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FINAL REPORT
AN INVESTIGATION OF THE MECHANICS OF
DISCONTINUITIES IN ROCK

supported by the U.S. Army Research Office, Geosciences Division

Dr. S. J. Mock, Technical Monitor

Grant Number: DAAL 03-86-K-0134
 Period: 8/86 - 1/90

Michael E. Plesha
 Department of Engineering Mechanics

Bezalel C. Haimson
 Geological Engineering Program

University of Wisconsin
 Madison, Wisconsin 53706

March 1990

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE		5. MONITORING ORGANIZATION REPORT NUMBER(S)	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION University of Wisconsin	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office	
6c. ADDRESS (City, State, and ZIP Code) Department of Engineering Mechanics 1415 Johnson Drive Madison, WI 53706		7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION U. S. Army Research Office	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAA03-86-K-0134	
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211		10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO.	PROJECT NO.
		TASK NO.	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) AN INVESTIGATION OF THE MECHANICS OF DISCONTINUITIES IN ROCK (unclassified)			
12. PERSONAL AUTHOR(S) Plesha, Michael E., and Haimson, Bezalel C.			
13a. TYPE OF REPORT Final Report	13b. TIME COVERED FROM 8/86 TO 1/90	14. DATE OF REPORT (Year, Month, Day) 1990, March, 29	15. PAGE COUNT
16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
		Rock Joints; Damage;	
		Friction; Sliding.	
19. ABSTRACT (Continue on reverse if necessary and identify by block number) In this project, we undertook a systematic investigation of the mechanics of discontinuities consisting of joints and fractures in rock. The specific objective of the project was the development of a physically motivated constitutive law for discontinuity behavior which includes effects such as asperity wear and rubblization. The approach was to idealize a discontinuity as consisting of a macroscopic slip surface with microstructural features consisting of interlocking asperity surfaces. An experimental program was concurrently conducted in order to provide guidance and corroboration in the development of a constitutive law. The constitutive law that was developed was numerically implemented and used to simulate the laboratory tests to help assess our success in understanding and quantifying true joint behavior.			
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL		22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

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1. Research Problem Statement

In this project, we undertook a systematic investigation of the mechanics of discontinuities consisting of joints and fractures in rock. The specific objective of the project was the development of a physically motivated constitutive law for discontinuity behavior which includes effects such as asperity wear and rubblization. The approach was to idealize a discontinuity as consisting of a macroscopic slip surface with microstructural features consisting of interlocking asperity surfaces. An experimental program was concurrently conducted in order to provide guidance and corroboration in the development of a constitutive law. The constitutive law that was developed was numerically implemented and used to simulate the laboratory tests to help assess our success in understanding and quantifying true joint behavior.

2.1 Introduction

In this research project, the mechanics of rock joints was studied with emphasis on stress-deformation behavior at the stress levels typical of the shallow depths associated with civil construction. Our objective was to identify important physical processes involved with rock joints, and to develop accurate, mechanically correct constitutive models for this behavior. The approach was through a combination of laboratory direct shear tests on natural and manmade rock joints and constitutive modeling by developing macrostructural relations using physically realistic microstructural models. Corroboration between the laboratory tests and the constitutive model was accomplished by computer simulation of the laboratory tests using the constitutive model in conjunction with finite element modeling. Thus, this research project involved extensive laboratory testing, analytical modeling, and development of finite element procedures appropriate for simulating rock joint behavior.

Our tests indicate that the behavior of rock joints is most strongly influenced by dilation and damage of asperity surfaces. Dilatancy is the tendency of two rough, initially mated surfaces to separate during relative sliding due to asperities of one surface riding up on those of the other. When dilatancy is unconstrained, the volume of the jointed rock mass increases. More typically, the overburden of rock provides resistance to dilatant deformations and the phenomenon of dilatancy manifests itself through increasing compressive stresses, which in turn tend to increase the tangential stresses required to produce additional sliding. Thus, dilatancy can serve as a strengthening mechanism. However, the asperity surfaces which produce the dilatancy may become damaged, particularly when the normal and tangential stress levels become large. This damage weakens the joint's frictional strength and hence, is a softening mechanism.

To uncover basic phenomena and to provide guidance in developing a constitutive law, we undertook a laboratory investigation that emphasized cyclic shear tests on artificial joints molded of a model material (hydrostone), but also included tests on natural rock joints. In support of this testing program, we designed and fabricated a precision servo-controlled direct shear testing machine. The results of these tests indicate that asperity damage can qualitatively be categorized as wear, in which surfaces are gradually degraded during frictional sliding, or asperity shearing, in which the asperities are catastrophically sheared off. These tests show that often both damage modes can occur in the same specimen, even when the compressive stress is constant. We

also observed that the damaged asperity material can play a significant role in effecting the subsequent behavior of the joint.

The objective of constitutive modeling is to develop relations between joint stresses and relative deformations that are accurate, comprehensive and mechanically correct. These models should be able to account for arbitrary sliding histories and should be able to replicate all of the important physics of true joint behavior. In addition, if at all possible they should be simple and have physical parameters that are meaningful and easy to determine from experiments. Our approach to develop such models has been by postulating simple, physically realistic microstructural constitutive laws for individual aspects of joint behavior. These models are then developed into a macrostructural theory and when taken in aggregate, provide fairly realistic and faithful quantification of the features of true rock joint behavior that we observed experimentally. In addition, there is well-founded hope that these models may prove accurate over a larger range of stress levels than those considered in the model's development since they are predicated upon the correct physics of the behavior we are trying to understand and replicate.

To assess our success in understanding and modeling of joint behavior, we perform computer simulations of our laboratory tests using the constitutive law that we developed. Good agreement between computer simulation and the actual test lends confidence to our success in understanding and quantifying the actual physical processes involved.

2.2 Laboratory Investigations

A laboratory experimental program of direct shear testing of joints was undertaken for the purpose of guiding and verifying the development of a constitutive model. The first stage of the program consisted of designing and fabricating a precision servo-controlled Direct Shear Testing Machine (DSTM). The DSTM is computer-driven using a sophisticated data acquisition and control program, has loading capacity of 500 kN in both the normal and shear directions and accommodates joint surfaces up to 150mm x 200mm (6 x 8 in). Shear displacements of up to 5 cm can be achieved in both directions. Two pairs of strategically located precision LVDTs provide reliable displacement readings in both the normal and the shear directions down to 0.5×10^{-3} cm. Details of the machine are given in reference [7].*

Tests on natural joints are our long-term goal for corroborating the analytical work. However, there are at least two major obstacles with conducting direct shear tests in natural joints: (a) they are extremely difficult to extract undisturbed and (b) no two natural joint specimens are likely to be identical for achieving test repeatability. We therefore concentrated our effort on testing artificial joints, with one set of tests conducted on natural joints extracted from a Niagara dolomite quarry in eastern Wisconsin.

In the process of selecting a suitable artificial material for joint

* Reference numbers correspond to the papers listed in Section 3 of this report.

testing, we developed and tested six different combinations of sand, barytes, gypsum cement and water, and finally settled on the use of a mixture of hydrostone (commercial gypsum cement) and water (100 parts hydrostone to 32 parts water by weight). We employed a single joint surface topography in all of the artificial samples consisting of symmetric 10° saw-tooth shaped asperities of 2mm height.

Complete direct shear loading cycle tests were run under constant normal stress. The following results were obtained in support of our constitutive modeling efforts:

1. The variation of normal stress with normal displacement was found to be approximately linear over the range of normal stresses considered, thus yielding a constant normal stiffness coefficient. Shear loading a joint under constant normal stress resulted first in a linear elastic behavior, indicative of a constant shear stiffness coefficient, followed by slip or plastic deformation. The level of shear stress at which slip occurred was predictable using a Coulomb friction idealization on the oriented asperity surfaces. Shearing of the joint in the reverse direction resulted in similar elastic deformation followed by slip. The angle of slope of the normal displacement versus shear displacement curve was approximately equal to the joint asperity angle. This angle typically decayed as the test progressed indicating that asperity surface damage was occurring.

2. In most tests, twenty complete loading cycles were carried out in each specimen to observe asperity degradation resulting from a potential dynamic load event which may generate several or more cycles. Generally, the following observations were made during this phase of the experiments. Joint dilatancy (normal displacements resulting from sliding due to asperities of one surface riding up on those of the other surface) decreased with cycling, indicating a decreasing asperity angle (or increasing asperity damage). The amount of dilatancy decrease was proportional to the normal stress level. The shear stress responsible for the slip also decreased with cycling, again because of decreased asperity angle.

3. Our observations of asperity degradation showed three modes of behavior, not all of which were always present: (a) An initial slow rate of damage (sometimes insignificant) occurring in the first few cycles (the number of which appears to depend on the normal stress level)^{**}. (b) Accelerated asperity damage^{***}. (c) Steady state mode during which additional degradation was small and seemingly constant from cycle to cycle. The asperity angle during this stage approached zero.

Tests on natural joints were used to corroborate the direct-shear mechanical behavior observed in artificial saw-tooth discontinuities. Results

^{**} This wear was an apparent result of sliding, and was not observed in highly normally-stressed joints.

^{***} This mode was characterized by asperity shearing behavior and was missing in joints subjected to low normal stresses.

of complete loading cycles in eight Niagara dolomite joints confirm that the general shear stress-shear deformation behavior is similar to that exhibited by the artificial joints. However, the slip stages of the loading cycles were accompanied by considerably more softening (decreased shear stress) than was observed in the artificial joints. Asperity degradation due to shear-load cycling was similar to that discussed above for the hydrostone specimens.

2.3 Analytical Investigation

Rock joint behavior is irreversible and history dependent. The most straightforward way to account for such behavior is by the use of incremental constitutive modeling in which rates, or increments, of joint deformations are related to the rates, or increments, of joint stress (or traction). We developed such a theory using macrostructural modeling to provide the overall framework for the constitutive law, and using microstructural modeling to specialize the relations for the behavior of rock joints.

On the macrostructural level, the necessary ingredients (assumptions) are:

1. The joint relative displacements are composed of an elastic (recoverable) part and a plastic (irreversible) part.
2. Changes of stress (or traction) are related to only the elastic part of the deformation.
3. A slip rule can be defined such that for a given state of stress, it will indicate whether or not slip will occur.
4. When slip does occur, the sliding direction is specified by a sliding rule analogous to the flow rule used in continuum plasticity; furthermore, this rule can be deduced from physical observations of sliding phenomena.

We found that all of these assumptions have ready physical interpretations that are supported by experimental observations [3, 8]. Following the derivation of references [3, 7] these assumptions lead to a general set of constitutive equations that are applicable to a variety of media-media contact problems. These equations relate increments of joint surface stress (or traction) to increments of joint surface relative deformation (i.e., sliding and opening displacements) and are valid for arbitrary sliding histories. To apply these equations to the problem of rock joint behavior, it is necessary to consider the microstructural features of a discontinuity.

Assuming that Coulomb's friction law holds on the asperity surfaces leads to a straightforward definition of the slip rule and slip potential, which as described above, specifies when and in what direction sliding will occur. Comparison of our numerical tests and experimental tests indicates that this combination of a surface idealization and friction law is quantitatively accurate. In fact, even when the joint's shape is much more complicated than the simple surface idealization, such as with natural joint samples, we usually observed good accuracy.

An additional ingredient that enters into the microstructural modeling is the treatment of damage due to wear of asperity surfaces. As indicated in our experiments, wear can drastically and irreversibly affect the behavior of a rock joint. Thus, the behavior of a joint at a low stress level may be drastically different than its behavior at a higher stress level that produces significant damage. This may be particularly significant for behavior during seismic excitation in which it is likely that rock joints will experience three or more complete cycles of sliding behavior.

We have expended considerable effort in modeling wear; references [6] and [8] give a thorough discussion of some of our findings. The most important observation that we have made is that wear is an energy-related process. In other words, destruction of a certain amount of asperity volume requires a specific amount of energy in the form of sliding work. Sliding work is the product of sliding distance and tangential stress. Because friction is dissipative, the sliding work never decreases and our idealization is that this work goes into destroying asperity surfaces. Our experiments and computer simulations indicate that this idealization gives good qualitative and quantitative agreement. Furthermore, as discussed in reference [6], this theory unifies some popular ad hoc wear models from the field of tribology with some of those that are used for rock joints.

To quantitatively compare the constitutive law with experiment, we often employed finite element simulation of the actual laboratory test. References [1] and [4] describe an effective finite element procedure for both quasi-static and dynamic problems using displacement-based contact finite elements. An important feature of the approach that we used is that standard finite element solution procedures and program architecture could be used to solve small displacement rock joint problems. This approach proved useful and effective for simulating laboratory tests, and in reference [4] (also see reference [2]), we show that it can be effectively applied to considerably more general problems involving structures and media having dilatant material interfaces and cracks.

In the course of our research, we have devoted attention to developing a physical interpretation of the constitutive law material parameters and for devising simple experiments and data analysis procedures for extracting the required material parameters. References [3], [5] and [7] describe some of the experimental techniques and data analysis procedures that we have used. Also, they describe a physical interpretation of some of the constitutive model's damage mechanisms.

3. List of Publications

The following technical papers have been written with either partial or full support of this research project.

1. Plesha, M. E., Eigenvalue Estimation for Dynamic Contact Problems, J. Engineering Mechanics, ASCE, Vol. 113, pp. 457-462, 1987.
2. Ballarini, R., and Plesha, M. E., The Effects of Crack Surface Friction and Roughness on Crack Tip Stress Fields, Int'l. J. of Fracture, Vol. 34, pp. 195-207, 1987.

3. Plesha, M. E., and Haimson, B. C., An Advanced Model for Rock Joint Behavior: Analytical, Experimental and Implementational Considerations, Proceedings of the 29th U.S. Symposium on Rock Mechanics, pp. 119-126, 1988.
4. Plesha, M. E., Ballarini, R., and Parulekar, A., Constitutive Model and Finite Element Solution Procedure for Dilatant Contact Problems, Journal of Engineering Mechanics, ASCE, Vol. 115, pp. 2649-2668, 1989.
5. Plesha, M. E., Hutson, R. W., and Dowding, C. H., Determination of Asperity Damage Parameters for Constitutive Models of Rock Discontinuities, Int'l. Journal for Numerical and Analytical Methods in Geomechanics, to appear.
6. Qui, X. and Plesha, M. E., A Theory for Dry Wear Based on Energy, submitted for publication.
7. Huang, X., Haimson, B. C., Qui, X., and Plesha, M. E., An Investigation of the Mechanics of Rock Joints - Part I, Laboratory Investigation, in preparation.
8. Qui, X., Plesha, M. E., Huang, X., and Haimson, B. C., An Investigation of the Mechanics of Rock Joints - Part II, Analytical Investigation, in preparation.

4. List of Scientific Personnel

The following personnel have been supported by this research project.

Professor Michael E. Plesha, principal investigator
 Professor Bezalel C. Haimson, principal investigator
 Xiangjun Qiu, graduate student
 Xiaofeng Huang, graduate student