Design of Foundations in Jointed Rock Masses

by
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SUMMARY – A review of laboratory tests on simple block-jointed materials under uniform compressive loading shows the strength of a jointed mass to be considerably less than that of its individual elements. This effect results from non-uniformity of load distribution within the jointed mass which leads to tensile fracture of individual elements and premature collapse of the mass. This mode of failure can be represented by the Brazilian test which is an extreme non-uniform loading condition and as such can be interpreted as the minimum compressive strength of unjointed material. The concept of Brazilian compressive strength, developed to define the lower limit of rock mass strength, has been applied to laboratory tests on jointed foundation models to explain their relatively low strength. The results of large scale foundation loading tests on jointed rocks show that the onset of irrecoverable deformation can be related to fracture initiation in the rock mass. The concept of Brazilian strength leads to a simple design procedure for foundations on jointed rock in which applied loading is restricted to less than that associated with large irrecoverable deformations and fracture of the rock mass.

1 INTRODUCTION

Rock has traditionally been accepted as an almost ideal material upon which structures may be founded.

Although its use in this role is extremely old, there is relatively little factual data available at the present time that will permit the design of rock foundations in a reasonable engineering manner.

Foundations for structures ranging from concrete dams to multi-storey buildings are commonly designed on the basis of presumptive bearing capacity related to rock type and degree of weathering. In the larger city areas where intense development has led to the accumulation of considerable experience supplemented by field tests, local building codes have evolved which apparently provide safe, but simplistic, guidelines for foundations in rock.

The extrapolation of this information to other areas and to other rock types is, however, hindered by the lack of understanding of the mechanics of foundation behaviour in jointed rock.

This paper sets out to review the results of small-scale laboratory testing, theoretical studies concerned with idealized rock masses and data from large scale testing of rock masses in the light of practical engineering requirements related to foundations on rock.

2 STRENGTH OF JOINTED ROCK MASSES

It is widely recognized that an essential feature of rock masses is the presence of discontinuities in the form of bedding planes, joints, fissures or faults which transect the mass resulting in an almost perfectly packed granular material. It is also well known that the strength of a rock mass is, in general, considerably less than that of the individual units of intact rock composing the mass. The reasons for this strength difference are not as yet fully explained due to the complexities associated with the inherently discontinuous nature of rock masses. Traditional engineering concepts, based on continuum theory, are inappropriate for understanding the deformation and collapse behaviour of jointed rock masses.

(a) Testing of Idealized Rock Masses

Over the past decade, research has been carried out to define the strength and deformability of idealized rock masses by means of relatively small scale laboratory tests on simple block-jointed systems composed of rock-like units. The literature is extensive in volume, but tends to be rather narrow in coverage in that simple block models consisting of a variety of artificial materials, e.g. gypsum plaster and plaster-sand mixtures, have been subjected to uniform polyaxial loadings. Brown & Hudson (Ref.1) have produced a comprehensive review of the present state of this work.

The results of several of these laboratory studies are presented in the following discussion to illustrate two factors which are believed to be fundamental characteristics of jointed rock masses. Firstly, that the strength of a rock mass is considerably less than that of its individual intact elements and, secondly, that even when subjected to a compressive boundary loading, collapse of a jointed mass can result from tensile failure of individual units.

(i) Unconfined Compression Tests on Jointed Plaster Models

Brown & Hudson (loc. cit.) have reported the results of unconfined compression testing of block-jointed plaster models in which the behaviour of square and hexagonally jointed systems were compared with that of an unjointed model. Their results are summarized as follows:-

TABLE I
COMPRESSIVE STRENGTH OF PLASTER MODELS

Specimen Type	Average Axial Stress at Peak Load (mPa)	Ratio Jointed to Unjointed Strength	Average Axial Stress for initial cracking (mPa)
Solid	33.5	100%	23.4
Square Jointed	20.9	63%	20.7
Hexagonally Jointed	11.0 19.6	33% 45%	10.2 12.9
Parallelepipedal Jointing	6.4	15%	6.4

In all cases, collapse of jointed models occurred following the formation of tensile fractures within individual blocks of the mass. In none of these tests was failure due to slip along joint planes due to lack of lateral restraint.

(ii) Laboratory Testing of Low-Porosity Aggregate

Rosengren & Jaegar (Ref.2) tested samples of a coarse grained marble which had been cracked on grain boundaries by thermal treatment to form a small scale laboratory model of randomly jointed rock. Their results indicated a strength reduction from 79.2 mPa for uncracked to 15.9 mPa for the cracked material in unconfined compression. Even at confining pressures of several megapascals the strength of cracked specimens was less than 50 percent of the intact material. The tensile strength of intact material was not reported but similar material has a tensile strength of about 9 mPa.

(iii) Testing of Simulated Rock Mass Models

Rosenblad (Ref.3) carried out a series of plane stress tests on a medium scale model of jointed material consisting of a sand-gypsum cement-water mix. The model was fully instrumented to record boundary loads and deflections as well as strain distributions within selected blocks of the model.

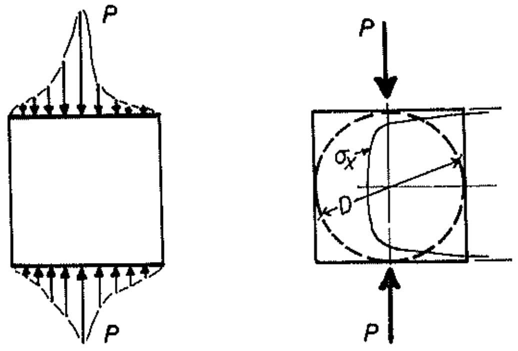
His results shows that the strength of a jointed mass is considerably less than that of an intact block, with failure due to vertical tensile fractures occurring at 30 to 40 percent of intact strength. In addition, Rosenblad noted that principal strain magnitudes and directions in a jointed mass are much larger and less predictable than for an intact block under similar loading conditions.

(b) Concept of Brazilian Compressive Strength

The dramatic reduction in strength of jointed masses below that of the unjointed materials almost certainly arises from differences in the internal load distribution patterns produced by different jointing patterns.

The rotational freedom of individual blocks in the mass constitutes a fundamental mode of deformation not possessed by intact material and leads to non-uniformity of load distribution within the jointed medium. An important consequence of non-uniformity in the loading of individual rock blocks is the development of induced tensile stresses normal to the major load axis (Ref.4). Since rocks are essentially brittle materials, fracture in indirect tension can result from non-uniform compressive loading.

The Brazilian test (Ref.5) is an extremely simple procedure for determining the compressive strength of rock samples under extreme conditions of non-uniform loading (Fig.1).



$$\text{Brazilian Tensile Strength} = \frac{2P}{\pi D}$$

$$\text{Brazilian Compressive Strength} = \frac{P}{D}$$

Fig.1 Non-Uniform Compressive Loading of Blocks

The diametral point loading used in a Brazilian test represents an extreme condition of non-uniform loading and hence Brazilian strength may be adopted as the minimum resistance to this type of loading. On the other hand unconfined compression represents a uniform loading condition and although failure often occurs by tensile splitting along the sample axis, unconfined compressive strength can be taken as an upper limit to rock strength under the most favourable condition of loading. Thus, the strength of a jointed rock mass will lie between the limits defined by Brazilian and unconfined compression tests. It has been demonstrated (Ref.6) for a variety of rock types that the strength of rock in uniform and non-uniform loading conditions can vary by an order of magnitude.

The results of compression tests noted in Sect.2(a) are presented in Table II normalized in terms of the unconfined compressive strength of unjointed material to demonstrate the concept of jointed mass strength.

TABLE II

RELATIVE STRENGTH OF JOINTED ROCK MASSES

Material	Jointing Pattern	Brazilian Strength	Strength at Initial Cracking	Ultimate Strength
Plaster (Ref.1)	Square jointing	19.4%	61.8%	62.4%
	Hexagonal Jointing	19.4%	29.8%	33–45%
	Parallelepipedal	19.4%	14.6%	14.6%
Cracked Marble (Ref.2)	Random jointing	17.4%	–	20.1%
Sand-gypsum cement-water mix (Ref.3)	Square jointing	21.9%	28–41%	45–57%

It is evident from these results that the fracture of individual blocks of a jointed mass in indirect tension does not necessarily indicate the approacn of complete collapse since the most adversely loaded elements will fracture resulting in more favourable distribution of loading. However, fracture initiation is likely to be associated with additional deflection of the loaded area and in this context will be important in assessing the bearing capacity of jointed rock masses.

(c) Tests on Jointed Foundation Models

Krsmanovic & Milic (Ref.7) performed a series of foundation tests on square jointed plaster models. Their results are summarized in Table III in terms of compressive strength of intact material.

TABLE III

RELATIVE STRENGTH OF FOUNDATION MODELS

Footing Type	First Visible Rupture	Penetration of Footing	Rupture of Foundation
Flexible - uniform contact pressure	18%	28%	50%
Rigid - non-uniform contact pressure	–	46%	62%

These tests indicate that the strength of individual blocks cannot be mobilized by footings in a jointed mass, but that rupture of the foundation mass can occur at average loadings of about half the strength of intact material. Cracking due to induced tensile loading can be expected at about 40 percent of the ultimate bearing capacity of the jointed foundation. Tensile strength of intact material was not reported in this study, however, since it is commonly about 10 percent of the unconfined compressive value, the non-uniform strength of blocks based on Brazilian loading would be calculated as about 15 percent of that value. This estimate is seen to agree very closely with the onset of visible cracking of blocks in the first model test.

(d) Load Distribution Experiments with Idealized Rock Masses
(i) Numerical Experiments

There is very little information available on the load distribution behaviour of blocky material subjected to foundation type loadings. Hammett (Ref.8) has initiated a theoretical study of this field via a series of numerical solutions for an idealized rock mass consisting of square blocks arranged to give continuous and discontinuous jointing systems at three different inclinations to the loading axis. The individual blocks are represented by linear elastic six noded finite elements, while the joints are both four and six noded elements with appropriate non-linear characteristics for shear and tensile loadings.

The numerical results from this study show that high stress and displacement gradients exist within individual blocks indicating that the traditional concepts average,stress and displacement behaviour,have little real relevance in the context of jointed rock foundations. The distribution of vertical stress for uniformly distributed surface loading of a mass with continuous horizontal and discontinuous vertical joints is shown in Fig.2 after non-linear joint slip and block interactions have been modelled. The vertical stress contours show that significant redistribution of load has occurred resulting in the majority of the load being transmitted along block diagonals. This leads to high stress concentrations at corners of the loaded diagonal due to block rotations. A consequence of the large stress variation within blocks is that results presented in terms of average stress conditions are invariability not in equilibrium with applied loads as for the model tests of Krsmanovic and Milic (Ref.7) where a 25 percent error occurs.

The orientation of joint sets to the axis of loading is one of the most significant variables on load distribution within jointed masses. For a joint system similar to that of Fig.2 but inclined at 45° to the vertical load axis, high stress concentrations are again apparent at corners of the blocks but anisotropic load distribution pattern is developed. Loads are transmitted more readily in the continuous jointing direction leading to the deeper penetration of high stresses in this direction than parallel to the discontinuous joint direction. Thus high stress gradients are induced along the the vertical diagonals of blocks immediately below the surface load. For the configuration where continuous jointing is vertical the applied load is transmitted almost entirely by columnar action of the loaded blocks. In this case, stress concentrations are not increased beyond those due to the lack of lateral load to transmission.

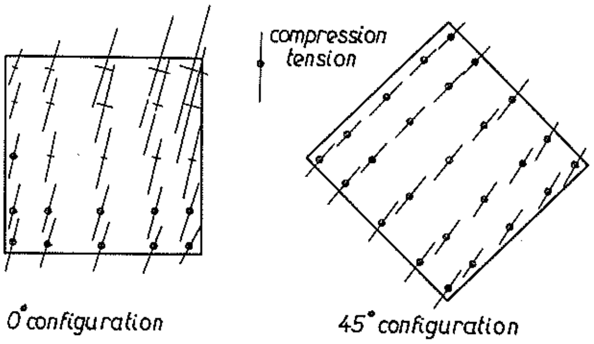


Fig.3 Typical Stress Tensors for individual blocks of jointed foundation mass.

Typical tensile stress conditions due to compressive stress gradients for horizontal (0°) and inclined (45°) jointing patterns are shown as principal stress plots within individual blocks of the jointed mass in Fig.3. In each instance, the greatest tensile stresses are adjacent to the corners of a block and the magnitude is approximately 10 percent of the highest compressive stress within the block. Since rock tensile strengths are about 10 percent of compressive strength, it is reasonable for material fracture to be initiated under tensile stress conditions.

(ii) Model Foundation Tests for Load Distribution

To assess the validity of numerical results, qualitative foundation load tests were carried out on an assemblage of high strength plaster blocks arranged in horizontal and inclined patterns. Loading was applied through a rigid steel footing and the model was restrained laterally by rigid vertical supports.

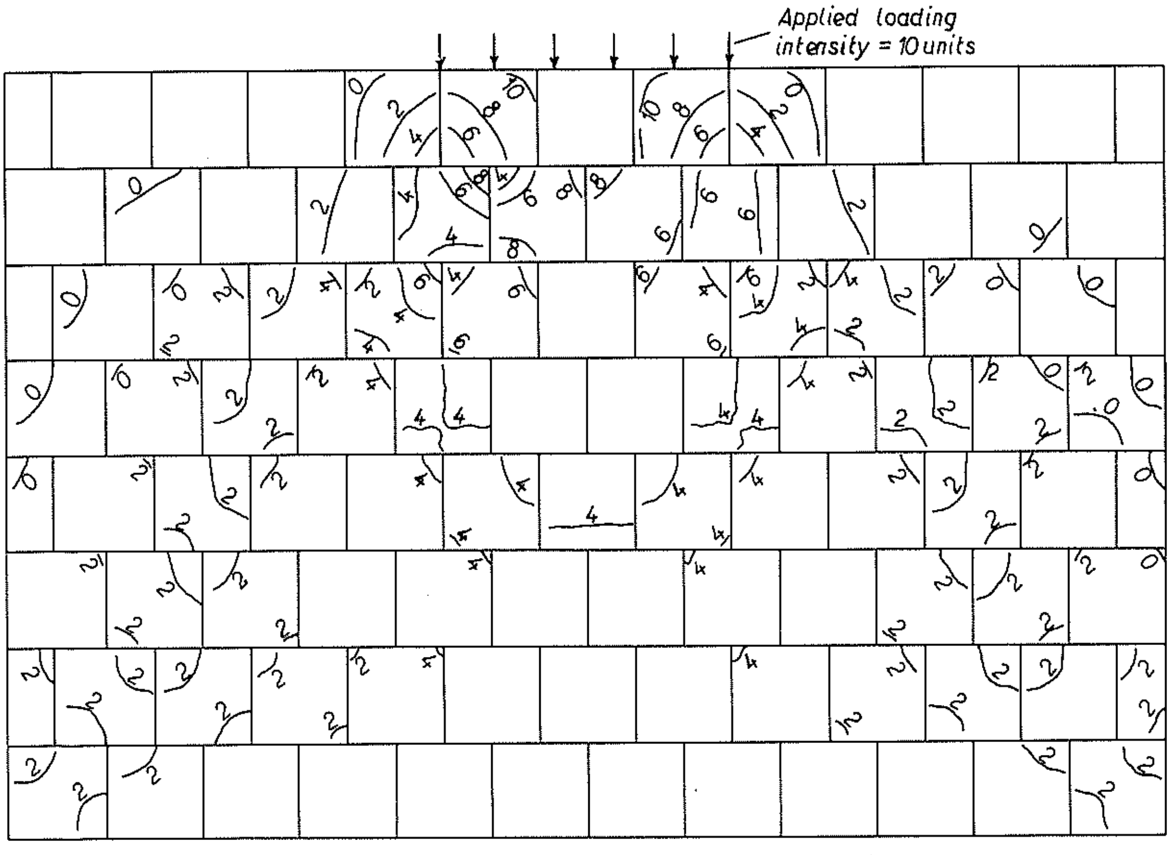
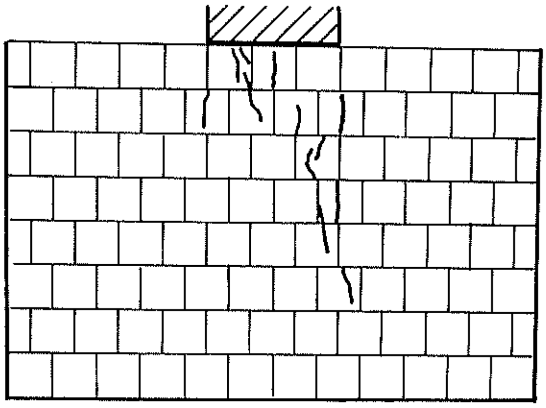
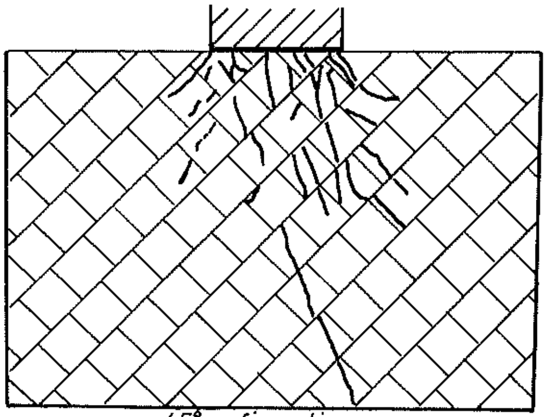


Fig.2 Numerical Results for Vertical Load Distribution in Jointed Mass

For the horizontal jointing pattern, block fracture was initiated directly below the footing edges and this was followed by the progressive development of sub-vertical fractures resulting from stress redistribution within the area beneath the footing. For the inclined joint configuration, block fracture again initiated at the corners of the loading platen. Progressive fracturing tended to concentrate in a direction transverse to that of the continuous joints confirming the anisotropic load distribution described from numerical results. Fig.4 indicates the extent and directions of block fractures for the horizontal and inclined jointing systems at the higher loading stages.



0° configuration



45° configuration

Fig.4 Foundation Fracture Patterns for Idealised Rock Masses

The load-deflection curves for both tests are shown in Fig.5 and indicate almost identical peak loading capacities for each jointing pattern while the stiffness is lower for inclined jointing. Points marked A and B show the loads for fracture initiation and, in both cases, they represent the onset of unstable and irrecoverable deformation behaviour. Prior to crack initiation, load-deflection curves are smooth and linear but as the number of cracks increase, sudden load and displacement changes occur.

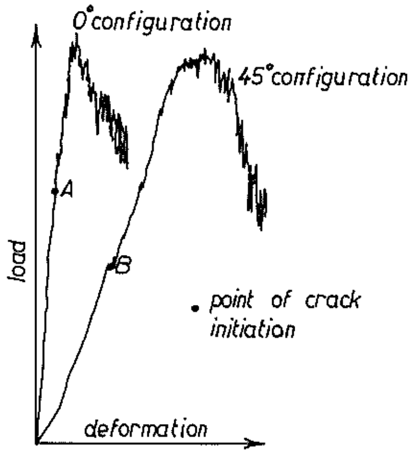


Fig.5 Load-deformation Response from Model Foundation Tests

As might be expected, the more uniform load distribution pattern typical of horizontal jointing results in a higher fracture initiation load than for inclined jointing. However, in both cases, initial cracking of the jointed mass occurs at 45 to 60 percent of ultimate load capacity as noted previously for the other model test results.

3 RESULTS FROM FIELD TESTING OF FOUNDATIONS

Although the literature contains reports of a large number of plate and foundation loading tests carried out in rock, the majority of these tests are of little use in the present context since maximum loading intensities are seldom sufficiently high to produce rupture, and intact rock strengths are not commonly reported. The main objective of tests reported to date has been to determine equivalent elastic parameters from which deformational response of the rock mass can be predicted.

(a) Test Results for Foundations on Massive Rock

Mackenzie (Ref.9) has reported the results of a series of small scale field loading tests carried out in essentially unjointed Sydney sandstone. He obtained an end bearing capacity approximately equal to the unconfined compressive strength of intact samples. While this result is consistent with the above concepts of rock mass strength, the simple relationship obtained cannot be taken as applicable either to jointed rock masses or to large foundation areas.

Peck(Ref.10) noted quite correctly that contact pressures approaching the crushing strength of rock can be developed under steel bearing piles but failed to recognise the significance of jointing to the bearing capacity of large diameter piles on rock. His general recommendation that ultimate bearing capacity be taken as the unconfined strength of intact material represents an unsafe design procedure for jointed rocks.

(b) Test Results for Foundations on Jointed Rock

(i) Brisbane Metamorphic Plate Loading Tests

Coffey & Hollingsworth Pty. Limited carried out a series of plate loading tests on moderately to slightly weathered, closely jointed argillite of the Brisbane Metamorphic Series (Ref.11). A range of plate sizes and loading intensities were used but the results from 300 mm diameter plates at two locations are particularly interesting in the present context since they were carried out to ultimate failure conditions. Load-deflection curves for these tests, presented in Fig.6 indicate that small substantially recoverable deflections occur in the initial loading stages, but the rate of increase in deflection with loading becomes much greater at higher intensities and deflections of an irrecoverable nature result.

Ultimate bearing capacities achieved in these tests vary from 7.5 to 12.5 mPa, while the loads corresponding to onset of irrecoverable deformation are respectively 3.5 and 6.5 mPa at surface deflections about 1 percent of plate diameter in each instance.

Typical average strength parameters for the rock material involved are Brazilian strength of 3.7 mPa, unconfined compressive strength of 18.2 mPa, confined compressive strength of 26.0 mPa and confined compressive strength of broken core sample of 13.7 mPa. Using the unconfined compressive strength value to normalize plate test data, the results are summarized in Table IV

TABLE IV

RESULTS OF PLATE LOADING TESTS
ON BRISBANE METAMORPHICS

Test Number	Load for Irrecoverable Deformation	Ultimate Bearing Capacity
A	19%	41%
B	36%	69%

which shows acceptable agreement between the Brazilian strength value of 20 percent and the loading intensities for irrecoverable deformation of 19 and 36 percent. It is also interesting to note that ultimate bearing capacities are a similar proportion of unconfined compressive strength to those reported in Sect.2(c).

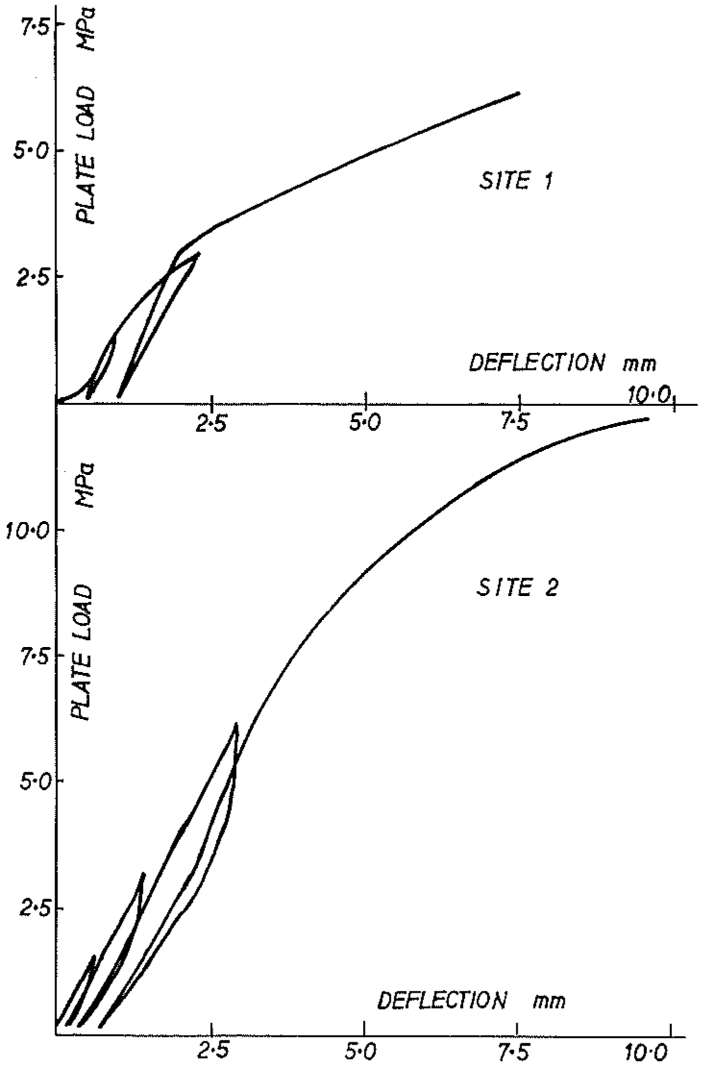


Fig.6 Load-deformation response for plate test in jointed Brisbane Metamorphic rock.

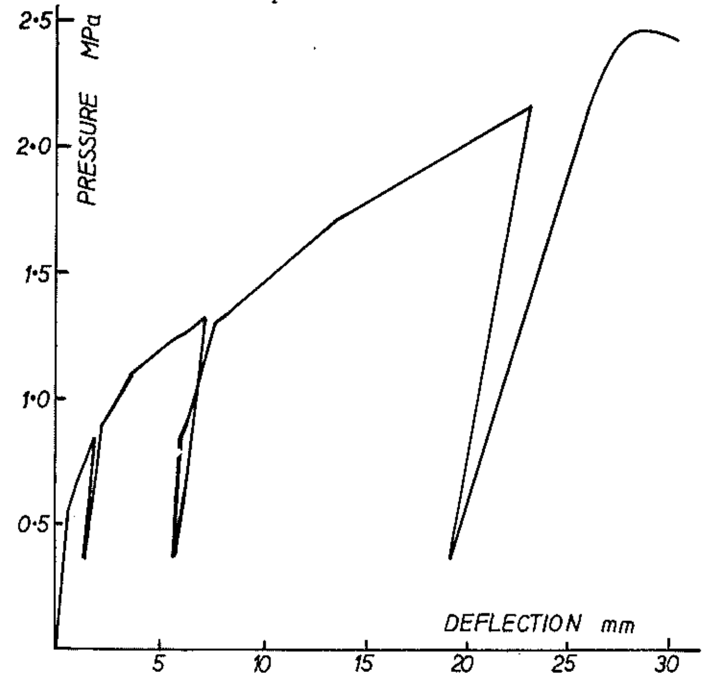


Fig. 7 Load-deformation response for caisson test in jointed Gladstone Argillite

(ii) Caisson Test on Gladstone Argillite

The results of a 450mm plate loading test carried out on completely to highly weathered argillite in Gladstone (Ref.12) are presented in Fig.7. Unfortunately, no test results are available for intact material from this particular location due to the closely fractured nature of the rock mass. However, the characteristic features of small recoverable deflection followed by large irrecoverable deformation with increasing load intensity leading to foundation rupture are illustrated. It is worthwhile to note that the onset of irrecoverable deformation occurs at about half of the ultimate bearing capacity value, indicating similar behaviour to that described for both plaster model (Sect.2(c) and Brisbane Metamorphic rock masses.

4 PROPOSED DESIGN METHOD FOR JOINTED ROCK FOUNDATIONS

Contributions to the displacement of a foundation on a jointed rock mass come from elastic deformation and rotation of rock blocks, from sliding along discontinuities, as well as from the brittle fracture of intact rock. Rupture within the rock mass will in general not lead to collapse of the foundation but will result in deformations of an irrecoverable nature. The available evidence indicates that deflection increases uniformly with loading until cracking of the rock mass results in sudden displacements. This highlights the need to be able to predict the loading intensity at which tensile fracture of the intact rock material is initiated. Deformations which increase uniformly with loading increments will be of minor consequence and the practical design requirement is to limit loading to below that which causes material fracture. It is therefore proposed that the allowable bearing capacity for jointed rock masses be taken as the Brazilian or minimum non-uniform compressive strength of intact rock material.

From a functional viewpoint, the most important aspect in selecting a suitable working load for a structure is its deflection behaviour under load. However, at this stage there appears to be no real prospect of utilising deflection performance per se on a simple design approach for foundations on jointed rock masses, due to both our inability to fully explore jointed rocks and limitations in our knowledge of rock mass behaviour. The practical alternative appears to lie in adopting rock mass strength criteria, (such as the Brazilian strength), which limit the magnitude of deflection and the degree of its irrecoverability.

In practice this approach is extremely simple, since test specimens can be obtained from the diamond cores recovered during normal site investigation works. The method offers particular advantages in closely fractured and jointed rock masses as only small (about 25 mm long) sections of core with minimal preparation are required. The Brazilian test procedure itself is extremely simple and may be carried out on site where desirable. Thus, it is possible to perform sufficient strength testing of the bedrock to build up a statistically representative model of the foundations even within quite severe economic constraints.

5 CONCLUSIONS

A review of available data has shown that the strength of jointed rock masses is dramatically less than that of the intact rock material. This reduction in mass strength is associated with the presence of induced tensile stresses in the individual blocks of a jointed mass subjected to compressive boundary loads. Tensile block stresses result from non-uniform load distribution within the mass and lead to premature fracture of the brittle rock material.

Block fracture is typically initiated at stress levels of 15 to 40 percent of the unconfined compressive strength of intact material while mass failure occurs at 30 to 60 percent of intact strength. The onset of cracking is characterised by sudden changes in load deflection behaviour, by higher rates of straining and by the increasingly irrecoverable nature of deformations.

Similar behaviour is evident from loading tests performed on jointed rocks and has led to the concept of Brazilian compressive strength as the loading intensity below which rock fracture and irrecoverable deformation are not induced.

A simple design procedure for foundations in jointed rock has been developed from the concept of Brazilian strength by taking allowable bearing capacity as equal to the strength of rock core samples tested in diametral compression. This approach overcomes the problems associated with attempts to predict settlement behaviour by restricting loading to less than that associated with large irrecoverable deformations of the rock mass. It is, of course, still essential to identify clay seams or other zones of weakness which might affect foundation settlements. Brazilian strength testing offers considerable advantages in terms of small specimen size, minimal sample preparation, simple test method suitable for on-site work and low testing costs compared to the more common rock mechanics test procedures.

6 REFERENCES

1. Brown, E.T. and Hudson, J.A. Progressive Collapse of Simple Block-Jointed Systems, Aust. Geomechanics Journal, Vol. G2, No.1, pp. 49-54.

2. Rosengren, K.J. and Jaeger, J.C. The Mechanical Properties of an Interlocked Low Porosity Aggregate, Geotechnique Vol. 18, No.3, September, 1968, pp. 317-326.

3. Rosenblad, J.L. Geomechanical Model Study of the Failure Modes of Jointed Rock Masses, Thesis (Ph.D) University of Illinois, Urbana, 1970.

4. Goodier, J.N. Compression of Rectangular Blocks, and the Bending of Beams by Non-Linear Distributions of Bending Forces, Trans. Am. Soc. Mech. Engr., Vol.54, No.18, 1932.

5. Brown, E.T. The Influence of Planar Discontinuities on the Shear Strength of a Rock-Like Material, Thesis (Ph.D) James Cook University of North Queensland, 1970.

6. Burman, B.C. A Numerical Approach to the Mechanics of Discontinua, Thesis (Ph.D), James Cook University of North Queensland, 1972.

7. Krsmanovic, D. and Milic, S. Model Experiments on Pressure Distribution in Some Cases of a Discontinuum, Rock Mech. Eng. Geol., Supp. 1, 1964.

8. Hammet, R.D. Thesis (Ph.D) in preparation, 1974.

9. MacKenzie, I.M. Foundation Load Tests on Sydney Sandstone, Proc. Rock Mech. Symp., University of Sydney, 1969.

10. Peck, G.M. The Rational Design of Large Diameter Bored Piles Founded on Rock, Proc. Rock Mech. Symp., University of Sydney, 1969.

11. Coffey & Hollingsworth Pty. Limited Unpublished Reports on Foundation Design for Proposed Government Precincts Building, Brisbane, 1967.

12. Coffey & Hollingsworth Pty. Limited Unpublished Reports on Foundations for Alumina Refinery, Gladstone, 1970.