第31回岩盤力学に関するシンポジウム講演論文集
(社)土木学会　2001 年1月　自由投稿論文(23)

EVALUATING STIFFNESS PROPERTIES OF NATURAL ROCK JOINTS BY LABORATORY TESTS

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This study presents laboratory test procedures to generate input data for numerical analysis regarding normal stiffness (K_n) and shear stiffness (K_s) of natural rock joints. Results show non-linear joint normal deformation implying that the value of K_n has to be established corresponding to the level of *in-situ* state of stress in the field. The pre-peak portions of the shear stress versus shear displacement curves are also found to be non-linear and a procedure is presented to establish an average value of K_s to be used in numerical analysis. Results also indicate that the value of K_n/K_s ratio is not a constant and depends on level of normal stress.

Key words: normal stiffness, shear stiffness, discontinuities, mechanical properties, rock mass

1. INTRODUCTION

Despite of understanding basic mechanism of joint shear and normal deformation[1)2)3)4)], representative values of both normal stiffness (K_n) and shear stiffness (K_s) for different types of discontinuities are still lacking. Consequently, there has been a tendency to relay on experience, literature review and /or empirical methods to establish their values for numerical analysis such as distinct element method (DEM). But such practice has a limitation, as these approaches are highly site-dependent. Therefore, attempts are needed to establish a fundamental procedure so that these parameters may be evaluated rationally.

This paper discusses laboratory compression test and shear test procedures to generate input data for DEM analysis regarding stiffness properties of natural rock joints. Details of the testing equipment employed for compression and shear test may be found in Esaki et al. (1999)[5)]. Test samples were collected from four different rock types: welded tuff, sandstone, shale and mudstone. Test specimens consist of boring cores (diameter: 55 mm), which were cut to suitable sizes and set in sample boxes (length: 14.8 cm, width: 13.0 cm and height: 6.15 cm) with a fixing medium composed of sand, epoxy resin and polyamide-polyamine in the ratio of 6.68:2.34:1, by weight, respectively.

2. EVALUATION OF NORMAL STIFFNESS

Compression test is carried out on a specimen containing a single joint. Since the compression test includes total deformations (joint + intact rock + system), one has to discard the deformations of intact rock plus system to visualize the net

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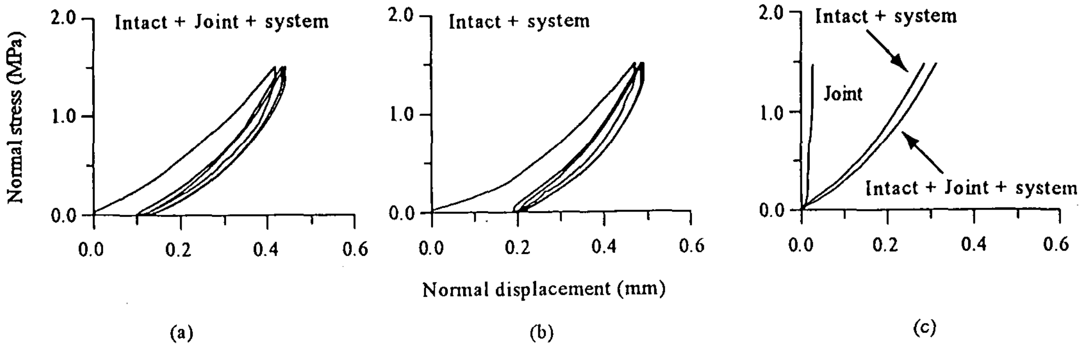
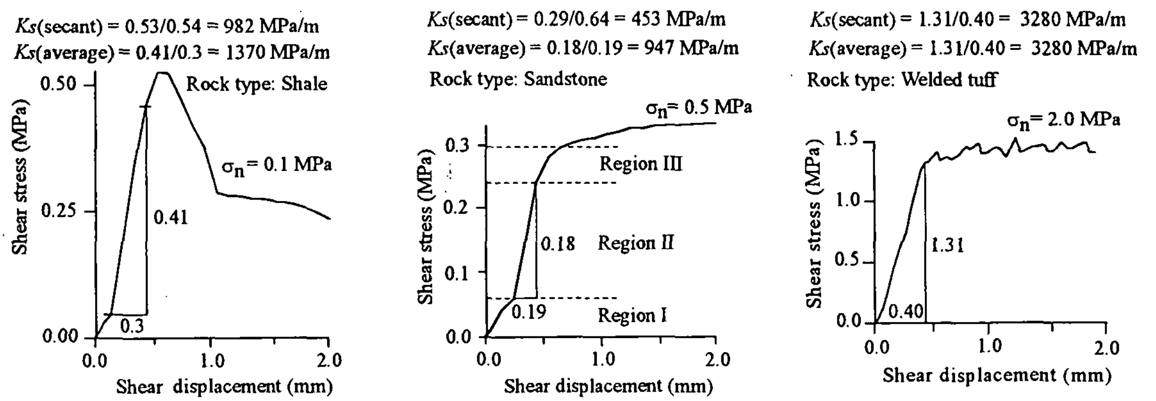


Fig.1 Normal stress versus normal displacement curves.

joint deformations. This can be achieved by visualizing the intact rock plus system deformations obtained while performing compression tests on an identical intact rock sample. To understand representative deformation pattern of these tests, it is necessary to perform the compression test with successive load/unload cycles so as to ensure the result from setting errors, which give increasing normal stiffness with successive load cycles. Afterwards, net joint deformations may be calculated as the difference between the deformation (last loading cycle depicting identical load and unload curve) of the intact specimen plus system and that of the system plus specimen containing a single joint (**Fig.1**). The curve related to joint in **Fig.1**(c) may then be utilized as of input data in DEM analysis. Alternatively, a single value of K_n corresponding to particular level of normal stress may also be calculated by using the hyperbolic equation proposed by Bandis et al. (1983)[2].

3. EVALUATION OF SHEAR STIFFNESS

As shown in **Fig.2**, the shear stress-deformation curves may be categorized broadly into three different types: (a) curve depicting non-linearity in pre-failure region and it shows a peak; (b) curve depicting non-linearity in pre-failure region and it has no peak; and (c) curve depicting linearity in pre-failure region and the peak region is absent. In case of (c), K_s value may be calculated on the basis of curve's slope, which is nearly constant through out the pre-failure region. But such approach



(a) Curve depicting non-linearity and it shows a peak.

(b) Curve depicting non-linearity and it has no peak.

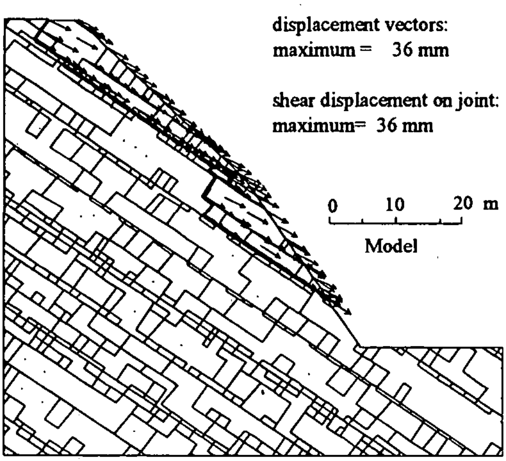
(c) Curve depicting linearity in pre-failure region and the peak is absent.

Fig.2 Different type of shear stress versus shear displacement curves.

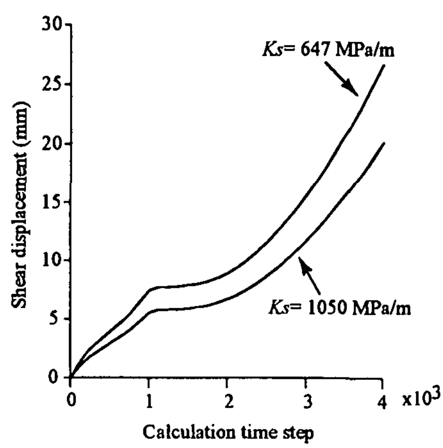
can't be applied for cases of (a) and (b), because curves are non-linear and they can broadly be subdivided into three different regions as shown in **Fig.2(b)**. Deformational feature of region I is that the stress/deformation ratio gradually decreases with increasing shear displacement and it may be interpreted as caused by closure of open voids and cracks. Region II may be considered linear elastic because of its nearly constant and/or slightly increasing the stress/deformation ratio. In region III, the ratio gradually decreases implying commencement of irrecoverable joint deformation. Peak point is the upper limit of this region. But if peak point is not identified as in the case of **Fig.2(b)**, its upper limit may be established corresponding to the point which refers the beginning of residual shear strength. To quantify this argument, definition of residual shear strength

Table 1 Features associated with different regions in pre-failure portion of shear stress versus shear displacement curve (related curve: **Fig.2(b)**).

Shear displacement (mm)	Shear stress (MPa)	Consecutive variation in shear stress (%)	Shear stress / displacement (MPa/mm)	Remarks
0.04	0.03	-	0.75	Region I
0.13	0.06	100	0.46	
0.24	0.06	0	0.25	
0.33	0.15	150	0.45	Region II
0.43	0.24	60	0.56	
0.54	0.28	17	0.52	Region III
0.64	0.30	7	0.47	
0.74	0.31	3	0.42	Consecutive variation in shear stress does not exceed 5 % over a displacement of more than 0.5 mm indicating residual shear strength has been reached
0.84	0.31	0	0.37	
0.93	0.31	0	0.33	
1.03	0.32	3	0.31	
1.13	0.32	0	0.28	
1.24	0.33	3	0.27	



(a) For both values of K_S the failure pattern was the same.



(b) Variation of shear displacement, based on the values of K_S, measured in a contact, near slope face, on the failure plane.

Fig.3 Results of DEM analysis performed using two different values of shear stiffness (K_S). During the model run, the value of other parameters were kept constant.

adopted in ISRM is utilized[6]. It states that if at least four consecutive readings give not more than 5 % of variation in shear stress over a shear displacement of more than 0.5 mm, it can be concluded that the residual shear strength value has been reached. This procedure is illustrated in Table 1. As the interval of data collection for shear displacement was set to be about 0.10 mm, the demarcation point identified by this method should not be considered as the precise location, but as an acceptable point to calculate the value of K_s (secant) to be discussed below.

The above-mentioned facts suggest that the data lying only in region II may be utilized to capture joint elastic deformation. Thus, the K_s (average) value, calculated as the slope of the straight line formed by idealizing the region II as linear elastic, should be equal to or lower than the value of K_s (tangent). Result further shows that the values of K_s (average) are significantly larger than K_s (secant) as shown in **Fig.2**. DEM analysis (**Fig.3**) carried out by UDEC[7] also reveals that the traditional method of utilizing K_s (secant) value in stability analysis gives larger displacements in comparing to cases in which K_s (average) is utilized, keeping the value of other parameters unchanged.

4. RESULTS AND DISCUSSIONS

Result shown in **Fig.3** is in agreement with the fact that the value of K_s has no influence on bringing about changes in mode of failure, which are function of strength and orientation of discontinuity involved. But the result has also convincingly depicted that the joints with a low stiffness will have larger joint displacements compared with the cases of joints having high stiffness. It thus sheds light on why this parameter has to be evaluated by carefully designed laboratory test instead of taking its value from published references. It further implies that the traditional method of utilizing K_s (secant) value in analysis may give larger displacements and thus may lead for extra rock reinforcement or rock support. On the other hand, K_s (tangent) may result smallest displacement and thus create a very strict condition for reinforcement design. This encourages inferring that K_s (average) value may be taken safely for numerical analysis if one is interested in obtaining amount of displacement of the rock mass (e.g. for reinforcement design) with acceptable accuracy. It is because such value lies between the tangent and secant value of K_s and thus its utilization in DEM analysis may be justified. Alternatively, DEM results obtained with different values (tangent, average and secant) may be compared to identify a suitable value for final analysis.

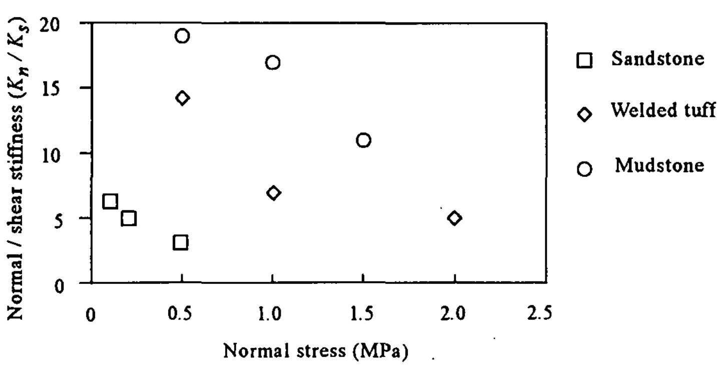


Fig.4 Normal stress versus (K_n /K_s) ratio plots.

Results also indicate that the normal to shear stiffness ratio is not a constant and depends on level of normal stress (**Fig.4**). It has been observed that, with normal stress level of less than 2 MPa, the K_n/K_s (average) ratio ranges from 3 to 6 in sandstone, from 5 to 14 in welded tuff and from 11 to 19 in mudstone revealing the fact that these parameters may differ not only with rock types but also to some extent from place to place. These parameters are also very sensitive to experimental techniques[8] and also with process of sample preparation. Collecting representative test samples is also difficult because the discontinuity in question may not be visible through out its length. These facts clearly suggest that the test results should be considered as a means of understanding possible range of the values, not as a means to establish a single precise value.

5. CONCLUSIONS

This study presents laboratory test procedures to generate input data for DEM analysis regarding normal stiffness (K_n) and shear stiffness (K_s) of natural rock joints. Results indicate that the joint normal deformation varies non-linearly with the value of normal stress and the value of K_n has also been observed to differ from sample to sample of the same discontinuity. It implies that K_n value may only be established satisfactorily by performing compression test on representatively selected and carefully prepared joint samples.

The pre-peak portion of shear stress versus shear displacement curves are characterized with linear as well as non-linear features depending on the nature of the joint surface being tested. In case of non-linear curves, it has been found that there is a conspicuous difference between the secant and average value of K_s. Results further indicate that the K_n/K_s (average) ratio is also not constant ranging from 3 to 6 in sandstone, from 5 to 14 in welded tuff and from 11 to 19 in mudstone with normal stress level less than 2 MPa.

Both K_n and K_s vary from sample to sample and the scattering range of their values is also remarkable even within the same rock type. These parameters are also very sensitive to experimental techniques and also with process of sample preparation. Collecting representative test samples is also difficult because the discontinuity in question may not be visible through out its length. These facts clearly suggest that the test result should be utilized as a range of input data. Afterwards, viewing the results of a simple numerical analysis performed using different values, taken from the range of the test results; a suitable value may be established for final analysis.

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