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Investigations into post-failure behaviour of rock and numerical simulation method

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Abstract

In this paper an objection is raised on types I and II of the complete stress-strain curve and post-failure behaviour of rock generally accepted home and abroad. In the light of the energy point of view and new experiment results, the irrationality of type II curve is demonstrated; and a new classification model is put forward. These new results were achieved when the uniaxial compression experiment for the brittle rock sample had been carried out with the axial strain rate kept constant by the newest generation of self-adaptable and servocontrolled testing machine for rock mechanics we developed jointly. An objection is also raised in this paper on the numerical simulation method for post-failure behaviour adopted at present and the future improvement orientation is proposed.

1 Introduction

In order to study the rock strength and deformation characteristics and the fracture development process, one of the basic means is to employ rock mechanics testing machine to carry out uni- or triaxial compression experiments for cylindrical rock samples.

Generally, the relational curve between axial loading applied onto the sample by the testing machine and the axial deformation of the sample is called force-displacement curve. When the variations of the cross section and length of the sample are trivial during the experiment, the force-displacement curve can be easily transformed into the stress-strain curve in name by a simple conversion.

It is well known that no matter what kind of testing machine is employed, the peak strength value of the rock can be achieved via uniaxial compression experiment. And the force-displacement curve before the peak strength value is achieved is called pre-failure behaviour curve; while that after the peak value is called post-failure behaviour curve. The complete force-displacement curve is called complete process curve which includes pre- and post-failure curves.

To study the complete stress-strain curve, especially the post-failure behaviour is a problem that the community of rock mechanics paid close attention to in the last 20 years, for it is of significance both in theory and application in rock engineering. For example, rock has been damaged in different degrees due to the multiple tectonic movements after the formation, therefore, the properties of the rock material in situ must be corresponding to those of post-failure behaviour of the rock in certain degree. In engineering, 'the fractured rock' could still support large loadings to some extent, especially when there are lateral supports.

However, it could not be sure to successfully obtain the force-displacement curve after the peak strength values in the experiments, for it is correlated to the functions of the testing machine and the experiment method.

In the case of 'soft' testing machine, as stored deformation energy of machine will be given out after the peak strength point, and the quantity of deformation energy is larger than the energy required to completely damage the rock sample after the peak value, so as to result in the failure of measuring the post-peak value curve due to an uncontrollable and rapid deformation of the sample till its complete fracture.

Therefore, in order to achieve the post-failure behaviour curve there are two ways to choose:

1. Simply increase the stiffness of the testing machine to decrease the deformation energy released from the testing system, this is the case of stiff testing machine. Since the stiffness of the 'stiff' testing machine could not be enhanced without any limit, and nor the operation is convenient, recently, therefore, less and less people are on this way.

2. Adopt rock mechanics testing machine with closed loop servo-control, which, in the

line of the feedback principle of closed loop system, automatically and continuously adjusts most or part of the deformation energy released from the testing machine. The released energy is absorbed by the machine itself rather than delivering to the rock specimen, so as to effectively put the sample damage process under control. And at the same time, the amount under control could be also exactly changed according to the desired function regularity, realizing the automatic control. Doubtless to say, the appearance of such kind of testing machine is an important progress in the development history of the testing machines.

In the last 20 years, lots of experimental researches and theoretical analyses have been made, and from the literature home and abroad, the complete process curve (mainly the post-failure behaviour curve) of the rock is divided into types I and II, which seems to be generally accepted, and no serious argument is raised on this subject.

The post-failure behaviour of the rock is often regarded as 'softening' phenomenon and the post-failure behaviour curve is considered as a constitutive relation. As a result such curve is often treated as a simulated object in the numerical simulation method, bringing it into the constitutive relation of the rock, and corresponding simulation methods and algorithms have been adopted.

2 Survey and discussion on the classification of types I and II of complete process curve of rock

2.1 *Classification of types I and II*

This classification was first proposed in [1]. Based on their uniaxial compression experiments (Figure 1) for six kinds of different rocks, Wawersik and Fairhurst suggested that the complete stress-strain curve be divided into two basic types (Figure 2a). And this classification is further conceptualized to be the pattern shown in Figure 2b.

From Figure 2 it can be seen that the difference between type I and type II of the complete stress-strain curve falls into the post-failure behaviour curve. The curve in type II represents the rocks with obvious brittleness.

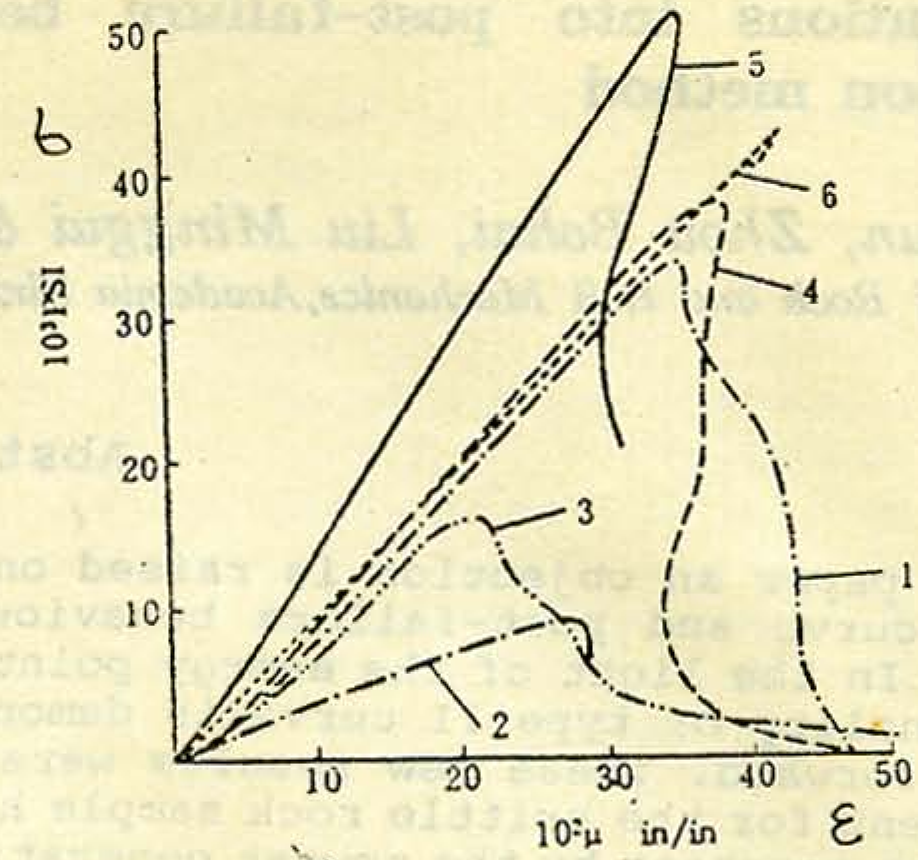

Figure 1 Curves of uniaxial compression experiments for six rocks, according to [1].

Type I { 1 charcoal grey granite I; 2 Indiana limestone; 3 Tennessee marble I }

Type II { 4 charcoal grey granite II; 5 basalt; 6 Solenhofen limestone II }

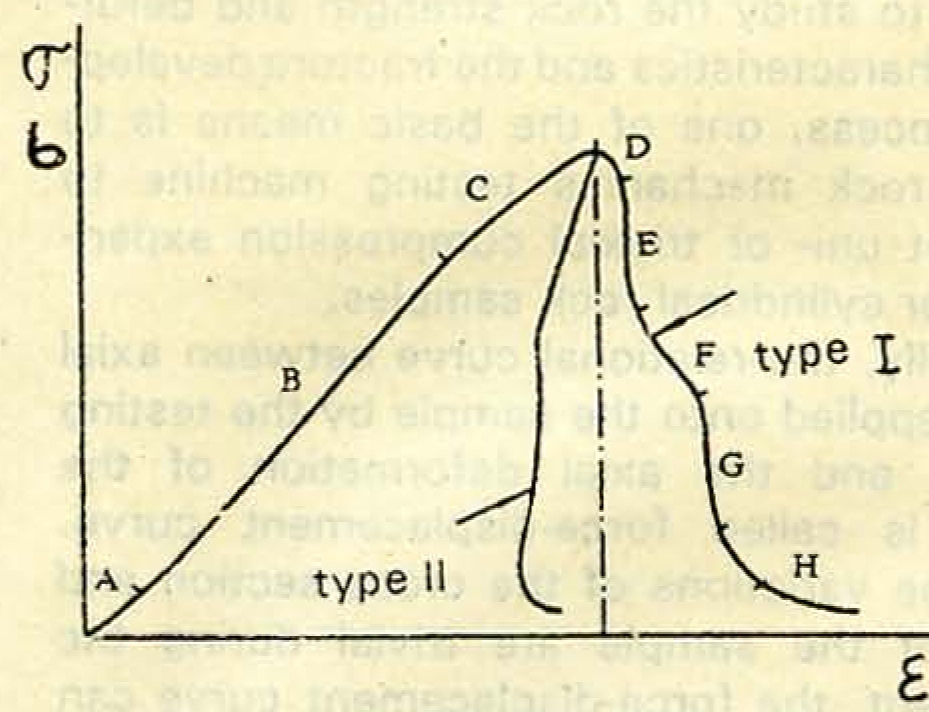

Figure 2(a) Two classes of stress-strain behaviour observed in uniaxial compression tests [1].

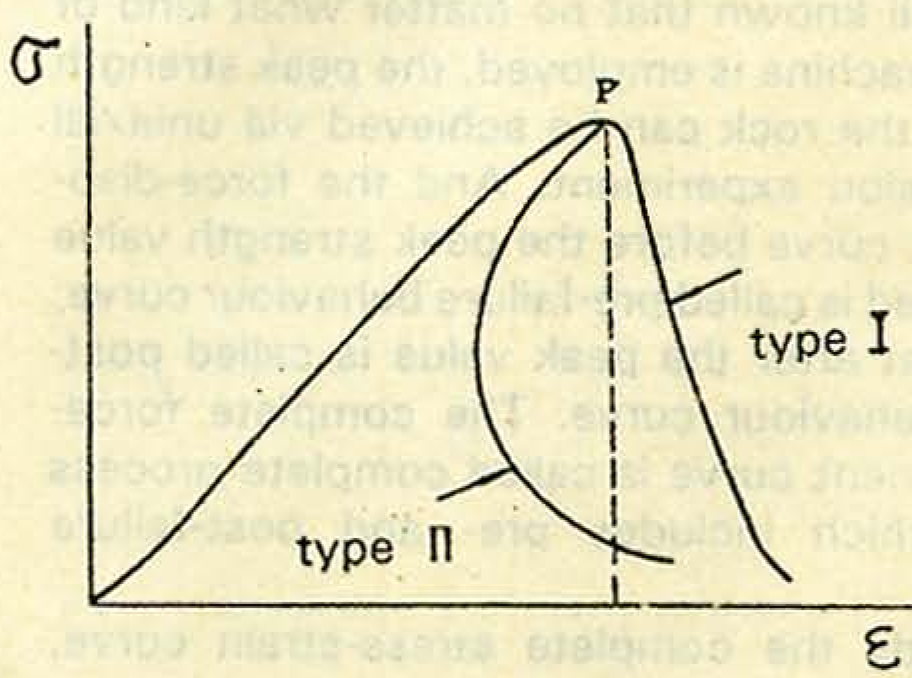

Figure 2(b) Basic pattern of two types of complete stress-strain curves universally adopted at present.

Figure 2 Classification of complete stress-strain curves.

In the conclusion Wawersik and Fairhurst sumof the rocks between type I and type II as 'In uniaxial quasi-static compression tests the complete stress-strain characteristics of the rocks studied here may be divided into two classes. For class I, fracture propagation is stable, in the sense that work must be done on the sample for each incremental decrease in load-carrying ability. For class II, failure is unstable or self-sustaining; to control fracture, elastic energy must be extracted from the material. the fracture of rocks in class II cannot be controlled even if a perfectly rigid testing machine could be used.'

The opinion on the classification of types I and II has been universally accepted and cited, among which [2], [3], [4] and [5] are some representatives.

2.2 *Experiment conditions for the formation of types I and II classification*

In rock mechanics experiments, the experiment conditions have great influence on the results.

In the experiment given in [1] there are three auxiliary hydraulic cylinders parallel to the sample. Passing the peak strength value when the decreasing tendency of the sample resistance is steeper than the unloading behaviour curve of the testing machine, counteraction will be artificially applied onto the loading system from the auxiliary hydraulic cylinders to cut off the development of the fractures of the sample. Hence, in many cases, it would result in the inversion of sample axial deformation.

So another application of force will be carried out onto the sample until the sample is fractured by the repetition of such procedure. When closed loop servocontrolled testing machine is used, circumferential strain rate is adopted as the control for the brittle rocks after the peak strength value to obtain the so-called type II behaviour curve of the brittle rocks.

2.3 *Discussion on the classification of types I and II*

2.3.1 In the above specific controlled conditions, the axial force and axial deformation have been under the complicated process of the repetition of loading-unloading, extension and contraction. Therefore, the obtained type II curve is nothing but the envelope curve of such complicatedrepetition of loading-unloading process. Whether the complete stress-strain curve of type II obtained as such could be considered as reflecting the nature of the brittle rocks with the behaviour curve is under suspicion. It seems that type II curve means to extract energy from the rock sample after the peak value. However, during the complicated loading-unloading process, large amount of plastic hysteresis loop would be formed. And each loop means the energy input from the testing machine to the rock sample.

2.3.2 Now that the complete process curve of the uniaxial compression experiment means the relational curve between the axial force and axial deformation acted on the rock specimen, then one of the principal variables of the relational curve is chosen to be the control, i.e. axial deformation rate (or axial strain rate) must be the most reasonable when the servocontrolled testing machine is adopted. Such choice would keep the axial strain variable of the rock sample in a simple condition with monotonous increasing and uniform increasing rate during the whole experiment process. Thus the behaviour curve obtain in this way would better reflect the nature of the material on the one hand, and on the other, it is easy to be generalized to complicated cases.

2.3.3 At present it is generally to take the circumferential strain rate of the sample as the control when the uniaxial compression experiment is carried out for the brittle rocks. This is because, in our opinion, the automatic control of the testing machine adopted at present is not perfect, therefore, the axial deformation rate of the brittle rocks taken as the control would often result in a situation of out of control.

2.3.4 From the point of view of energy, it can be seen from the analysis of the complete stress-strain curve shown in Figure 2b that the vertical line at strength point P after the peak value is a separatrix. If the post-failure curve falls into its right hand side, it would be the so-called type I curve, this means that the energy compensation is needed during the rock sample damage. If it falls into the left hand side, it would be type II curve. If the complete stress-strain curve of type II is indeed the reflection of the nature of the brittle rocks, then energy compensation for the rock sample of brittle rocks is unnecessary during the post-failure process after the peak value, rather, energy 'extraction' should be carried out from the rock sample so as to control the fracture process. Hence, the logical inference from the energy point of view should be that if type II curve is reasonable, no matter what kind of testing machine is adopted, it will be out of control for the fracture process of the brittle rocks with type II curve when their axial deformation strain rates are kept constant. This is because the testing machine must work on the rock sample when the axial deformation is kept in a condition of monotonous and uniform increasing velocity.

2.3.5 In our opinion, to demonstrate the irrationality of types I and II classification, new experiment study should be carried out aiming at achieving post-failure behaviour curve of the brittle rocks under the condition that the axial deformation rate is kept constant. In order to attain this object, we developed the new generation of advanced closed loop servo-controlled rock mechanics testing machine.

3 New experimental results by the new generation of closed loop servo-control rock mechanics testing machine

3.1 *On the servocontrolled machine used at present*

Most of the testing machines adopted at present with closed loop servo-control manner follow the line of the traditional simulation control, recently there is also the machine abroad with digital direct control, i.e. DDC manner. The important feature of these two control manners is to adopt a fixed adjustment loop. When the system is adjusted, parameters would be fixed ignoring the change of the experiment object.

3.2 *New generation of self-adaptable control testing machine*

The new testing machine we developed recently has the following features:

1. *Multifunction*

Since the unique design method is employed, there is not any large rigid structural parts, and the machine could be used in various mechanical experiments, for example, uni- and triaxial compression experiments and tensile tests (5cm of diameter for the sample); direct shear test ($20 \times 30 cm^2$) and fatigue tests with various wave forms.

2. *High frequency response*

Many advanced technologies and rational measurements are adopted in our design so that the high frequency response of the system is guaranteed, the frequency for fatigue test could reach as high as 20Hz or more. And at the same time, energy consumption is decreased as possible as we can.

3. *Self-adaptation*

Advanced self-adaptable control is adopted, all of the control functions are realized by the computer, which can make system identification and automatic optimization during the experiment processes. In other words, no matter how the mechanical features of the rock sample change, it will guarantee the system to be at the optimum control during the experiment process for the beginning to the end.

3.3 *New experimental results* on the complete stress-strain curve

At present, we have already carried out, with this testing machine, uniaxial compression experiments on many rock samples with different properties. It cannot be overemphasized that the satisfactory post peak curves after the peak value have been achieved for almost all of the brittle rocks under the condition that the axial strain rate is kept constant. Figure 3 shows the complete stress-strain curves of some typical brittle rocks. And the uniaxial compression experiments for these rocks have also been carried out on the 815.03 closed loop servocontrol testing machine by MTS Co., USA. However, when the axial strain rate is kept constant, it is out of control for brittle rocks after the peak value.

These rocks, according to their brittleness, should be classified as those of type II mentioned above, but from Figure 3, it is known that when the axial strain rate is kept constant, their post-failure behaviour curves obtained are absolutely different from those of traditional type II. Therefore, our experimental results fully demonstrate the irrationality of the so-called type II curve, hence, nor the classification of type I and II.

4 New insight on the post-failure behaviour and complete stress-strain curve

To sum up, we could obtain the following conclusion in respect to our newest experimental results that the fracture processes for most of the brittle rocks that used to be classified as type II can be controlled and their perfect post-failure behaviour curves can be attained when the axial strain rate is kept constant. Therefore, the above-mentioned classification of types I and II is unreasonable. Thus we suggest the model shown in Figure 4 be taken as the new model for the post-failure behaviour and complete stress-strain curve.

This new model takes the vertical line after peak strength point P as the limit line. Under the condition that the axial deformation rate is kept constant the post-failure behaviour curves for most of the rocks fall into its right hand side. The brittler the rock, the steeper the slope (for absolute value) at the curve after the peak value of the rock, i.e. the nearer to the limit line, and there are obvious small benches on the curve. This is due to the complicated factors such as the abrupt local fracture which leads to the rapid decrease of the resistance and the handicap of the fracture propagation. While the more ductile the rock, the smoother the slope at the post-peak curve.

In our experiments, there are few special cases in which the fracture processes are out of control. This is because the post-failure curves of these kinds of rocks almost overlap of the vertical line passing point P. Nevertheless, with the perfection of the testing machine and the advancement of the technologies concerned, it is believed that such special cases will be less and less.

The new model suggested needs to be further supplemented, corrected and improved with lots of experiments.

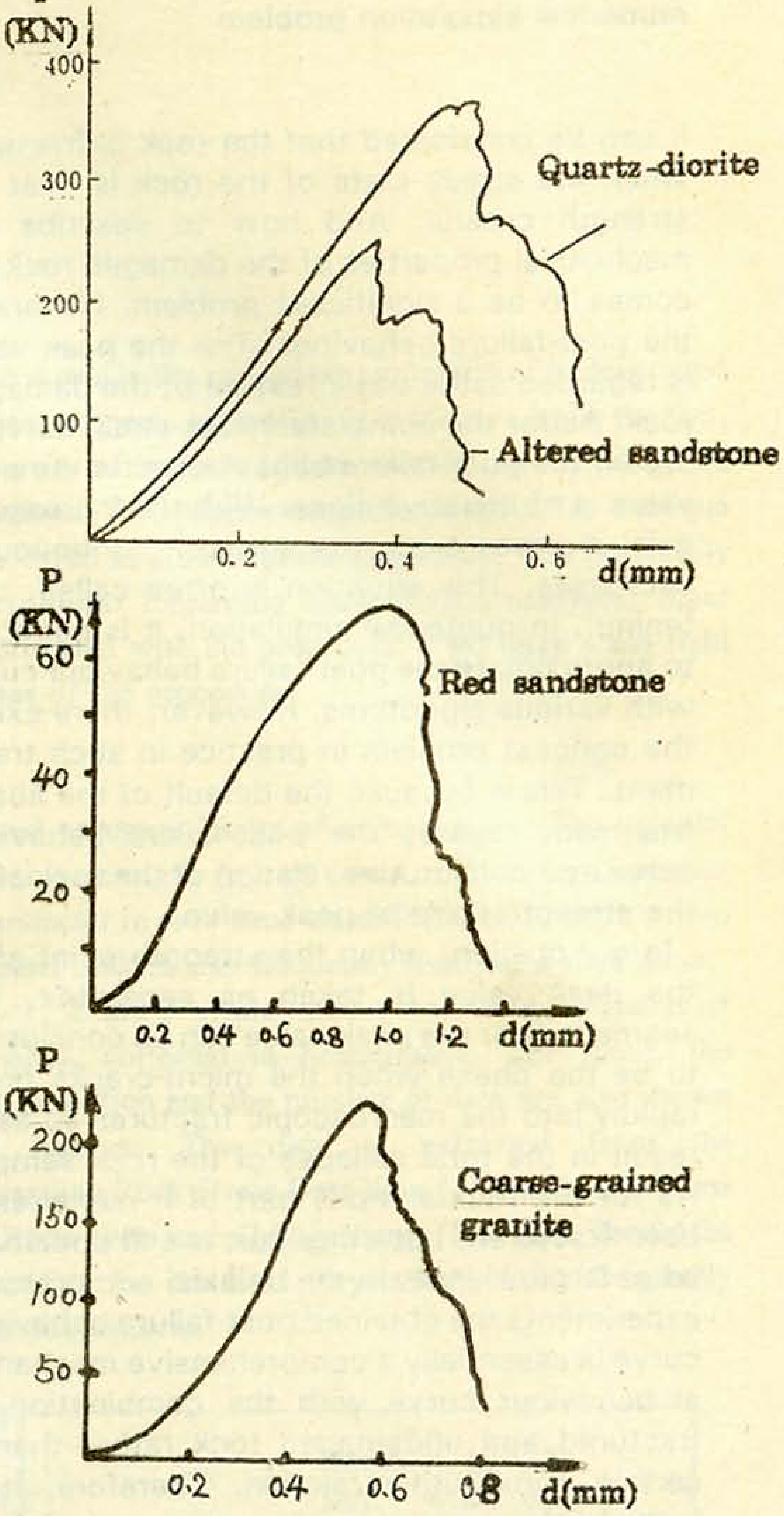

Figure 3 Complete force-displacement curves with self-adaptable control testing machine with axial strain rate being kept constant ($\epsilon = 5 \times 10^{-6}$/sec).

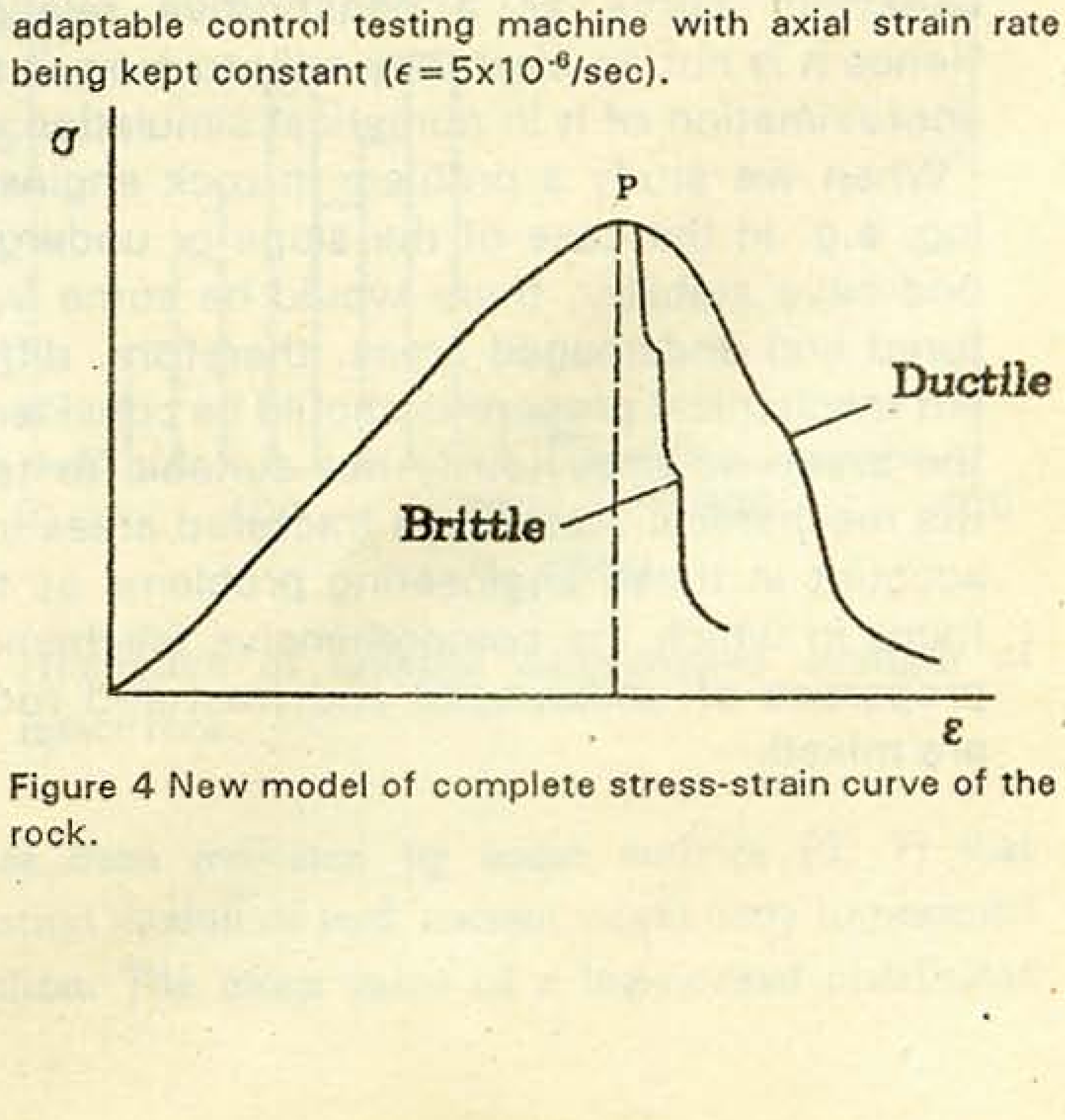

Figure 4 New model of complete stress-strain curve of the rock.

5 Insights on the post-failure behaviour and numerical simulation problem

It can be considered that the rock is fractured when the stress state of the rock is over the strength criteria. And how to describe the mechanical properties of the damaged rock becomes to be a significant problem. Generally, the post-failure behaviour after the peak value is regarded asthe basic feature of the damaged rock. As for the complete stress-strain curve of type I, the post-failure behaviour after the peak value is of negative slope. With the increase of axial displacement, the strength continuously decreases. This situation is often called 'softening'. In numerical simulation, it is generally to approximate the post-failure behaviour curve with various algorithms. However, there exists the concept problem in practice in such treatment. This is because the default of the above treatment regards the post-failure behaviour curve as a constitutive relation of the rock after the strength point of peak value.

In our opinion, when the strength point after the peak value is taken as separatrix, the segment after the peak value can be considered to be the phase when the micro-cracks grow rapidly into the macroscopic fractures so as to result in the total collapse of the rock sample. As for the rock sample, part of it has already been fractured, but other part is still undamaged at large. Hence, in the uniaxial compression experiments the obtained post-failure behaviour curve is essentially a comprehensive mechanical behaviour curve with the combination of fractured and undamaged rock rather than a certain constitutive relation. Therefore, it is inappropriate to consider this post-failure behaviour curve as a constitutive relation. Hence it is not an ideal way only to pursuit the approximation of it in numerical simulation.

When we study a problem in rock engineering, e.g. in the case of the slope or underground cave stability, there would be some fractured and undamaged areas, therefore, different mechanical properties should be considered the areas. It is obviously not suitable to take the mechanical features in fractured areas into account in these engineering problems as the focus in which the comprehensive mechanical properties of undamaged and fractured rocks are mixed.

When the post-failure behaviour curve given here is further studied, it can be seen that post-failure curves for the obvious brittle rocks are generally steeper, and there is a small bench in the curve. It can be analyzed that when the fracture develops rapidly the post-failure behaviour of such rocks generally tends to be vertically dropping down, while the bench shape is the result of the local handicap of the fracture. Thus there would be some negative slope in combination of these properties. As for the obviously brittle rocks, the basic mechanical properties after the strength point of peak value can be considered as dropping down vertically, i.e. the model with tremendous stress drops, this probably fits the practical situation in a better way. If such things do happen, then it becomes very important to introduce the method of how to reasonably describe the abrupt stress drop after the rock damage in numerical simulation. So far as the obviously brittle rocks are concerned, it would be reasonable to study the description of the abrupt decrease of the stress drop after the rock damage. Compared with the study of the 'softening' description, it would be more practical.

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