Fourth Australia - New Zealand
Conference on Geomechanics,
Perth, 14-18 May 1984

Frictional Characteristics of Planar Concrete-rock Interfaces under Constant Normal Stiffness Conditions

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SUMMARY A series of direct shear tests conducted on planar concrete-rock interfaces at a range of normal stiffness and initial normal stress conditions are reported. It is demonstrated that under these conditions the peak angle of friction is dependent on both normal stiffness and initial normal stress while the residual angle of friction is essentially independent.

1 INTRODUCTION

For most geomechanical problems such as in the case of rock slope stability, the frictional characteristics of rock surfaces sliding relative to each other are evaluated by direct shear tests under constant normal load conditions. This approach is appropriate since in-situ forces normal to the potential failure planes are essentially constant. However, in other problems involving shear displacements, the forces normal to the plane of shear can be far from constant. Such a case is encountered during the development of side resistance of concrete piles which are formed in rough rock sockets. When such a pile is loaded, the pile shaft is displaced vertically relative to the surrounding rock, and because of the roughness of the socket and the relative stiffness and strength of the rock and concrete, this relative shear displacement is accompanied by a dilation of the socket diameter as shown in Figure 1. The forces acting on the side of the concrete pile as it is displaced are not constant but increase as dilation increases. It has been demonstrated (Johnston, 1977; Williams, 1980) that the normal stress operating on the pile shaft is directly proportional to the stiffness of the surrounding rock mass and therefore the development of side resistance is a function of constant normal stiffness.

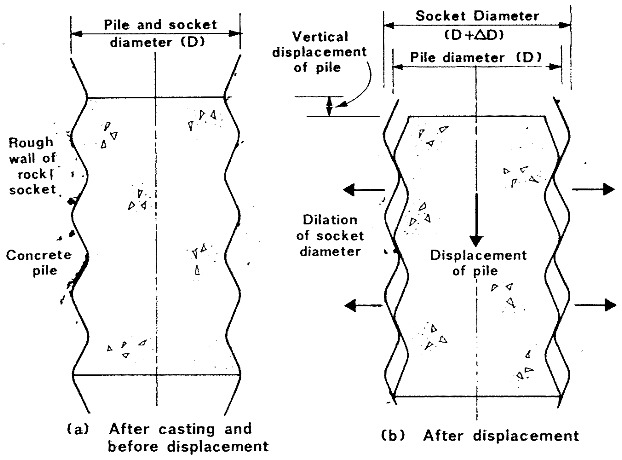

Figure 1 Socket dilation during pile displacement.

As part of a continuing programme of research, the authors have been investigating the shear characteristics of concrete-rock interfaces under constant normal stiffness conditions. Particular emphasis has been placed on the quantification of roughness and its influence on shear behaviour and mechanisms.

For a variety of reasons, not least of which was the inherent variability of natural rock materials and surfaces (Lam and Johnston, 1982; Choi, 1983; Lam, 1983), it was necessary to develop a synthetic rock material which simulated the natural soft rock but which had constant and reproducible properties and surface finishes. This synthetic rock which is known as Johnstone, could be produced by casting and compression in steel moulds. The top compression plate could be suitably shaped to produce any desired surface finish in the resultant synthetic rock specimen. After curing, concrete could be cast against these predefined surfaces to produce the desired concrete-rock interface for subsequent testing. The interface shapes ranged from idealised regular triangular asperities to much more irregular shapes representative of socket wall finishes.

The interfaces produced by this process had preselected first order roughness characteristics which were defined by the overall shape of the press plate of the mould. However roughness is a relative term. Between these first order roughness features, the localised surface finish of the interfaces, although relatively planar, possessed a degree of roughness. This second order roughness or grain was defined by the localised machined finish of the press plates of the mould. Figure 2 defines the distinction between first and second order roughness for regular triangular asperities.

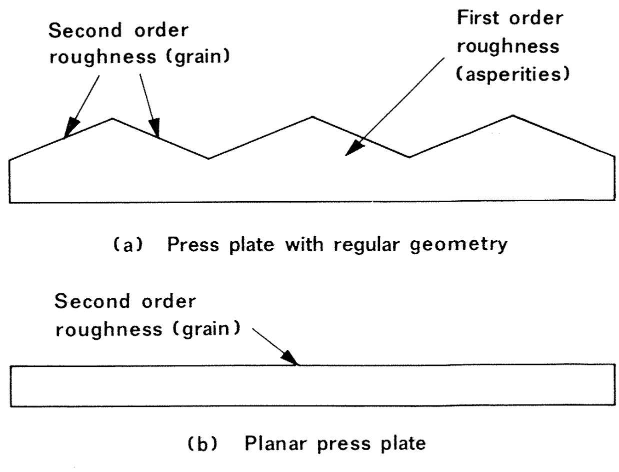

Figure 2 First and second order roughness

Although the overall programme was aimed at establishing the influence of these first order roughness profiles on the shear characteristics of the interfaces, it was necessary to establish the influence of the relatively planar second order roughness features or grain for subsequent analysis. Since this grain was constant for all the different press plates used, only one grain finish was examined.

This paper therefore presents the frictional characteristics of this planar concrete-rock interface under constant normal stiffness conditions.

2 PREPARATION OF TEST SPECIMENS

A comprehensive account of the rationale and methods of Johnstone production and its relationship to the naturally occuring Melbourne mudstone may be found in Choi (1983). The synthetic rock is produced from a mixture of mudstone powder of predefined grainsize distribution, cement, water and a set accelerator which is compressed in moulds. Once excess porewater pressures have dissipated, the compression load is removed, the mould stripped and the specimen allowed to cure for several weeks in a high humidity environment. A major factor influencing its reproduction as a synthetic rock is the compressive stress applied during preparation. The greater this stress, the lower the voids ratio and hence the less weathered is the mudstone modelled. In the investigation reported herein only one specific model material has been considered and it is of 16% saturated water content produced by a compressive stress during production of 4.47 MPa. The resultant unconfined compressive strength of this particular form of Johnstone is approximately 3.4 MPa.

The surface finish of the rock specimen is produced by a compression mould press plate which is machined to the same second order roughness as all other press plates used in the overall investigation. The surface finish characteristics of the specimens has been quantified by a Talysurf Profilometer and a typical roughness profile is shown in Figure 3. The centre line average (CLA) is about 8.5 μm. Figure 4 shows the appearance of a final specimen.

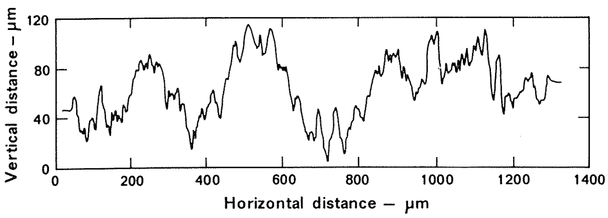

Figure 3 Typical roughness profile of planar interface

In this series of tests, the concrete was cast on the rock specimen without intial bonding. This was achieved by placing a layer of thin plastic foodwrap over the rock surface before pouring the concrete on top. Once the concrete had set, the plastic was removed and the concrete block replaced. Although the presence of the plastic must have had some influence on the degree of fit of the matching faces, this was the same preparation technique employed with much rougher interfaces where bonding was excluded and therefore consistent.

The completed specimen was then vacuum saturated in a desiccator prior to its mounting in the test equipment.

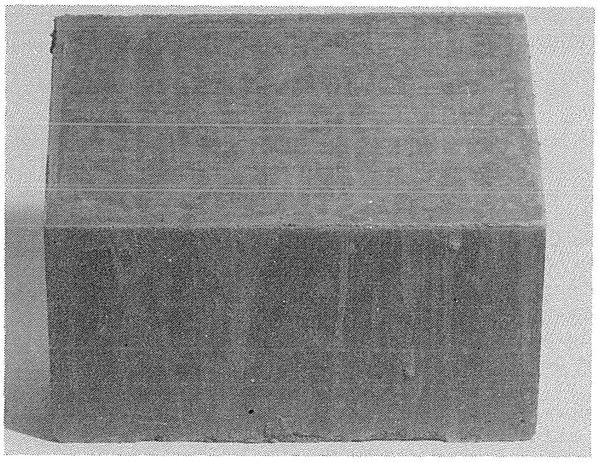

Figure 4 Typical planar surface specimen

3 CONSTANT NORMAL STIFFNESS MACHINE

The principles, design and operation of the constant normal stiffness direct shear machine used in this programme of research are fully described in Lam (1983) and to a more limited extent in Lam and Johnston (1982). Figure 5 shows an overall view of the machine with the principle described by Figure 6. The bottom box containing the rock specimen can move only in a horizontal plane while the top box containing the matching concrete block can move only in a vertical plane. When a shear force is applied to the bottom box, any dilation of the concrete-rock interface will act against a steel spring of predefined constant stiffness to produce an increase in normal stress on the interface. By varying the stiffness of the spring, a

TABLE I

ANALYSIS OF PEAK FRICTION PARAMETERS

Normal Stiffness	Amonton's Law $\tau'_p = \sigma'_n \tan \phi'_p$		Coulomb's Law $\tau'_p = c'_p + \sigma'_n \tan \phi'_p$			Power Law $\tau'_p = M_p(\sigma'_n)^{N_p}$		
kPa/mm	ϕ'_p deg	r	c'_p kPa	ϕ'_p deg	r	M_p	N_p	r
0	37.5	1.00	20.6	36.8	1.00	1.52	0.90	1.00
85	34.7	1.00	36.2	32.3	0.99	1.81	0.85	1.00
350	33.3	1.00	22.4	32.0	0.99	2.71	0.77	0.98
950	30.4	1.00	24.3	28.9	1.00	1.19	0.89	1.00

range of constant normal stiffness, K, conditions can be modelled. Also by adjusting the screw jack located immediately below the steel spring (Figure 5), a range of initial normal stresses, σ'_{no} may be employed.

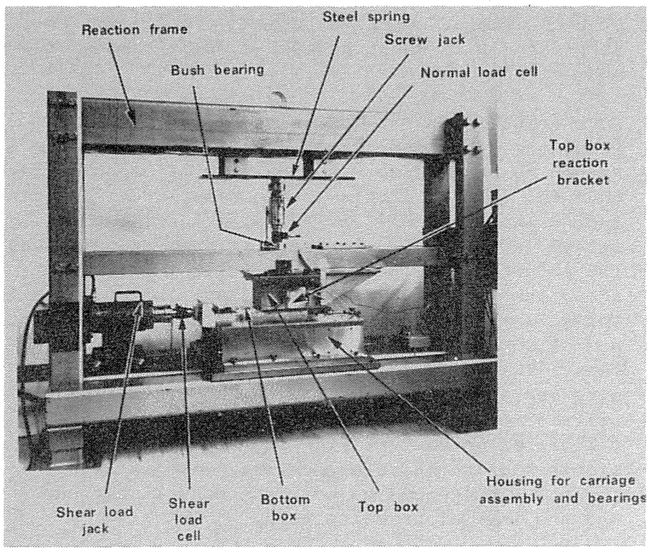

Figure 5 Overall view of testing machine

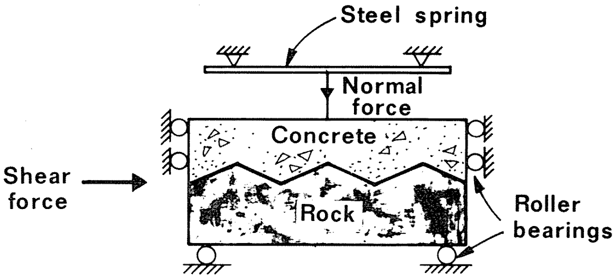

Figure 6 Principle of testing machine

4 TEST PROGRAMME AND RESULTS

A total of 19 individual tests were conducted at constant normal stiffnesses of 0, 85, 350 and 950 kPa/mm. For each value of constant normal stiffness, a range of initial normal stresses were applied. Figure 7 shows the results obtained for each test. The rate of shear displacement was 0.05 mm/min and, as discussed by Lam (1983), this rate was appropriate to the derivation of drained or effective shear strength parameters.

5 PEAK FRICTION PARAMETERS

The results given in Figure 7 have been represented in Figure 8 in the form of peak shear stress against initial normal stress for the range of normal stiffnesses considered. Three methods of correlating this data have been considered and the results are displayed in Table I. On the basis of the respective coefficients of correlation, r, it would appear that each method of interpretation is equally relevant.

The application of Coulomb's Law has yielded only small values of peak cohesion, c'_p, when compared with the unconfined compressive strength of the material. Therefore, it seems reasonable to ignore the cohesive component and make use of the single parameter of peak angle of friction, ϕ'_p, as yielded by the application of the simpler Amonton's Law of friction. This latter correlation shows that for zero normal stiffness, which corresponds to constant normal stress conditions, the peak angle of friction is about 37.5°. However, as the normal stiffness is increased, the peak angle of friction is reduced. At a normal stiffness of 950 kPa/mm, the peak angle of friction is about 30.4°. These best fit angles of friction corresponding to the application of Amonton's Law have been superimposed on Figure 8.

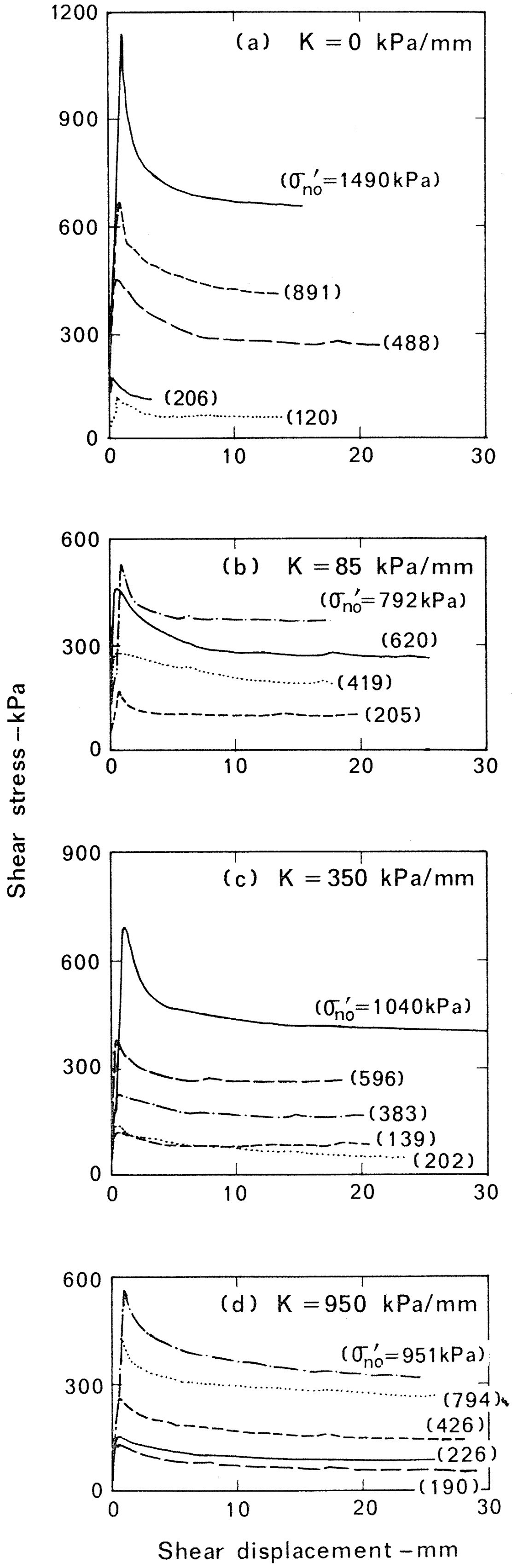

Figure 7 Shear stress-displacement results

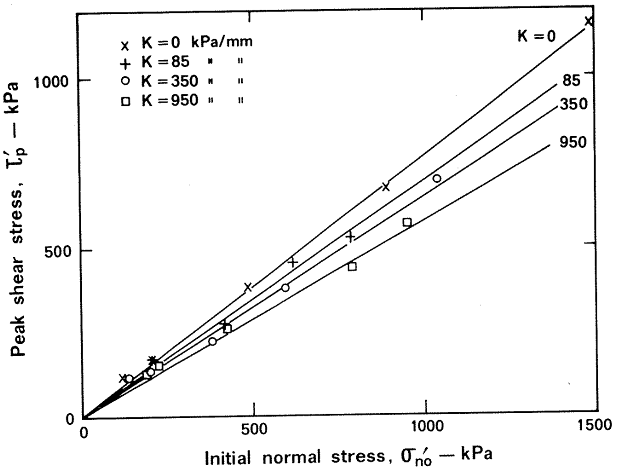

Figure 8 Peak shear stress as a function of initial normal stress

It must be noted however, that both Coulomb's Law and Amonton's Law state that friction is independent of normal stress. The plot of the peak stress ratio (τ_p'/σ_{np}') or the tangent of the peak angle of friction (tan ϕ_p') against initial normal stress for different normal stiffness conditions is presented in Figure 9. The value of σ_{np}' used in this representation is the normal stress at peak shear stress and because of dilatant effects, it is a little different from the initial normal stress, σ_{no}'. This figure demonstrates that initial normal stress level has a significant effect on peak angle of friction. Relatively high values are observed at low initial normal stresses but these values decrease as the initial normal stress is increased.

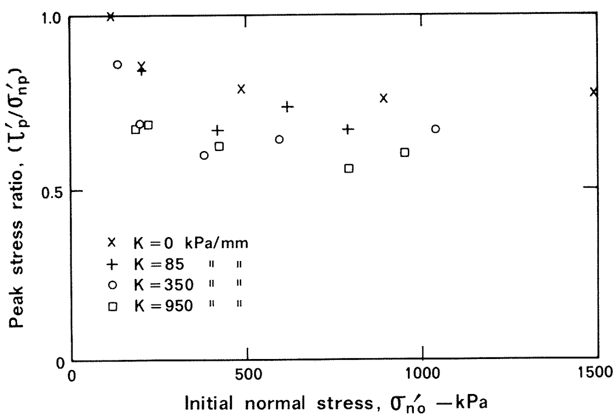

Figure 9 Peak stress ratio (τ_p'/σ_{np}') as a function of initial normal stress

The observed non-linearity of peak angle of friction can be attributed to the different mechanisms involved for different initial normal stress levels. At low normal stress, sliding on the grain sides gives rise to dilation of the interface and therefore a higher angle of friction. At high initial normal stress however, dilation is suppressed with shearing taking place through the body of the grains.

Furthermore, the peak friction of these planar interfaces also depends on normal stiffness. Referring to Figures 8 and 9, it will be observed that the peak shear stress decreases with increasing normal stiffness for the same initial normal stress level. When relative displacement commences, the interface will attempt to dilate by sliding along the inclined sides of grains. However small this dilation is, it results in a net increase in normal stress because of the applied normal stiffness. This increase reduces the measured shear stresses and consequently also the observed angle of friction. It follows therefore that the peak frictional characteristics of this relatively smooth planar concrete-rock interface is significantly influenced by both the normal stiffness and the initial normal stress.

6 RESIDUAL FRICTION PARAMETERS

Figure 10 presents the test results for residual shear stress against initial normal stress for the range of normal stiffness considered. The same three methods of interpretation as were used above were applied to the residual parameters as shown in Table II. Acccording to the respective values of correlation coefficient, r, each method of interpretation appears equally relevant once again. Similarly because of the relatively small value of residual cohesion, c_r', derived, Amonton's Law may be used as a reasonable representation of the frictional characteristics. However, on the basis of the parameters given in Table II, the normal stiffness seems to have a much smaller influence on the residual angle of friction. Although some minor fluctuations have been presented, all derived values of residual angle of friction fall into the narrow band between 19.1° and 24.3°, with an overall mean weighted value of 23.0°.
In order to examine in more detail the influence of initial normal stress on the residual angle of friction, Figure 11 presents the residual stress ratio, (τ_r'/σ_{nr}'), or the tangent of the residual angle of friction (tan ϕ_r') against initial normal stress for different normal stiffnesses. As before, the normal stress used in the stress ratio is that measured value of normal stress developed at

TABLE II

ANALYSIS OF RESIDUAL FRICTION PARAMETERS

Normal stiffness	Amonton's Law $\tau_r' = \sigma_n' \tan \phi_r'$		Coulomb's Law $\tau_r' = c_r' + \sigma_n' \tan \phi_r'$			Power Law $\tau_r' = M_r (\sigma_n')^{N_r}$		
kPa/mm	ϕ_r' deg	r	c_r' kPa	ϕ_r' deg	r	M_r	N_r	r
0	24.2	1.00	21.5	23.2	1.00	0.71	0.94	1.00
85	24.3	1.00	2.8	24.1	1.00	0.65	0.94	1.00
350	23.5	1.00	0.0	23.6	0.99	0.42	1.00	0.98
950	19.1	1.00	0.0	19.1	1.00	0.29	1.03	0.99

residual conditions. This figure shows that the residual angle of friction is much less dependent on initial normal stress with only a relatively small variation recorded for the range of initial normal stresses considered.

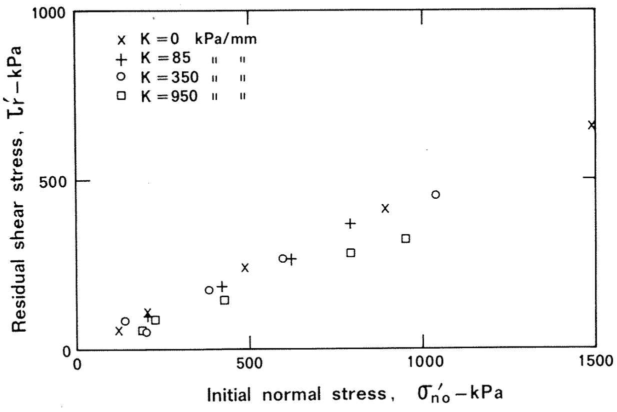

Figure 10 Residual shear stress as a function of initial normal stress

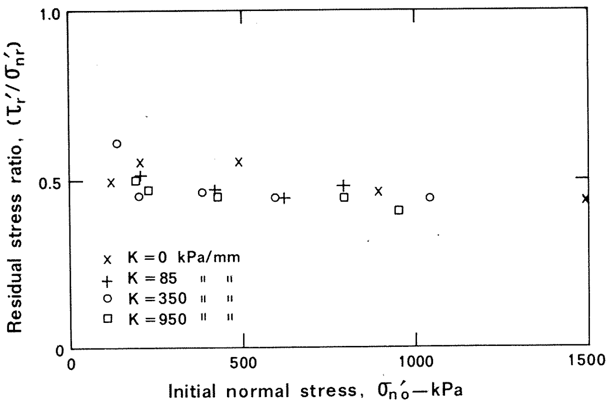

Figure 11 Residual stress ratio (τ_r'/σ_{nr}') as a function of initial normal stress

On the basis of these results, it would appear that the residual frictional characteristics of the interface are essentially independent of normal stiffness and only marginally dependent on initial normal stress.

These observations are consistent with the fact that at relatively large shear displacements, the peaks of second order asperities will have been sheared or ground off to produce the observed rock flour and indurated crust which covers the surfaces of the interface. Therefore with this powder forming a "lubricating" film, there will essentially be no surface texture in the form of grain roughness to cause dilation of the interface. Therefore normal stiffness and intial normal stress can have little influence on the residual angle of friction.

Kenney (1977) has noted that residual friction is influenced primarily by particle size distribution and mineralogy, and is a function of the unbonded rock flour produced. Since the Johnstone specimens were composed of 97.5% mudstone (Lam, 1983), the residual angle of friction for these planar interfaces should be the same as natural mudstone. Williams (1980) obtained residual angles of friction of between 21° and 24° for mudstone ranging between slightly weathered to almost completely weathered. These latter results appear consistent with those values quoted above.

7 CONCLUSIONS

On the basis of a series of direct shear tests conducted on planar concrete-rock interfaces, it is demonstrated that the peak frictional characteristics are dependent on both the initial normal stress and the normal stiffness. For zero normal stiffness which corresponds to the constant normal stress conditions, the peak angle of friction was found to be about 37.5°. However, with an applied normal stiffness of 950 kPa/mm, the peak angle of friction was significantly reduced to about 30.4°.

The residual angle of friction however, was found to be essentially independent of both initial normal stress and normal stiffness. The values obtained were in the range of 19.1° to 24.3° and therefore comparable with the mudstone from which the test specimens were made.

It would appear therefore that even for very smooth sockets formed in soft rock, the side shear resistance must depend on the initial normal stresses across the interface and also on the surrounding rock mass stiffness.

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