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On the load capacity and fracture mechanism of hard rocks at indentation loading

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ABSTRACT

The load capacity of selected hard rocks subjected to circular flat punch indentation is investigated. The compacted zone underneath the indenter is assumed to be limited and only responsible for the load transition to the rest of the material. Therefore, the theory of elasticity is used to define the stress state in a semi-infinite medium loaded by a flat punch indenter. The final load capacity is related to the formation of a sub-surface median crack that initiates due to tensile hoop (circumferential) stresses. Therefore the final failure should occur at a force level in which the hoop stress is greater than the tensile strength of the rock. Since the tensile stress is distributed over a volume of material, tensile crack failure can occur at different locations with tensile hoop stress depending on where the most critical flaw is located. Therefore, the initiation of the median crack that should be responsible for the final load capacity is treated as a probabilistic phenomenon. This process is described by Weibull theory which will be used as a failure criterion. It is assumed here that the opening of median crack triggers a final violent rupture, therefore the assumption in Weibull theory, that the final failure occurs as soon as a macroscopic fracture initiates from a microcrack is fulfilled. The effective volume is calculated for a semi-infinite medium loaded by a flat punch indenter. The material properties of Bohus granite obtained from three point bending tests are used as reference values in describing the Weibull size effect. The experimental results for the stamp load capacity of three selected hard rocks are taken from the literature. They are considered similar rocks to the reference material in this paper, which is Bohus granite. The model describes the observed load capacity with a very good accuracy for all three rocks. It is likely that the presently proposed methodology is applicable for other types of semi-brittle materials and indenter shapes.

1. Introduction

The fracture system and the load capacity of brittle and semi-brittle materials loaded by an indenter, has been widely investigated in the literature.[1–10] To analyze the fracture system, the focus is obviously on the formation and propagation of different types of cracks during the indentation process together with the development of a compacted zone created immediately beneath the indenter. Depending on the brittleness of the material and based on its microstructure, and the amount of defects such as pores and microcracks, the boundary between the crushed zone and the fractured zone is changed. The crushed zone is believed to develop due to high compressive stresses very early during the indentation process and then transmits the force to the rest of the material.[11] The formation of different types of cracks including radial, conical and median cracks in the fractured zone, however, is connected to tensile stresses generated due to the indentation problem and is observed during the loading stage.[2,3,5,7] On the other hand, the initiation of lateral cracks, also called side cracks, is suggested to be related to the expansion of the fractured rock material under the indenter as the load is increased.[1] However, the main reason for the further formation of the lateral cracks during the unloading stage is suggested to be driven by residual stresses at the boundary of the compacted zone.[3,7] Different cracking patterns were observed in sharp indentation of glass both at loading and unloading stages depending on the glass composition, which reflects itself in ductility or brittleness of the material.[12]

The load bearing capacity of rocks during a flat punch indentation test, also called stamp test, has been historically used in the mining industry to characterize the rock properties and its response at drilling and excavation processes.[1,6] The stamp strength σ_{ST}, which is the mean contact pressure at failure, of rocks has been found to be affected by the indenter size and the effect of this size dependency is more pronounced in case of brittle rocks as compared to ductile rocks.[1] The stamp strength together with the crater volume formed in the rock during the

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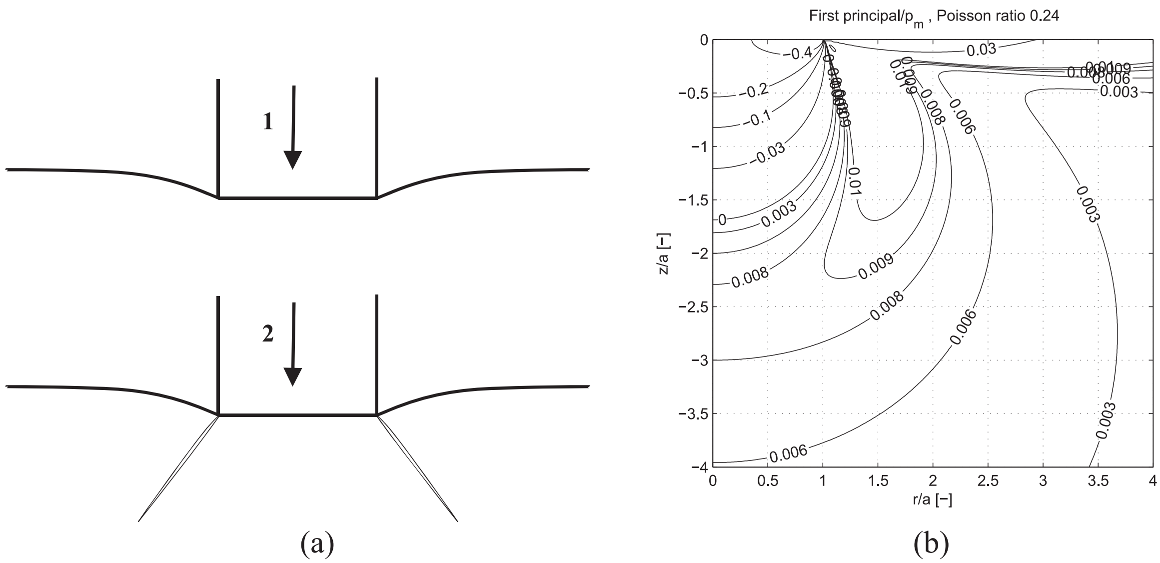

Fig. 1. (a) Indentation with a cylindrical flat-ended punch and formation of Hertzian crack (taken from [1]). (b) The contour plot shows the solution of the first principle stress in a non-fractured linear-elastic medium.

stamp test is used for design of efficient drilling tools and also for the prediction of the drilling rate.[6] Substantial efforts were made to predict the load capacity of the rock, during a stamp test, based on elasticity theory together with different failure criteria.[5] It was observed that cracks and microcracks are formed in the rock prior to the final failure. While the well-known Hertzian crack is formed due to the first principal stress during loading, the crack propagates in a stable manner and the crack front becomes concealed in the region with intense micro-cracking.[5] Therefore, the load capacity and final failure was connected to the initiation of a sub-surface median crack due to the tensile hoop (circumferential) stress, which is the second principal stress except centrally below the indenter. However, the suggested model is not able to predict the load capacity of the rock in the indentation test with an acceptable accuracy.[5] The force-penetration response of rocks under sharp indenters has also been widely investigated and the fragmentation mechanism is explained.[13,14] The sharp conical indentation test has the advantage of self-similarity in the problem compared to the flat punch indentation of different sizes but this will also lead to a situation where plastic (irreversible) deformation is introduced immediately at contact.

Weibull statistics and the weakest link theory has been widely used to define the failure probability of a structure and to explain the statistical scatter in the strength of identical specimens.[15,16] Furthermore, the statistical theory of size effect based on the Weibull model has also been applied to describe the size effect on the tensile strength of brittle and semi-brittle material with a random distribution of flaws and defects. One of the assumptions in this theory is that total failure occurs as soon as a macroscopic fracture initiate from a microcrack. Another assumption is the absence of any characteristic length and therefore the material should not contain sizable inhomogeneities.[17] Hence, the application of the Weibull theory and Weibull size effect on brittle and semi-brittle material should be made with extra caution and the fulfillment of the assumptions should be checked carefully.

In this work, the focus is towards an investigation of the load capacity of selected hard rocks subjected to circular flat punch indentation. The compacted zone underneath the indenter is assumed to be limited and only responsible for the load transition to the rest of the material. Therefore, the theory of elasticity is used to define the stress state in a semi-infinite medium loaded by a flat punch indenter. A tensile failure criterion is used and it is assumed that the final load capacity is related to the formation of a sub-surface median crack at the symmetry line. The median crack initiates due to tensile hoop stresses. Therefore the final failure should occur at a force level in which the hoop stress is greater than the tensile strength of the rock. For the tensile strength, the Weibull size effect is adopted and the strength of the rock is scaled using an effective volume. The effective volume is calculated based on the part of the material that is subjected to a positive hoop stress. Therefore, the initiation of the median crack, responsible for the final load capacity, is treated as a probabilistic phenomenon. The experimental results for the stamp load capacity of selected hard rocks are taken from the literature and a fairly close agreement is obtained with the model predictions.

Finally, it should be mentioned that a possible application of the present results concerns percussive drilling. As a first approximation then, dynamic effects could be addressed by changing the explicit values on the tensile strength accounting for rate effects.

2. Elastic stress field from a rigid flat punch

For most types of rocks, the indenter, which is made from hardened steel or hard metal, can be considered as relatively rigid. The elastic modulus is at least a few times higher than the rock. Therefore, in this context the stress field from the indentation is studied using the solution for a rigid punch in an elastic medium, for which the stress state is comprehensively given e.g. in [18].

Early during a stamp test with a flat punch, i.e. at comparably low force compared to that of the final rupture, high tensile radial stresses form close to the surface just outside the rim of the indenter. These stresses lead to shallow ring cracks around the indenter and gradually form the well-known Hertzian crack. Below the surface, but still outside its periphery, tensile stress (first principal stress) extends downwards in a circular shape, reaching inwards below the indenter, but at a lower value. As the indenter force increases, however, subsurface tensile cracks may be expected to form also in these places (Fig. 1).

Eventually the region with high enough tensile stress to cause failure encompasses also the region centrally below the punch. Here both hoop and radial stress components is first principal (they are equal) and the direction of the crack can then be expected to extend downwards and side wards. This type of crack has been named a median crack. In an elastic treatment the depth at which this occurs depends only on the Poisson's ratio and the size of the contact zone, for typical values ($\nu \approx 0.2 - 0.3$) at about 2–3 times the radius of the punch. It is suggested here that when the median crack opens it triggers the final violent rupture that is associated with the indentation test,