Scale Effects in Rock Masses 93, Pinto da Cunha (ed.) © 1993 Balkema, Rotterdam, ISBN 90 5410 322 1

On the effect of block size on the shear behaviour of jointed rock masses

A.A.Al-Harthi & S.R.Hencher
Department of Earth Sciences, University of Leeds, UK

ABSTRACT: Conflicting predictions of the influence of block size on rock mass shear behaviour are reviewed. It is concluded that block size (scaled) is not, by itself, a parameter that can be used to predict behaviour. Other factors such as the potential failure mechanisms will influence mass strength.
A systematic study is reported in which the behaviour of jointed physical and numerical models of three different block sizes are compared. Variables include joint orientation, joint pattern and surface roughness (itself variously scaled). All models relate to failure into an underground opening.
It is demonstrated that failure mechanisms are quite different for rock masses of different scaled block sizes. Conclusions are drawn relating the influence of block size to strength for given joint network configurations and to stand up time.

1 INTRODUCTION

Many of the factors controlling shear strength and deformation of rock masses are still poorly understood. Nevertheless, it is clear that block size is one of the most important factors controlling rock mass behaviour. In the case of underground construction for example, rock masses comprising larger blocks tend to be less deformable than more closely jointed rock and develop favourable arching and interlocking. Block size can be described either in terms of the average dimension of typical blocks or by the total number of discontinuities intersecting a unit volume of the rock mass. The descriptive terms are given by Brown (1981).

2 STRENGTH OF JOINTED ROCK MASS

Strength and deformability of rock masses have been investigated in the laboratory by many researchers, including Brown (1970), Ladanyi and Archambault (1970), Einstein and Hirschfeld (1973), Barton and Hansteen (1979) and Barton and Bandis (1982). Results from laboratory studies using models show that many different failure modes are possible in jointed rock and that the internal distribution of stresses and the failure mechanisms can be highly complex.

A few in-situ tests have been carried out to study the effect of size on rock mass compressive strength (Bieniawski and Heerden, 1975) and on rock mass modulus (Bieniawski, 1978) and Heuze (1980) reviewed work to that date. These investigations indicated a reduction in rock mass strength and modulus with increasing size up to a certain size above which scale is apparently insignificant. It is important to note that the derived relationships are highly site-dependent, since the scale effect is primarily governed by the local fracture network.

The studies of Barton and Hansteen (1979), Hoek and Brown (1980 and 1988), Barton and Bandis (1982), and Hoek et al., (1992) have apparently conflicting conclusions regarding the influence of block size on the strength and deformability of jointed rock masses. The empirical failure criterion, developed by Hoek and Brown (1980) and then modified by Hoek et al., (1992) is based in part on the consideration that strength and deformability rock masses increase with increasing block size.

Barton and Bandis (1982) carried out biaxial loading tests on models comprising various block sizes but separated by discontinuities consistently formed by a method of tensile fracturing and therefore of similar roughness. The models failed by shear along discontinuities together with slight block rotation and it was found that the models of smaller block size had the highest shear strength.

This paper describes a series of tests designed to investigate the mechanisms controlling behaviour of closely jointed rock masses with the aims of explaining the apparent discrepancy between the results of previous workers.

3 PHYSICAL AND NUMERICAL MODELLING

A systematic study of the influence of block size on the rock mass behaviour during failure into an underground opening has been carried out by base friction modelling and numerical modelling, (UDEC-BB). The behaviour of rock masses comprising three different block sizes have been investigated whilst varying factors such as joint pattern and surface roughness.

A rectangular opening shape of 200 mm width (representing a 20 m wide opening in the prototype) was selected so that the influence of parameters such as block size, joint orientation, and roughness angle could be observed easily.

3.1 Base friction modelling

The use of base friction modelling for simulating rock mechanics problems, the development of a new modelling material, the modification of scaling criteria, and the use of new techniques for simulating rough discontinuities in physical modelling as employed are discussed and reviewed by Al-Harthi and Hencher (1992).

More than 100 simple physical models with two sets of joints dipping at a constant angle, but in opposite directions have been constructed. Models have incorporated different block sizes, discontinuity inclination angles and roughness angles in order to evaluate the influence of these factors on mass behaviour. Strength of the rock mass may be related to the angle of draw (line of minimal disturbance) above the roof of the opening which may be readily measured.

Examples of models of three different block sizes but a constant dip angle of 45° and a constant roughness angle along joints of 10° are presented in Figure 1.

Measured angles of draw from tests on models containing joints with a roughness angle $i=10°$ are presented in Figure 2(a) and for models with planar joints in Figure 2(b). From Figure 2(a), it is apparent that the larger the block size, the higher the angle of draw. Where the dip angle is less than 50° the angle of draw is similar for block sizes of 1 cm and 2 cm, but for 3 cm block size models the angle of draw again is higher due to arching.

In models incorporating joints with planar surfaces the angle of draw is essentially consistent for all block sizes for joints dipping at any particular angle except for the largest block size (3 cm block size) where the dip angle was less than 45°. It was noted that interlocking, arching and the formation of new tension cracks were important mechanisms during the failure of all models formed from the larger blocks.

From Figure 2, it can be concluded that factors other than block size such as joint orientation and roughness will influence failure mechanisms and therefore the rock mass strength and deformability. In general however, it was observed that the larger the block size, the higher the angle of draw no matter what the roughness of the joints. Furthermore, as the roughness angle was increased, the differences between the angles of draw increased. It was also noted that models of small block size needed considerably more time to deform than those comprising larger blocks.

(a)

(b)

(c)

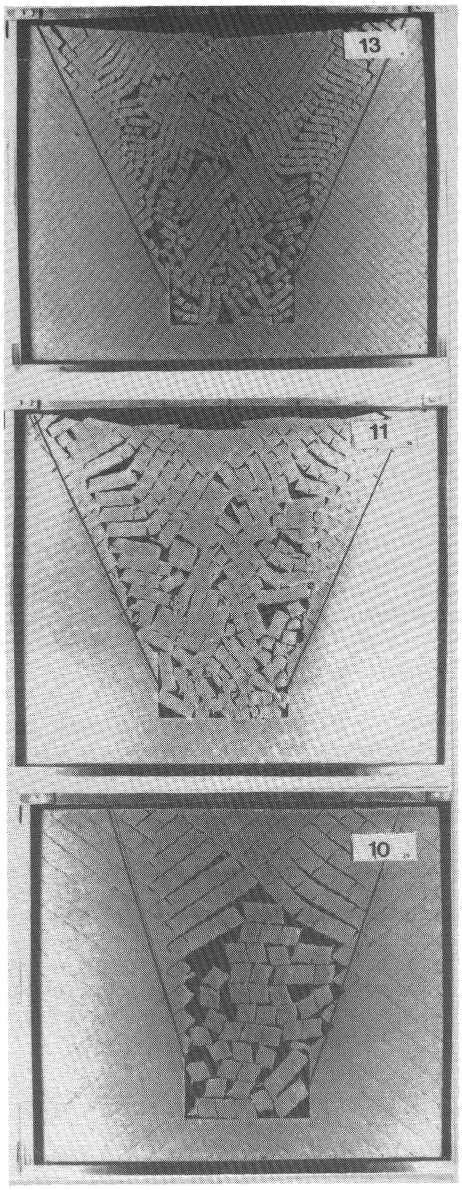
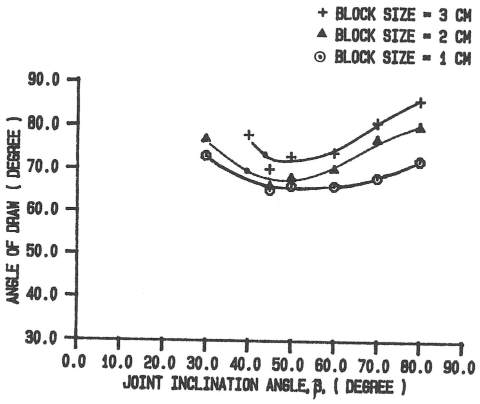
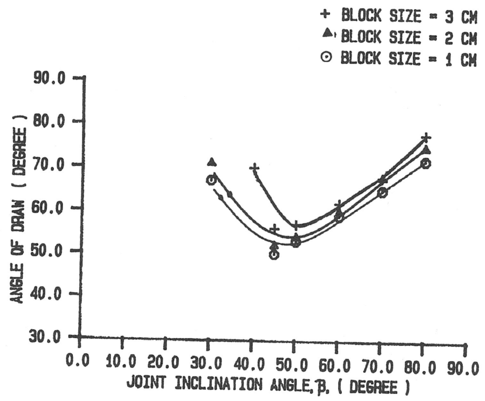


Fig. 1: Base friction models of cross-continuous pattern showing the influence of block size on the angle of draw (where $\beta = 45°$, bs = 1 cm (a), 2 cm (b), and 3 cm (c)



(a) roughness angle = 10°



(b) roughness angle = 0°

Fig. 2: The influence of block size on the angle of draw

It should be noted that the joint roughness angle as defined here represents the angle of deviation of saw teeth of fixed base length from the average discontinuity dip direction. Cutters of base lengths 1 cm and 2 cm were used to investigate the influence of asperity height on behaviour. Examples of results are presented in Figure 3 for joints with a roughness angle of 5° and block size 1 cm. The influence of surface roughness amplitude is shown clearly for joints inclined at between 40° and 60°.

In summary, the results from tests using base friction models indicate that rock masses comprising relatively large blocks are more stable, less deformable and give higher angles of draw than masses of smaller block size.

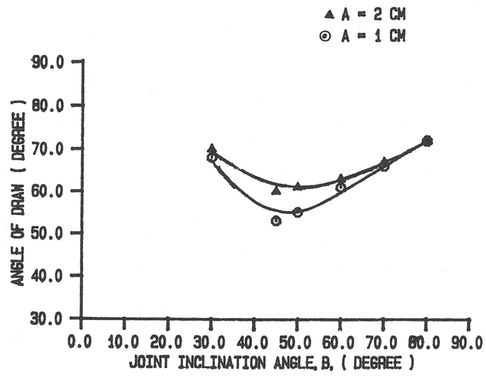


Fig. 3: The influence of roughness amplitude on the angle of draw (where roughness angle (i) = 5° and block size = 1 cm)

In models of small block size, failure generally involves buckling and rotation, whilst in models of larger block sizes, sliding with interlocking is the dominant failure mechanism.

From some models where failure involved simple sliding of single blocks along rough surfaces it was observed that the smaller blocks were more stable than larger blocks possibly due to different dilatant geometries during over-riding and rotation. It was generally observed that models comprising smaller blocks took longer to collapse.

3.2 Numerical modelling (UDEC)

The Distinct Element Method (DEM) is a powerful and versatile numerical method for simulating discontinuum behaviour which was originally developed by Cundall (1971). It is based on relaxation principles and overcomes some of the shortcomings of other numerical methods such as Finite Element and Boundary Element which are suitable for continuum models. In DEM, dynamic and static relaxation techniques are used to solve Newton's laws of motion to determine the forces between, and the displacements of units during the progressive, large scale deformation of discontinua (Cundall, 1971; Hoek et al., 1991; and Itasca, 1992).

The Universal Distinct Element Code (UDEC) employs the Distinct Element Method and follows the early work of Cundall (op cit). The code has undergone continual development since 1971 as outlined by Itasca (1992).

UDEC-BB of version (1.82) has been used to construct models of various block size, joint orientation and roughness in order to evaluate their influences on the rock mass behaviour (e.g. deformability) and on overall stability of underground excavations. Analyses have been carried out on essentially similar models to some of those tested using the base friction technique.

Examples of the results from numerical models carried out to investigate the influence of block size for a constant joint dip of 45°, joint friction angle (ϕ) of 30° and joint roughness coefficient (JRC) of 8 are illustrated in Figure 4. In these examples, block size was the only variable factor.

The preliminary results from numerical models confirm those from the physical models in that models of small block sizes are more deformable and less stable than those of large blocks. The failure mechanisms in models of small blocks mainly involve buckling at the roof and flexural toppling of rows of blocks toward the opening in the sidewalls. In models of larger blocks, sliding and interlocking of blocks dominate the behaviour.

As in the tests on physical models, it was noted that numerical models of small block size required considerably more time to deform than did models of large block size.

4 CONCLUSIONS

Systematic studies using base friction and numerical models of regularly jointed rock masses containing underground openings indicate that closely jointed rock masses are more deformable and give lower angles of draw above the opening roof than those comprising larger block sizes. Behaviour is influenced by joint pattern, orientation and roughness as well as block size.

Buckling and flexural toppling are the dominant modes of failure for models of small blocks, whilst sliding and interlocking are the dominant failure processes for models of large blocks.

Masses comprising smaller blocks require considerably longer for failure mechanisms to develop fully.

It was found that the Barton-Bandis criteria is broadly applicable where sliding is the dominant failure mode in the rock mass, whereas the Hoek-Brown criterion is more suitable for completely jointed rock masses. The application of both criteria are dependent upon the potential failure mechanisms.

Further testing is needed to explore the limiting constraints of scale effects and to evaluate the sensitivity of behaviour to minor changes in modelling, such as joint persistence and continuity.

ACKNOWLEDGEMENTS

The Saudi Arabian Government in particular, King Abdulaziz University, Jeddah, is thanked for their support of A. Al-Harthi during his research at the University of Leeds.

REFERENCES

Al-Harthi, A.A. and Hencher, S.R., 1992. Physical and numerical modelling of underground excavations in dilational rock masses. Pre-prints of 2nd ISRM Conference on Fractured and Jointed Rock Masses, Lake Taho, California, U.S.A.:608-615.

Barton, N., and Hansteen, H., 1979. Very large span openings at shallow depth: deformation magnitudes from jointed models and F. E. analysis. Proc. 4th Rapid Excavation and Tunnelling Conf., Atlanta, 2:1331-1353.

Barton, N. and Bandis, S., 1982. Effect of block size on the shear behaviour of jointed rock (keynote lecture). Proc. 23rd U.S. Symp. on Rock Mechanics, Berkeley, California, Society of Mining Engineers of AIME, :739-760.

Bieniawski, Z.T., 1978. Determining rock mass deformability: experience from case histories. Int. J. Rock Mech. and Min. Sci., 15:237-247.

Bieniawski, Z.T. and Van Heerden, W.L., 1975. The significance of in-situ tests on large rock specimens. Int. J. Rock Mech. and Min. Sci., 12:101-113.

Brown, E.T., 1970. Modes of failure in jointed rock masses. Proc. 2nd Cong. of Int. Soc. Rock Mech., Belgrade, 2:3-42.

Brown, E.T., 1981. Rock characterization, testing and monitoring, ISRM suggested method, Pergamon Press, Oxford, England, 211 p.

Einstein, H.H., and Hirschfeld, R.C., 1973. Model studies on mechanics of jointed rock. J. Soil Mech. and Found. Div., ASCE, 99:229-242.

Heuze, F.E., 1980. Scale effects in the determination of rock mass strength and deformability. Rock Mechanics, 12:167-192.

Hoek, E. and Brown, E.T., 1980. Empirical strength criterion for rock masses. J. Geotech. Engng. Div., ASCE, :1013-1035.

Hoek, E. and Brown, E.T., 1988. The Hoek-Brown failure criterion - 1988 update. Proc. 15th Canadian Rock Mechanics Symposium, :31-38.

Hoek, E., Wood, D. and Shah, S., 1992. A modified Hoek-Brown failure criterion for jointed rock masses, Proc. EUROCK '92 on Rock Characterization, ISRM, Chester, British Geotechnical Society, Paper 37, :209-214.

Itasca, 1992. UDEC - User Manual, Version ICG 1.82, Itasca Consulting Group Inc., Minneapolis, Minnesota, U.S.A.

Ladanyi, B. and Archambault, G., 1970. Simulation of shear behaviour of a jointed rock mass, Proc. of 11th Symp. on Rock Mech., AIME:105-125.

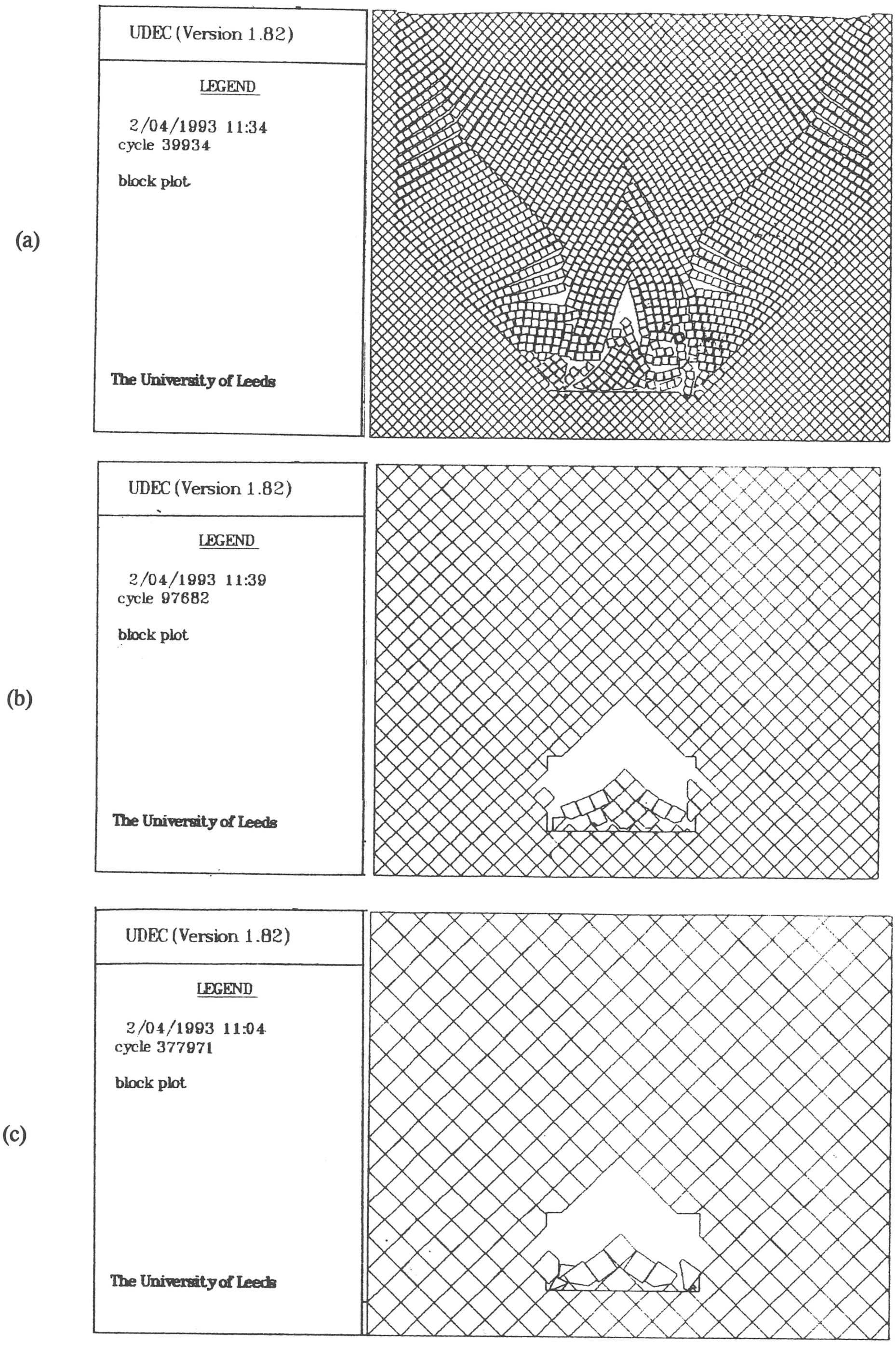


Fig. 4: Numerical models of cross-continuous pattern showing the influence of block size on the deformability and stability of underground opening (where $\beta = 45°$, bs = 1 cm (a), 2 cm (b), and 3 cm (c))