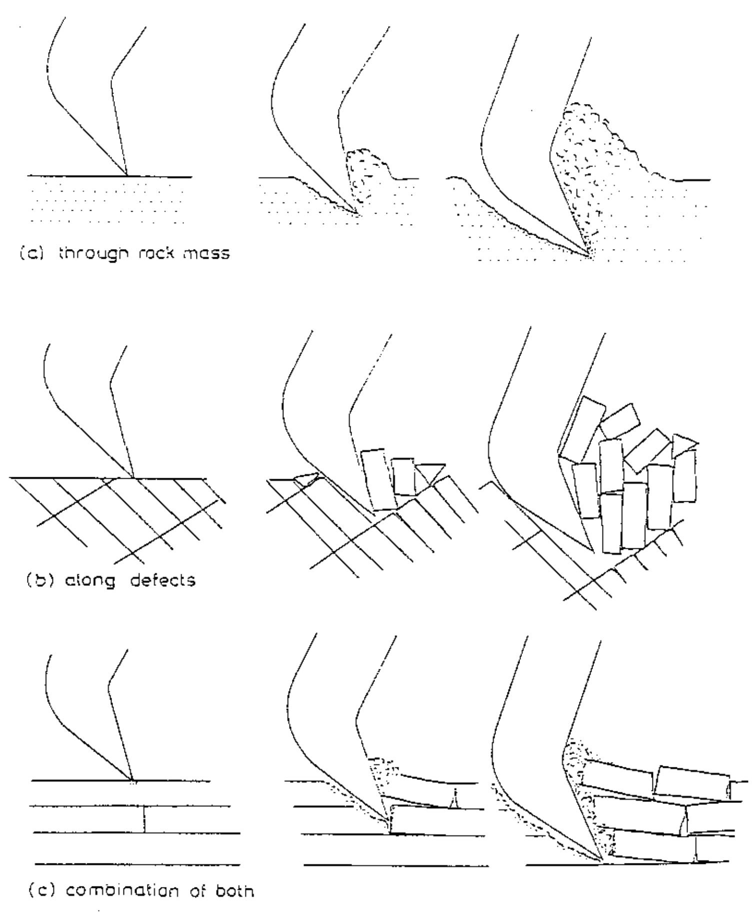

Fig 4: Initial penetration mechanisms

Five basic mechanisms have been observed during the part of ripping in which the bulldozer moves forward, essentially cutting the rock. These mechanisms include ploughing or loosening, crushing, splitting and flexing, tearing and prying out of boulders, as shown in Figure 5. The main factors affecting which mechanism occurs seem to be the strength of the rock mass and the nature, orientation and frequency of the defects.

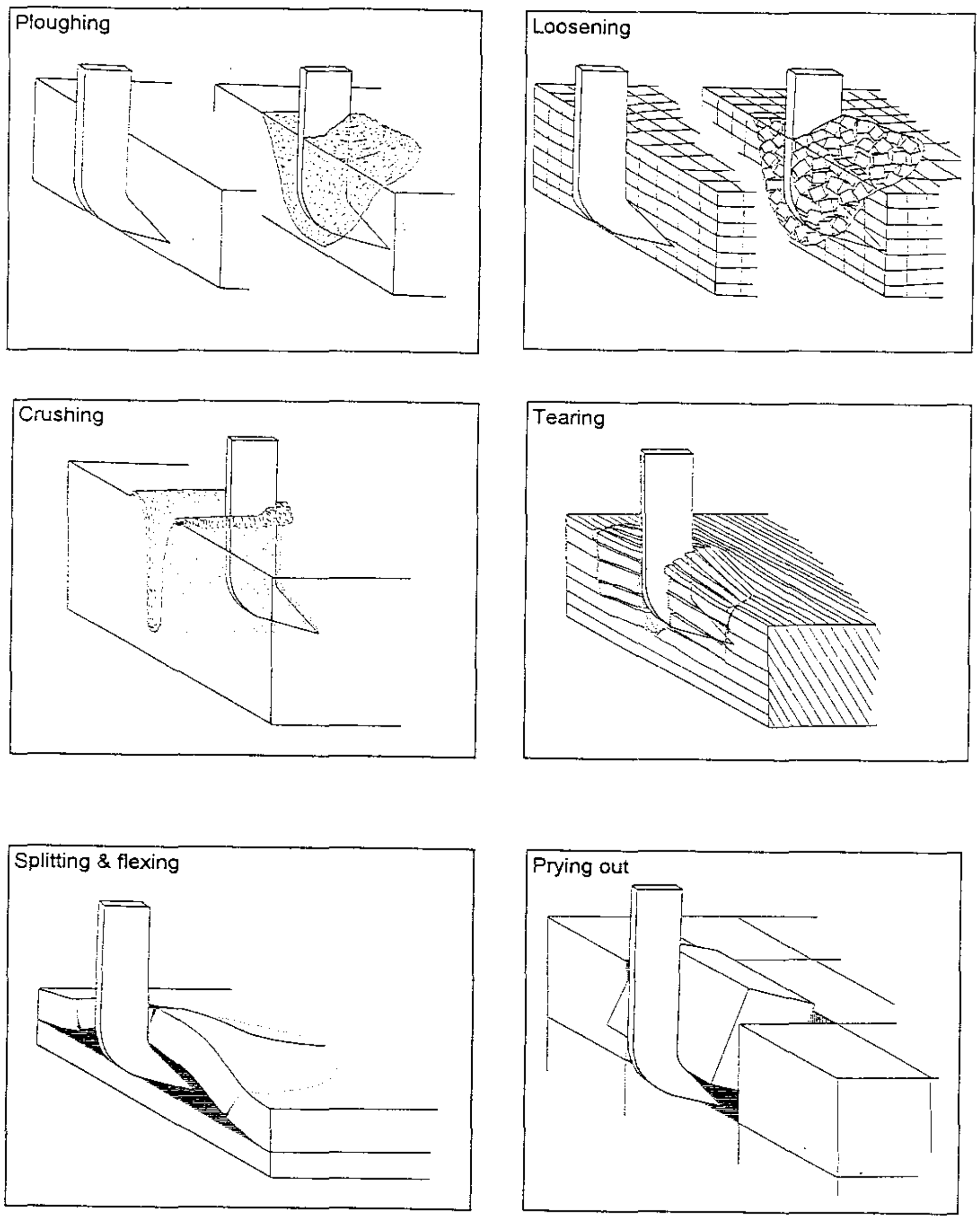

Fig 5: Ripping mechanisms

7 NUMERICAL MODELLING

Numerical modelling of some of the ripping mechanisms observed in the field was attempted. Simple hand analyses and two-dimensional modelling were found to be inadequate to model the three-dimensional and dynamic process of ripping. A three-dimensional distinct element program, 3DEC, written by Peter Cundall of Itasca Pty Ltd, was used to model the loosening mechanisms in strong jointed rock. One of the models analysed is illustrated in Figure 6.

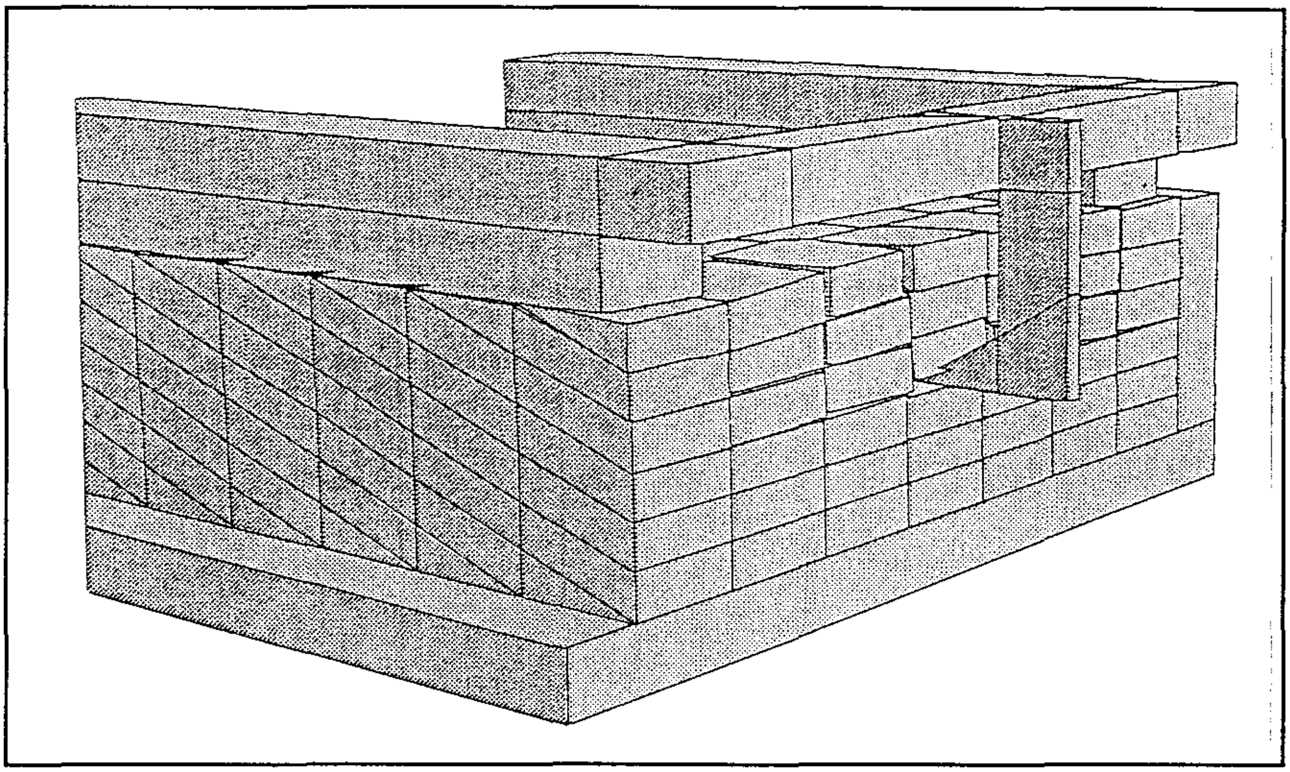

Fig 6: Three dimensional model for numerical analysis.

The three-dimensional modelling found that different dips and orientations of defects had varying resistances to penetration of the ripper boot into the rock. Decreasing the boot angle and increasing the angle between the underside of the boot and the horizontal improved the boot's penetration into rock. The applied loads required to move the model tyne were found to be much greater than could be expected in the field and increasing the initial depth of penetration did not influence the difficulty of penetration.

Considerable limitations were found in using numerical methods to model the ripping process. In particular the distinct method only modelled either rigid blocks or fully deformable blocks and could not model the combination of crushing or shearing of blocks which occur in most types of ripping. The exponential increase in time required to calculate each cycle as the tyne penetrated the rock and more rocks were displaced meant that it was only possible to study the initial penetration of the boot into rock.

8 LABORATORY SIMULATION OF PENETRATION BY TYNE

Laboratory scale modelling of the penetration of the ripper boot into massive rock was undertaken. An artificial sandstone was developed using a combination of sand and plaster, and a scale model of a ripper tyne was constructed and instrumented with strain gauges. Following testing the strain gauge results were analysed using a least squares analysis procedure to obtain the vertical and horizontal forces acting on the model tyne during ripping.

Scale model tests were performed on 5 samples of artificial sandstone which had three different unconfined compressive strengths. The forces on the tyne were monitored during vertical displacement, horizontal displacement and a combination of both vertical and horizontal displacement.

The scale modelling showed that the main mechanisms of failure in massive artificial sandstone are crushing during vertical penetration and a series of chipping mechanisms as the boot is displaced horizontally. A typical example of the horizontal forces measured during horizontal displacement is given in Figure 7.

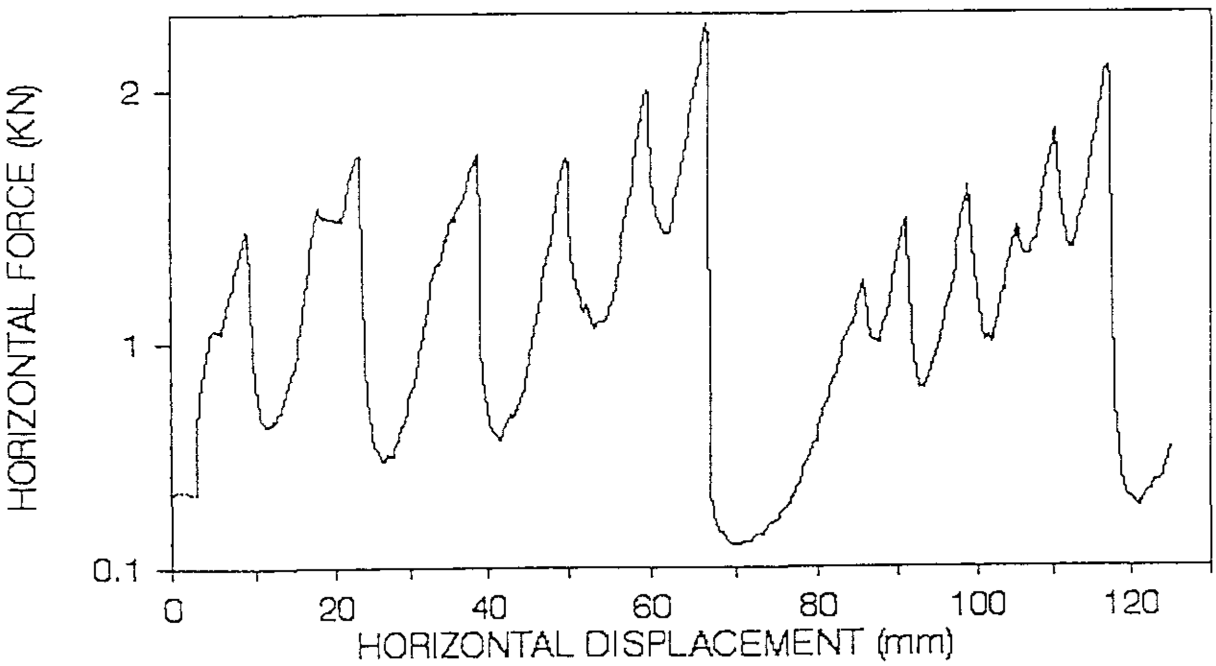

Fig 7: Horizontal forces measured during laboratory scale modelling.

The scale modelling found that the forces on the ripper boot increased parabolically with increased depth of the boot and increased unconfined compressive strength of the artificial sandstone. There was no significant difference between the forces on the ripper boot for the different speeds used in the tests and the different spacings between the runs also had very little effect except when the ripping runs were spaced very close together.

9 INSTRUMENTATION OF BULLDOZER TYNE

In order to verify the results of both the laboratory testing and the numerical modelling, a full scale bulldozer tyne was instrumented to measure the forces acting on the tyne during normal ripping operations. Essentially the same techniques were used to instrument and measure the forces as for the laboratory scale modelling, that is strain gauges were attached to a full scale tyne, together with tiltmeters to monitor the angle of the tyne. During ripping the instruments were monitored using cables attached to strain gauge amplifiers and the data was stored on a portable computer. The ripping trials were also videoed for later reference.

Two instrumented trials were carried out. One was located in a series of interbedded carbonaceous siltstones and fine sandstones, thinly bedded with two orthogonal sets of near vertical joints spaced at 500 mm to 600 mm. The other trial was in essentially massive high strength sandstone. The aim of the trials was to measure the forces on the tyne as the bulldozer varied the depth of the tyne, the angle of the tyne and the orientation of ripping.

The trials confirmed that the forces acting on the tyne occurred in a series of peaks similar to those monitored in the laboratory. A sample of the horizontal forces measured during a ripping run is shown in Figure 8. In the field the depth and angle of the tyne were difficult to control exactly, and the variability of the rock strength and the presence of defects in the ripped area made these peaks less regular than those in the laboratory scale modelling. The speed of the bulldozer was much greater than that modelled in the laboratory testing and the frequency of the peaks increased

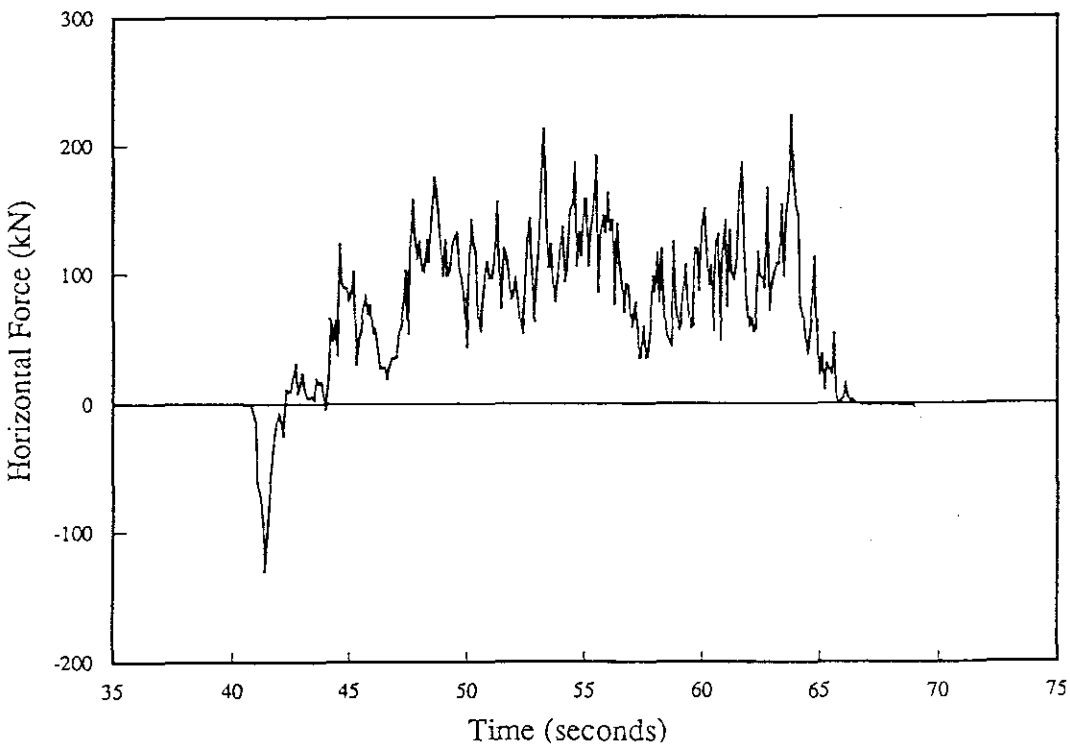

Fig 8: Horizontal forces measured on instrumented full scale bulldozer.

Analysis of the results showed that the force on the tyne was proportional to the square of the depth, that the angle of the tyne significantly affected the forces, that the first runs in any area had significantly higher forces than the following runs, and that in closely jointed rock there was no significant difference in force with different orientation of the ripping runs.

The variation of force with unconfined compressive strength was not tested but the peak forces from ripping in massive sandstone with a UCS of 35 to 47 MPa were significantly higher than those for ripping in closely jointed and layered siltstone with a UCS of 53 MPa. The average forces on the tyne for ripping in both these areas were similar.

10 COMPARISON OF OTHER PREDICTION METHODS USING FIELD DATA

The field data collected during the research project was used to compare prediction methods proposed by other authors. Most of the prediction methods predict rippability using descriptive terms such as easy ripping or hard ripping rather than in terms of productivity. A general relationship between the ease of ripping and productivity as measured in this research project has been adopted as below although it should be noted that these boundaries are not clearly defined.

PRODUCTIVITY (m^3/hr)	EASE OF RIPPING
0 - 250	Very difficult
250 - 750	Difficult
750 - 1500	Medium
1500 - 3000	Easy
3000 - 7000	Very easy

Comparisons were made with all of the well known methods for predicting rippability as well as some of the less well known methods using the field data collected during this project. The results show that none of the methods is significantly better than the others with very poor correlation coefficients as listed below. In fact better correlations can be obtained by using solely measured UCS results for each site, or the seismic velocity.

PREDICTION METHOD	CORRELATION COEFFICIENT R^2 WITH MEASURED PRODUCTIVITY
Franklin	0.196
Weaver	0.102
Smith 1986	0.083
Smith 1987	0.150
Minty & Kearns	0.170
Kirsten	0.185
Scoble & Muftuoglu	0.234
Singh, Denby & Egretli	0.254
Hadjigeorgiou & Scoble	0.044
UCS	0.32
Seismic Velocity	0.32
Prediction equation based on statistical analysis of data from this research	0.58

Comparisons of the measured productivities with predictions based on Weaver's rating system and Kirsten's rating system are shown in Figures 9a and 9b.

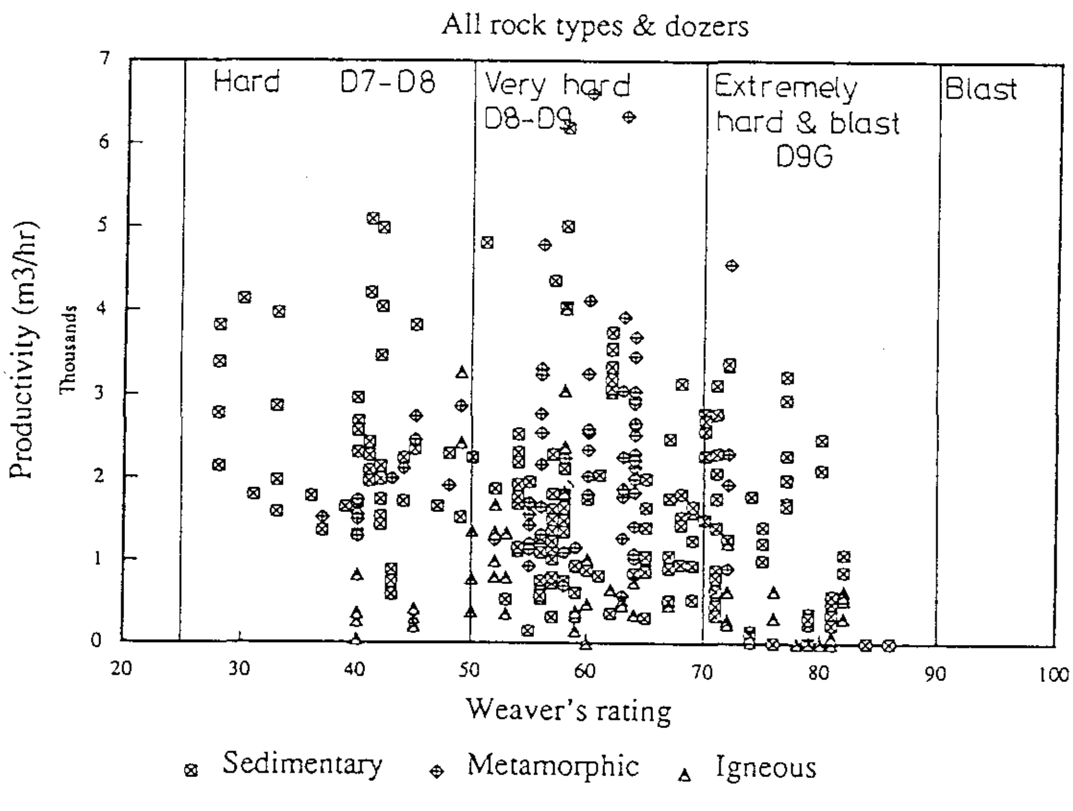

Figure 9a: Measured productivity compared to Weaver's rating.

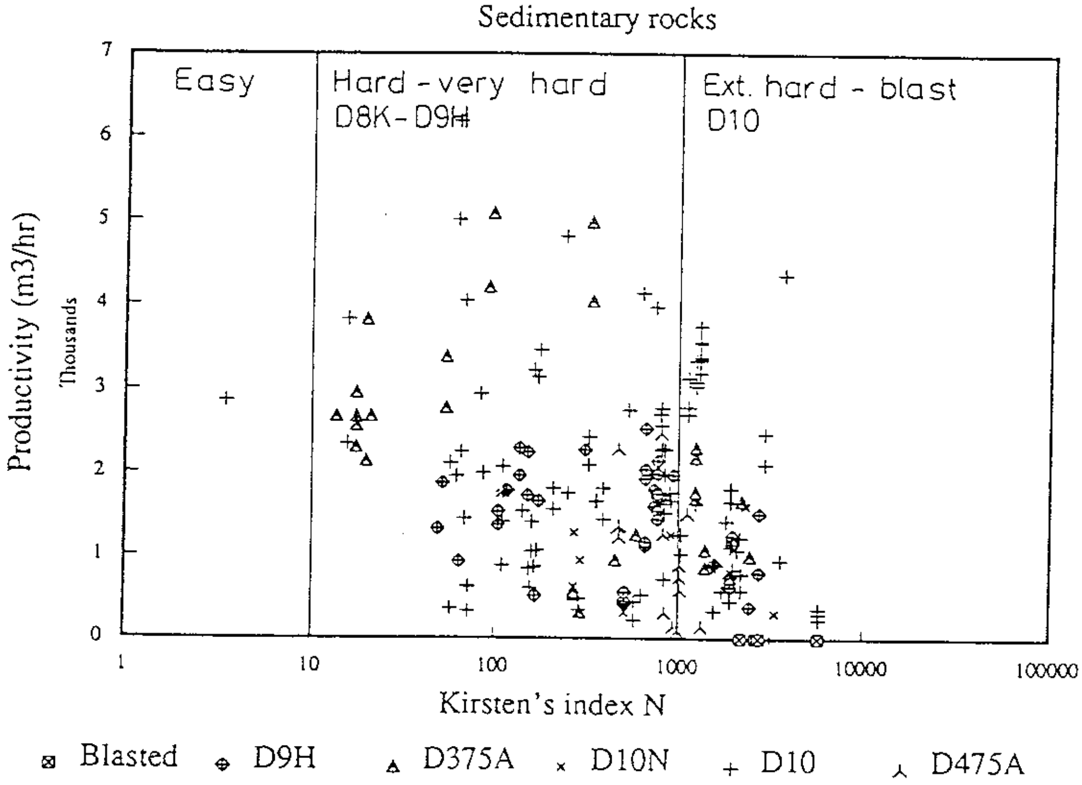

Fig 9b: Measured productivity compared to Kirsten's Index.

11 ANALYSIS OF RESULTS AND RECOMMENDED METHOD FOR PREDICTING PRODUCTIVITY OF RIPPING

The results of each section of the research project were summarised and compared.

Comparison of the results from the laboratory modelling and the field bulldozer trials showed that the direct scaling of forces from one to another was not possible due to differences in speed, UCS and geological and operational variations, but there was a clear correlation between the forces acting on the tyne during ripping and each of depth and UCS. In each case the relationship seemed to be parabolic. The relationship between force and depth is shown in Figure 10.

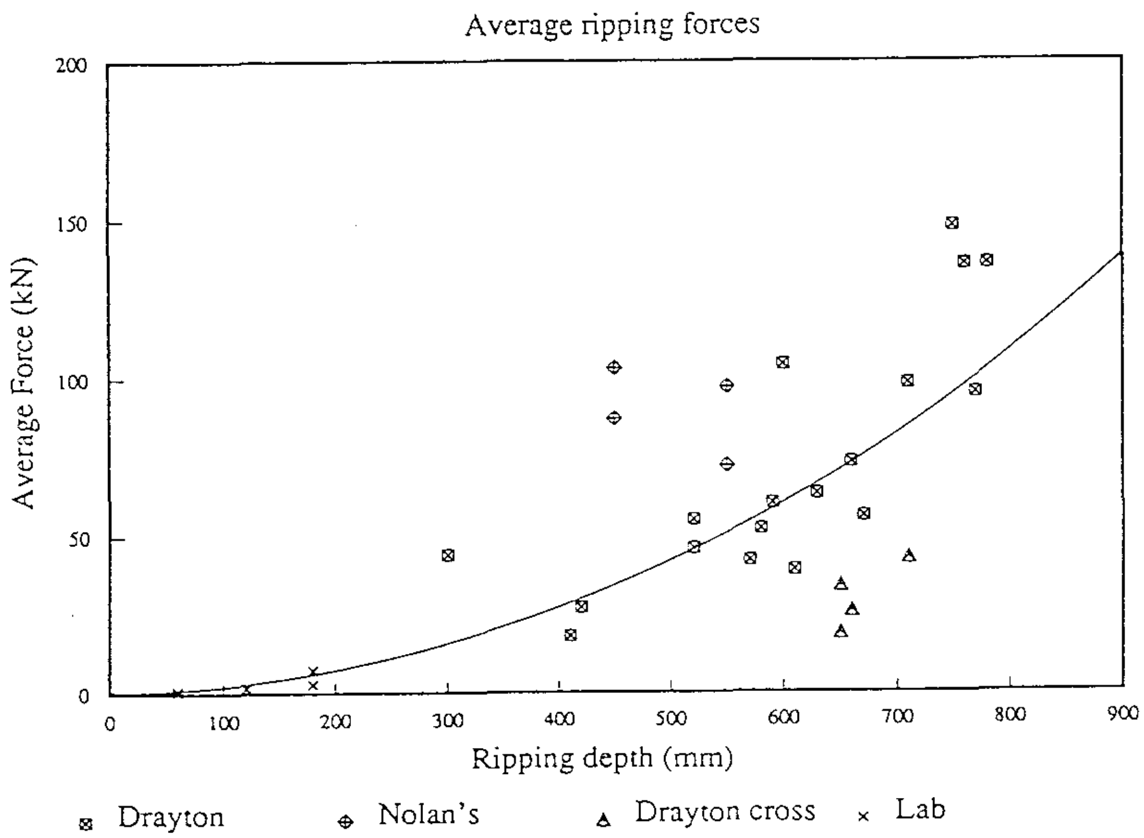

Fig 10: Average force versus ripping depth from full scale trials and laboratory scale modelling.

Using an equation obtained for the relationship between the peak ripping force and UCS from the laboratory tests, and assuming that the ripping trial performed in massive sandstone was near the limit of ripping, estimates were made for the upper limits of UCS for penetration and ripping in unjointed sandstone.

Equations for predicting the likely productivity on a site are given, but it is emphasised that a good knowledge of the geological conditions present on a site is probably the most important factor for predicting rippability and any local knowledge of ripping in similar geological environments must be given great importance in any assessment. The equations assume that the bulldozers will be in good condition and driven by skilled operators. The use of poor equipment and unskilled operators may lead to very significant reductions in productivity.

The productivities calculated from the equations are estimates of the volume of previously undisturbed rock which is loosened during ripping, assuming that the ripper tyne is in the ground 100% of the time. These productivities can be converted to overall project productivities by assessing the amount of time the bulldozer will spend reversing, turning, dozing, pushing scrapers, undergoing maintenance or standing idle. Whether or not these productivities are economic or not will depend entirely on the economic factors influencing each project and should be individually determined.

The equations for predicting productivity are based on analysis of a large data base with over 500 sets of detailed data relating measured bulldozer productivity with the geology of the specific area being ripped. This data base is significantly larger and more detailed than any other published data. The estimation of productivity also gives a more objective comparison of ripping than the existing methods of assessing rippability.

12. REFERENCES

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