

A NON-DESTRUCTIVE METHOD OF DETERMINING ROCK STRENGTH

ROBERT J. ALLISON

Department of Geography, University of Durham, Durham, DH1 3LE, U.K.

Received 4 September 1987

Revised 4 March 1988

ABSTRACT

Rock material strength is an important component of many geomorphological studies. Current methods for determining this parameter result in sample destruction, preventing further analysis. A new non-destructive technique is described for indirectly determining material strength, by measuring Dynamic Young's Modulus. Tests have been conducted on Jurassic Portland Limestone and Upper Cretaceous Chalk to assess the apparatus. Young's Modulus is becoming an increasingly important rock material property.

KEY WORDS Rock strength Dynamic Young's Modulus

INTRODUCTION

Rock strength is an important material property of any geotechnical survey. It forms a component of many investigations where the relationships between rock characteristics and landform morphology are assessed (Cooks, 1979, 1981, 1983; Day, 1981, for example). A particularly fine example of this is the study of rock slopes by geomorphologists which, since the work of Terzaghi in 1962, has become increasingly focused on rock mechanics theory and rock mass properties as controls on morphology. Previous work, by Johnson and Walthall (1979) for example, emphasizes the importance of gathering detailed geotechnical data, stating that without such information results are incomplete and somewhat speculative. In addition, rock strength is a parameter required in slope stability analysis and it is also a standard component of rock mass strength classifications (Moon, 1986; Selby, 1980, 1982). Perhaps most significantly, although parameters such as rock strength provide a link between the extremes of geomorphological mapping on the one hand and the detailed quantitative and geotechnical investigation of natural landforms on the other there is, as Whalley (1984) notes, still need for a geomorphological understanding of rock slopes in terms of engineering behaviour.

A major problem associated with measuring rock compressive strength is that standard techniques result in sample destruction. It is consequently impossible to retest specimens and eliminate variations arising from using different samples, when further analysis is required. There is also evidence to suggest that material strength is not necessarily the best single indicator of rock competence or resistance to erosion. As Attewell and Farmer (1976) note, material strength is almost certainly too simple a criterion to define the reaction of intact rock to external forces. A more adequate description can be obtained by considering variables such as rock elastic properties. Dynamic Young's Modulus is such a parameter.

The Grindosonic apparatus can be used to determine the Dynamic Young's Modulus of a material and hence indirectly assess rock strength. This is a non-destructive technique and as such two advantages can be immediately identified. First, the results for individual samples can be corroborated by repeated analysis

under constant conditions. Secondly, the controlled conditions of a laboratory testing program can be varied and samples reexamined, to identify consequent changes in material characteristics.

Results are presented here for tests which have been conducted on the Jurassic Portland Limestone and Upper Cretaceous Chalk. A laboratory program was designed to assess the accuracy and potential application of the ultrasonic Grindosonic apparatus to geomorphological studies. This included a program of testing using the new equipment and sample analysis by Triaxial Hoek Cell, permitting the direct comparison of ultrasonic Dynamic Young's Modulus results with similar data obtained using an established technique.

TECHNIQUE

The non-destructive test apparatus utilizes the principle that elasticity theory can be applied to rock materials by directly measuring the fundamental vibration frequency of a rock sample of regular dimensions following shock excitation. The measurement of elastic material properties can be related to rock hardness and strength and as Cooks (1983) notes, elasticity may be the single most important factor in determining the behaviour of rock when subject to the process of weathering. Modulus of elasticity is thus perhaps the single most important geotechnical material property to the geomorphologist.

The equipment used in this study, an example of ultrasonic pulse velocity testing equipment (Neville, 1981), analyses the transient vibration pattern of a rock specimen. Samples are struck to set up a mechanical vibration pattern, rather than being subject to continuous flexure. The vibration pattern is converted into an electronic signal via either a piezoelectric detector held in contact with the test piece or a microphone placed directly beneath the sample. The signal is amplified by the apparatus before being fed to the instrument input. If the signal exceeds a predetermined minimum level required for analysis, the time of eight wave passes is measured. A short interval between striking the sample and measurement prevents the analysis of initial spurious wave patterns which have complex harmonics and occur when the test piece is initially struck. The lapsed time appears as a result in the equipment display panel and is known as the 'r' value.

Any vibrating sample will experience damping relative to its elastic properties. The decay of a vibration pattern set up in a hard rigid test piece will take much longer than the same flexure in soft material of similar geometry and dimensions. The result given by the apparatus thus constitutes a direct measure of sample rigidity or hardness. The natural frequency of vibration of any sample is determined by specimen shape, weight and density. By utilizing these details together with the relevant 'r' value, Young's Modulus of Elasticity can be determined.

FIELD SAMPLING AND LABORATORY TESTING

The blocks of rock extracted at each location were removed along intersecting discontinuities using a hammer and chisel. The orientation of each piece was recorded to permit specimen preparation and testing relative to field disposition. At least three test pieces were prepared from two blocks extracted at each point, providing a minimum six samples per site. Before test pieces were cut the weathering rind was removed to eliminate the effects of surface strength reductions.

Upper Cretaceous Chalk and Jurassic Portland Limestone of the Isle of Purbeck, central southern England, were chosen for analysis for a number of reasons. The outcrops both lie within the same structural unit, the Purbeck Monocline, which trends east to west, runs at a slightly oblique angle to the coast, and has a gentle plunge to the east (Burton, 1937). Both rock units are carbonate based sediments with a large number of accessible outcrops throughout the Isle of Purbeck. Despite this similarity, there are marked differences between the two materials. Portland Limestone is a bioturbated, hard, crystalline shelly limestone (Arkell, 1947) while the Chalk in Purbeck comprises a series of bioturbated, white and grey limestones (Kennedy and Garrison, 1975). Topographic changes conform to both lithological and structural variations (Jones *et al.*, 1983), while the morphological characteristics of the coastal cliffs suggest that there are significant changes in material geotechnical properties.

Test pieces to be used with the ultrasonic apparatus can be cut to a variety of shapes including bars, cylinders, and discs. There are, however, nominal limits for sample dimensions. For this study bar shaped

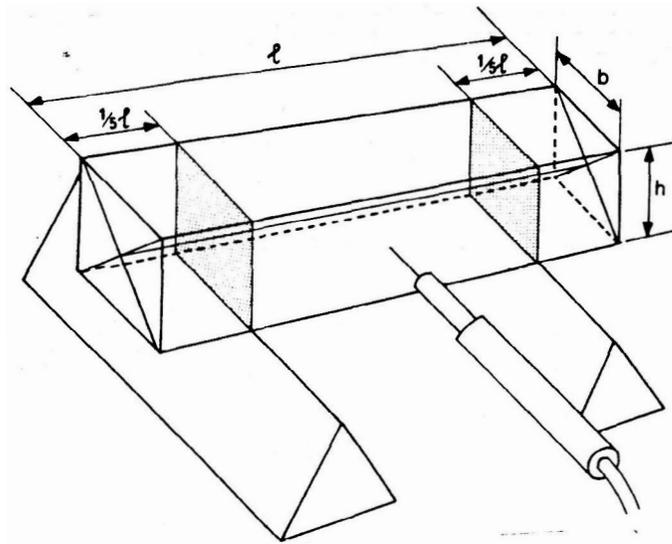


Figure 1. Fundamental flexural vibration and test constraints for Grindosonic ultrasonic test samples

specimens were prepared. These must have a length to thickness ratio of more than three and the width of the bar should be less than one third the length (Figure 1). Beyond these limits the calculations gradually lose accuracy. Test pieces were cut in the same direction relative to bedding and machine ground to minimize variations in cross-sectional area and non-square edges. Both cause significant changes in the vibration pattern. Once prepared the samples were washed, dried at 60°C to constant weight, and left to cool in a desiccator. Tests were conducted with samples resting on a foam rubber mat. The piezoelectric detector was held in contact with the sample in the centre of one of the side faces and the top of each bar was struck at its central point using a thin glass rod. Twenty 'r' tests were conducted on each sample. The results seldom varied by more than ± 0.5 per cent. The mean 'r' value was used with details of sample mass and geometry to determine Dynamic Young's Modulus.

Triaxial Hoek Cell specimens were prepared to a diameter of 38 mm using a diamond edged coring bit. Sample ends were ground to a tolerance of ± 0.1 per cent and testing was conducted at confining pressures (σ_3) of 15 MN m⁻², 30 MN m⁻², and 60 MN m⁻². Standard test procedure was adopted (Brown, 1981). The axial load was applied incrementally via a hand pump normally used for bleeding the cell of air. This permitted a close analysis of stress-strain relationships, since readings of the latter could be taken at small constant increments of the former. Results are presented as graphs of deviator stress ($\sigma_1 - \sigma_3$) against axial strain ($\Delta l - l_0$) and values of stress at failure are drawn as Mohr's Circles.

RESULTS

Tests on Chalk

Dynamic Young's Modulus values for the Chalk derived from ultrasonic tests on oven dried samples show considerable variation, ranging from 52.53×10^6 kN m⁻² to 30.12×10^6 kN m⁻² (Table I). A spatial trend can be seen in the data, with a reduction in Modulus values from north to south across the Chalk outcrop. These changes can be related to the regional structure and in particular the change from steeply dipping to flat lying material in the different limbs of the Purbeck Monocline. The Chalk at Studland has a Dynamic Young's Modulus of 36.92×10^6 kN m⁻² and exhibits a shallow dip of 10°N, while Stonehill Down Chalk has a Dynamic Young's Modulus of 44.09×10^6 kN m⁻² and a steep dip angle of 85°N, for example.

Table I. Grindosonic results for Chalk

Sample Site	Dry Dynamic Young's Modulus (10^6 kN m^{-2})	Saturated Dynamic Young's Modulus (10^6 kN m^{-2})	Modulus Change (10^6 kN m^{-2})
Studland	36.92	27.01	-9.91
Ballard Down	42.88	30.15	-12.73
Ullwell	52.53	46.28	-6.25
Currendon Farm	31.84	6.40	-25.44
Stonehill Down	44.09	42.01	-2.08
Arish Mell	48.05	44.07	-3.95
Lulworth Cove	37.58	24.10	-13.57
St. Oswalds Bay	30.12	28.82	-1.30

Triaxial Hoek Cell compressive strength results, represented by Mohr's Circles of Stress (Vickers, 1983; Lambe and Whitman, 1979), show similar trends to Dynamic Young's Modulus values (Figure 2). Studland Bay Chalk has a yield strength of 14 MPa at 60 MPa confining pressure, while Stonehill Down Chalk has a yield strength of 123 MPa at 60 MPa confining pressure, for example. The failure envelope for each set of tests provides details of the mechanical characteristics of the rock. There is a distinct difference in the envelope curve of those Chalk samples displaying high and low Dynamic Young's Modulus values. At Stonehill Down the envelope is characteristic of brittle failure with little sample deformation before the yield strength is exceeded. Conversely, the samples from Studland Bay have envelope curves which illustrate ductile failure.

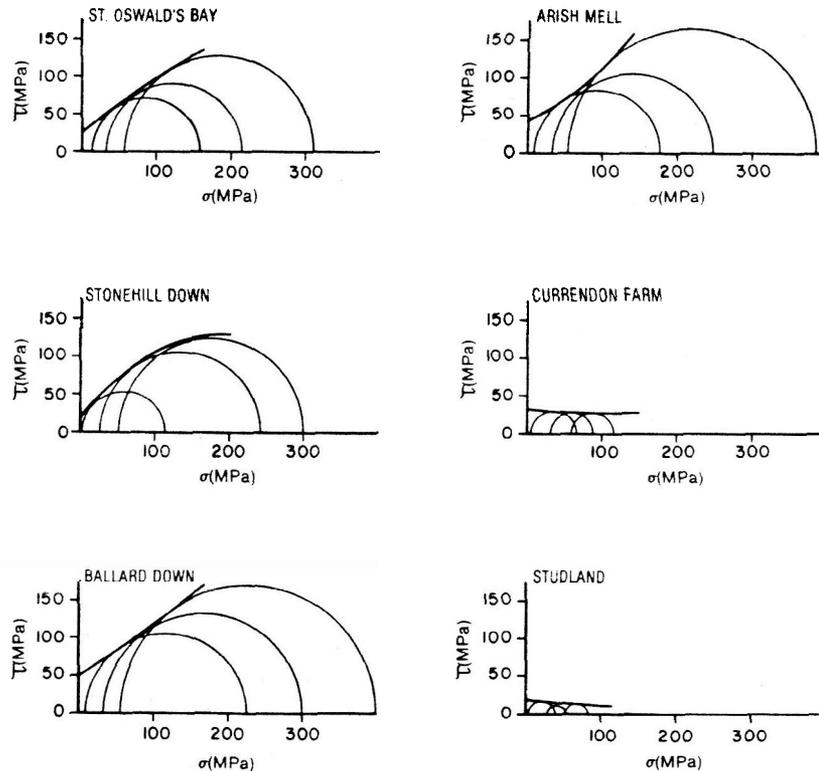


Figure 2. Triaxial Hoek Cell compressive strength data for Chalk

This was confirmed by the barrelling of specimens during testing. It can thus be inferred that the material displaying low Dynamic Young's Modulus values can distort without actually failing. Also material with high Modulus values is more highly consolidated, stronger, and has a greater resistance to weathering and mass failure than material exhibiting ductile failure, which is weaker.

Tests on Portland Limestone

As with the Chalk, the Portland Limestone shows a range of Dynamic Young's Modulus values, suggesting that material strength and resistance to erosion varies for this rock material (Table II). A broad east to west decrease in Modulus values can be defined, although this effectively highlights a change in material properties across the Purbeck Monocline from north to south, since different parts of the structure crop out along the coast. This variation is confirmed by the Triaxial Hoek Cell data. The results fall into four groups (Figure 3). The Portland Limestone at Durdle Door exhibits the highest compressive strength, being the only location where yield strength at 60 MPa confining pressure exceeds 150 MPa. Stair Hole, Lulworth Cove, Worbarrow Tout, and Emmett's Hill results all form a second group, with high yield strengths between 145–150 MPa at 60 MPa confining pressure. Thirdly, yield strengths between 100–125 MPa at 60 MPa confining pressure occur at Fossil Forest, Bacon Hole, Pondfield, Seacombe, and Tillywhim. Finally, at Winspit and Kimmeridge, yield strength at 60 MPa confining pressure is less than 100 MPa.

The Dynamic Young's Modulus and compressive strength results for the Portland Limestone again mirror the data for the Chalk in as much as the spatial changes can be linked to the regional structure. At Durdle Door bedding dips at almost 90° and the rock material has a Dynamic Young's Modulus of $59.23 \times 10^6 \text{ kN m}^{-2}$. At Bacon Hole where bedding dips at 32°N the Dynamic Young's Modulus is $46.63 \times 10^6 \text{ kN m}^{-2}$ and at Seacombe, where bedding is almost horizontal, the Dynamic Young's Modulus is $40.82 \times 10^6 \text{ kN m}^{-2}$.

Correlation of test results

Of greatest importance to this study is the correlation of yield strength data against Dynamic Young's Modulus values, since this confirms the use of the ultrasonic apparatus as a technique for studying material strength characteristics. The results from the individual tests already suggest a close association between these data and the trends have highlighted spatial associations between the measured material characteristics and regional structure. There are clear linear relationships for both rock types. A correlation between Dynamic Young's Modulus and sample yield strength at 60 MPa shows strong associations of $r=0.99$ for Chalk and $r=0.92$ for Portland Limestone. Perhaps more significantly, both sets of data lie on the same regression line

Table II. Grindosonic results for Portland Limestone

Sample Site	Dry Dynamic Young's Modulus (10^6 kN m^{-2})	Saturated Dynamic Young's Modulus (10^6 kN m^{-2})	Modulus Change (10^6 kN m^{-2})
Tillywhim	56.97	55.16	-1.81
Seacombe	40.82	33.17	-7.65
Winspit	39.78	33.51	-6.27
Emmetts Hill	79.38	76.46	-2.92
Kimmeridge	40.80	38.09	-2.71
Pondfield	43.72	38.70	-5.02
Worbarrow Tout	58.16	54.79	-3.37
Bacon Hole	46.63	39.67	-6.96
Fossil Forest	53.09	48.18	-4.91
Lulworth Cove	61.90	56.94	-4.96
Stair Hole	51.35	51.38	+0.03
Durdle Door	59.23	46.95	-12.28

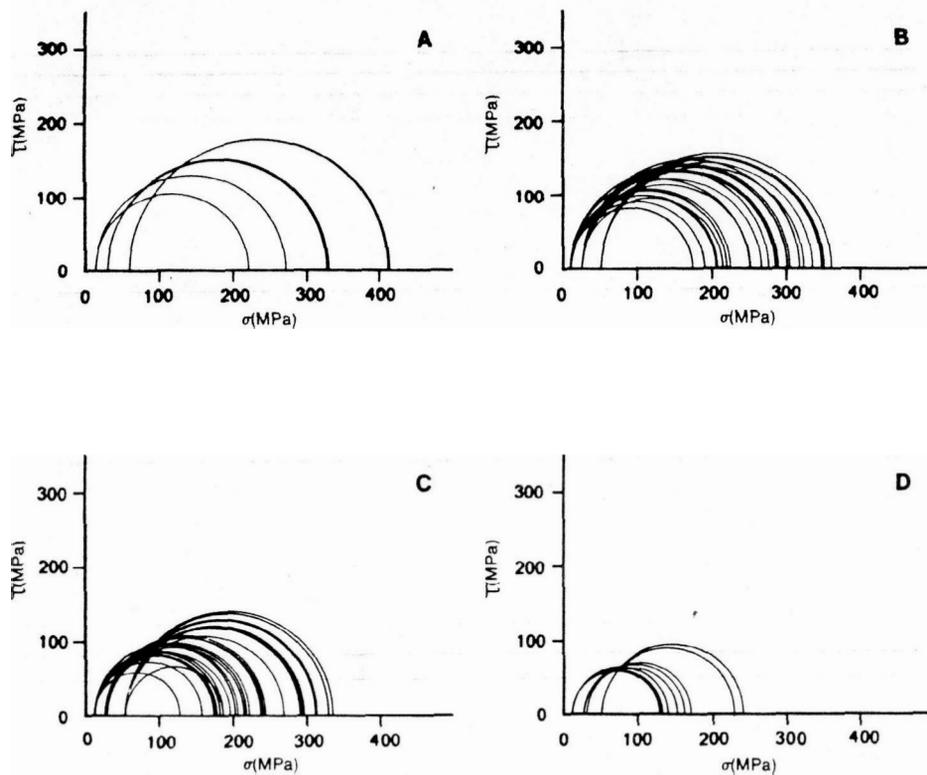


Figure 3. Triaxial Hoek Cell compressive strength data for Portland Limestone. A: Durdle Door; B: Stair Hole; Lulworth Cove; Worbarrow Tout; Emmetts' Hill; C: Fossil Forest; Bacon Hole; Pondfield; Seacombe; Tillywhim; D: Winspit; Kimmeridge

(Figure 4), with a correlation of $r=0.98$. A linear relationship between Dynamic Young's Modulus and yield strength can therefore be defined for the materials:

$$\sigma = cEd \quad (\text{EQ1})$$

where:

$$\begin{aligned} \sigma &= \text{compressive strength} \\ c &= \text{constant} = 6.505 \\ Ed &= \text{Dynamic Young's Modulus} \end{aligned}$$

This is a more fundamental relationship, suggesting that the association between Dynamic Young's Modulus and compressive strength may be similar for a variety of carbonate based sedimentary rocks. There is thus good support for using Dynamic Young's Modulus values calculated using this type of apparatus as a measure of rock material strength and strength related parameters.

The results are significant in a number of respects. It is clear that Dynamic Young's Modulus can be considered a direct measure of material strength, rigidity, and hardness. Perhaps more importantly, the ultrasonic pulse velocity testing apparatus is a useful tool for calculating Dynamic Young's Modulus of Elasticity and since tests can be repeated on the same specimens, studies can be made of those environmental parameters which affect the rock properties. A preliminary investigation of this nature was conducted by saturating the ultrasonic samples under vacuum to constant weight (Carter and Matthews, 1977). Retesting was then undertaken to examine the effects of water saturation on material strength. This is particularly relevant to this study, since many of the coastal cliffs plunge directly into the sea and saturation of material below sea level is likely to reduce the overall stability of the slope.

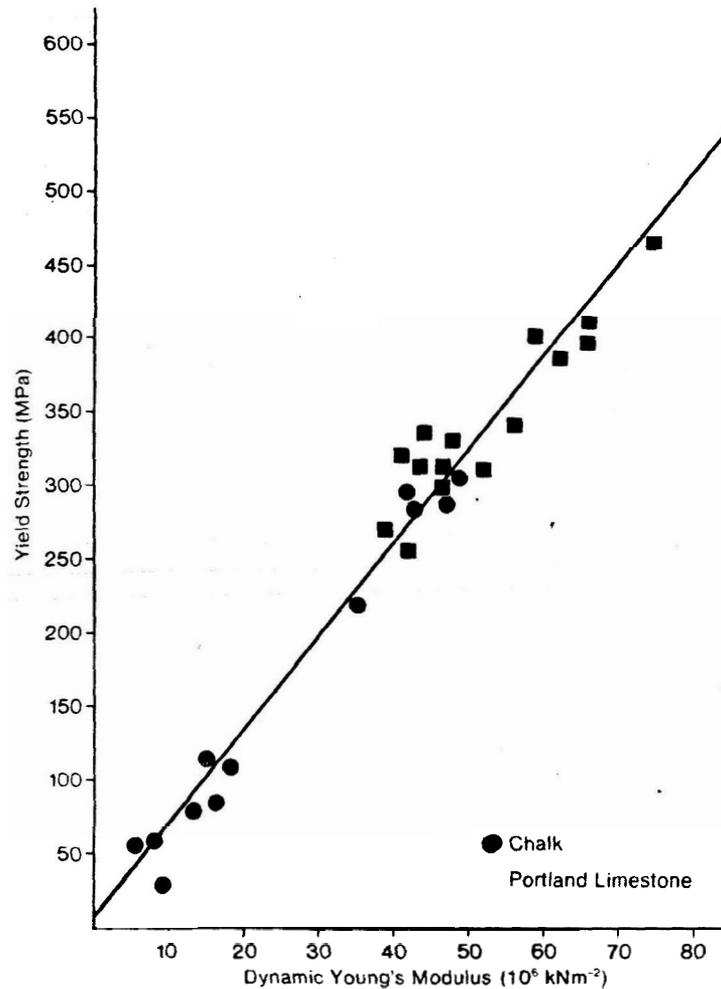


Figure 4. Relationship between Grindosonic Dynamic Young's Modulus and Triaxial Hoek Cell yield strength at 60 MPa

Chalk samples show a decrease in Dynamic Young's Modulus upon saturation (Table I). This drop in values is not uniform, although it does generally remain the case that those cliffs which display the highest material strength under dry conditions remain the most competent under saturation. All but one of the Portland Limestone test pieces also show a decrease in Dynamic Young's Modulus on saturation (Table II). These identified changes in the results serve to illustrate the advantages of this test technique. Thus it seems evident that not only should Dynamic Young's Modulus receive careful consideration in landform analysis but also that the ultrasonic apparatus is a suitable technique for determining this parameter.

CONCLUSION

It seems clear that there is scope for the application of ultrasonic pulse velocity testing apparatus in geomorphological research. The Grindosonic ultrasonic pulse velocity testing apparatus has been successfully tested here. Dynamic Young's Modulus, a measure of material strength, can be calculated by a non-destructive technique, which allows multiple testing under different controlled conditions. Tests conducted on Portland Limestone and Chalk samples, using the ultrasonic apparatus, correlate well with data obtained

using the standard Triaxial Hoek Cell. Indeed it appears that Dynamic Young's Modulus of Elasticity should form a significant part of any geotechnical investigation into the properties of rock materials.

ACKNOWLEDGEMENTS

The research was commenced while in receipt of a NERC research studentship and is being continued with funding from the Addison Wheeler Fellowship, University of Durham. The author expresses his thanks to Professor D. Brunsten for valuable discussions during the course of this work. The figures were kindly prepared by the staff of the Drawing Office, Department of Geography, University of Durham.

REFERENCES

- Arkell, W. J. 1947. *The Geology of the Country Around Weymouth, Swanage, Corfe and Lulworth*, H.M.S.O., London, 385 pp.
- Attewell, P. B. and Farmer, I. W. 1976. *Principles of Engineering Geology*, Chapman and Hall, London, 1045 pp.
- Brown, E. T. 1981. *Rock Characterisation, Testing and Monitoring*, Pergamon, Oxford, 211 pp.
- Burton, E. St. J. 1937. 'The origin of Lulworth Cove, Dorsetshire', *Geological Magazine*, **74**, 337-383.
- Carter, D. J. and Matthews, A. P. 1977. 'The measurement of porosity of irregular vulgar shaped rock samples using a modified liquid saturation technique', *Geotechnique*, **27**, 435-437.
- Cooks, J. 1979. 'Die verband tussen lithologie en landvorme', *South African Geographer*, **7**, 125-135.
- Cooks, J. 1981. 'Rock quality measured by seismic wave velocity as a factor in landform development', *South African Journal of Science*, **77**, 517-521.
- Cooks, J. 1983. 'Geomorphic response to rock strength and elasticity', *Zeitschrift für Geomorphologie*, **27**, 483-493.
- Day, M. J. 1981. 'Rock hardness and landform development in the Gunong Mulu National Park, Sarawak, Eastern Malaysia', *Earth Surface Processes and Landforms*, **6**, 165-172.
- Johnson, R. H. and Walthall, S. 1979. 'The Longdendale landslides', *Geological Journal*, **14**, 135-138.
- Jones, M. E., Allison, R. J., and Gilligan, J. 1983. 'On the relationships between geology and coastal landforms in central southern England', *Proceedings Dorset Natural History and Archaeology Society*, **105**, 107-118.
- Kennedy, W. J. and Garrison, R. E. 1975. 'Morphology and genesis of nodular Chalks and hardgrounds in the Upper Cretaceous of southern Europe', *Sedimentology*, **22**, 311-386.
- Lambe, T. W. and Whitman, R. V. 1979. *Soil Mechanics, S. I. version*, Wiley, New York, 553 pp.
- Moon, B. P. 1986. 'Controls on the form and development of rock slopes in fold terrain'. in Abrahams, A. D. (Ed.), *Hillslope Processes*, 225-243.
- Neville, A. M. 1981. *Properties of Concrete*, Pitman, London, 779 pp.
- Selby, M. J. 1980. 'A rock mass strength classification for geomorphological purposes: with tests from Antarctica and New Zealand', *Zeitschrift für Geomorphologie*, **24**, 31-51.
- Selby, M. J. 1982. 'Rock mass strength and the form of some inselbergs in the central Namib Desert', *Earth Surface Processes and Landforms*, **7**, 489-497.
- Vickers, B. 1983. *Laboratory work in soil mechanics*, Granada, London, p. 170.
- Whalley, W. B. 1984. 'Rockfalls', in Brunsten, D. and Prior, D. B. (Eds), *Slope Instability*, 217-256.

NOTE A number of different types of ultrasonic pulse velocity apparatus are commercially available. Further information on the Grindosonic technique, used in this study, can be obtained from the manufacturers: J. W. Lemmens-Elektronika N. V., Research Park B-3044, Leuven-Haasrode, Belgium.