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Effect of introducing porosity in numerical simulation of rock indentation by drilling insert

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Abstract

Rock cracking under indentation test need to be described to help drilling tools designers find the best shape and position of inserts in a roller cone tool, in order to increase the drilling efficiency.

This paper presents a numerical study of indentation test using a finite element program: Code Brigth.

Modified Mohr Coulomb model is used to describe the rock behaviour and the cracks induced. This model offers the possibility of introducing heterogeneity into the material: in our case the porosity.

Cracking appears in the sample under loading. This is due to the consideration of the heterogeneity of the rock introduced in form of porosity.

Results of all these modelling calculations are compared to an experimental study to make sure that modified Mohr Coulomb model describes well the rock behaviour under indentation test.

Keywords

Rock indentation, drilling insert, porosity, numerical simulation

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1 Introduction

A single quasi-static indentation test consists of a forced insertion to a surface of rock with respect of a loading program. This prediction of the induced damage and its result, can be beneficial to the drilling tools designers. One or two inserts provide guaranteed contact be-tween the roller-cone and the rock in the drilling process.

For this reason, the prediction of the damage caused by simple indentation and double indentation tests is helping the engineers to predict the damage induced by the full tool and later the efficiency of the tool.

The application of several numerical models and tools has been employed to simulate the effect of indentation on the rock damage and cracking.

The mechanics of classical fracturing defines three basic modes of cracking, distinguished with reference to loading mode (Rao (1999)), namely Mode I traduced by normal tensile stress perpendicular to the crack surface. Mode II, the shear stress mode, acting parallel to the crack surface but perpendicular to the propagation direction of the crack. Mode III where shear stress is parallel to the plane crack and parallel to the crack propagation direction. Rao et al. considers that cracking occurs in I-II mixed mode, the tensile cracking is the most common failure mode. The same phenomenon was also confirmed by other researchers (Tapponnier and Brace (1976) Swartz and Taha (1990); Whittaker et al. (1992)

There is also an approach for simulating the progression of brittle fracture: it consists on adopting a brittle elastic-plastic model (Lacroix and Amitrano (2013)). This approach can capture the behaviour of materials that exhibit limited plastic deformation before failure, bridging the gap between purely elastic and purely brittle failure models and is often based on a linear failure criterion Mohr-Coulomb or on a non-linear criterion such as Hook-Brown failure criterion, wherein elastic properties (Young's modulus and / or Poisson's ratio) of the rock sample are variable (Amitrano and Helmstetter (2006) Chemenda et al. (2009)). Hajiabdolmajid et al. (2002) developed a progressive fracture model of rocks, depending on the loss of cohesion and increasing of friction.

Liu et al. (2001) highlights in his study the interaction of stress fields and crack networks caused by neighbouring inserts. In simultaneous loading of several inserts, the spacing is a very important parameter in the design and operation of the rock drilling machines due to the interaction between the induced cracks networks by adjacent inserts which causes the formation of chips. This phenomenon plays a significant role in optimizing the efficiency and energy consumption of rock drilling operations. It seems that in the simultaneous loading with an appropriate spacing, the interaction of fields stresses induced by two inserts gives a handset crack depth to form large pieces of rock fragment. This interaction offers the possibility of minimizing the amount of specific energy responsible for rock excavation.

In their numerical study, Souissi. et al (2016), used Mazar damage model to simulate the rock damage under a spherical insert. Several single-indentation tests using a spherical insert were modelled with various insert penetration depths and rates. Then, the radius of the induced damaged zone beneath the insert was evaluated and compared with the radius of the cracked zone obtained experimentally by Souissi et al. (2015) for the three rock types. Good agreement was found between the numerical and experimental results, which shows that Mazars' (1984) model describes well the behaviour of hard rocks during a single-indentation process and confirms that rock-damage evolution is governed mainly by the increase in material extension.

In the present study, we choose to use a modified version of Mohr Coulomb model used usually for describing the soil desiccation.

This model offers the possibility of introducing heterogeneity into the material: in our case the porosity.

Numerical results are then compared to experimental results performed previously (Souissi et al 2015).

2 Brief description of modified Mohr-Coulomb Model

A visco elasto plastic model is used in this numerical study. Modified Mohr Coulomb model, basically made to describe the desiccation process in a soil dominated by heterogeneity (initial distribution of porosity)

This model assumes that the state of stress is defined by two independent variables: the *net stress* $\sigma_{net} = \sigma - u_a$ and *suction* s = $P_a - P_w$, which are used to explain the unsaturated soil behaviour. In our case, suction is equal to zero. The proposed model is written in the context of the elastic-Visco plasticity.

$$\frac{d\varepsilon}{dt} = \frac{d\varepsilon^{e}}{dt} + \frac{d\varepsilon^{p}}{dt} \tag{1}$$

Where: ε is the total strain, ε^e is the elastic deformation and ε^p is the plastic deformation.

The viscoplastic constitutive model:

$$\frac{d\varepsilon^{p}}{dt} = \Gamma \left\langle \Phi(F) \right\rangle \frac{\partial G}{\partial \sigma} \tag{2}$$

Where Γ is the viscosity, F is the yield function; G is the plastic potential and Φ is a stress function:

$$\Phi(F) = F^{m} \tag{3}$$

The yield function F is defined by the following expression:

$$F = q - \delta p' - c\beta \tag{4}$$

Where q is the deviatoric stress, c is cohesion, m is a parameter that depends on the material, δ and β are defined by the following expression:

$$\delta = M = \frac{6\sin\phi'}{3-\sin\phi'} \qquad \beta = \frac{6\cos\phi'}{3-\sin\phi'} \tag{5}$$

With ϕ' is the friction angle. The flow rules are not associated, (F ≠ G) the plastic potential G is written by replacing ϕ' by $\varphi = \frac{2}{3}\phi'$. Invariants used in the models are defined as:

$$p = \sigma_{oct} = \frac{1}{3}I_1 = \frac{1}{3}\left(\sigma_x + \sigma_y + \sigma_z\right) \tag{6}$$

$$q = \frac{3}{\sqrt{2}}\tau_{oct} = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_x-\sigma_y\right)^2 + \left(\sigma_y-\sigma_z\right)^2 + \left(\sigma_z-\sigma_x\right)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} \tag{7}$$

The crack development was due to the behavior of the proposed model in Code-Bright: the calculations were run using a Mohr Coulomb modified criteria proposed by (Trabelsi et al. 2011). This model is able to link cohesion to porosity. The equation of the model is written as proposed below:

$$C(s,\phi) = C(\phi) = B\,\frac{(|f(\phi)| + f(\phi)}{2} \tag{8}$$

Where:

$$f(\phi) = 1 - (\frac{\phi}{\phi_0})^n \tag{9}$$

$$C(\phi) = \frac{(|f(\phi)| + f(\phi)}{2} \tag{10}$$

where ϕ is the soil porosity, ϕ0 is a reference porosity, and n is a material parameter that characterizes the shape of the cohesion-porosity function (Trabelsi et al. 2011)

3 Model Set up

3.1 Rocks characteristics

The rock specimen is considered as heterogenous material. The modified Mohr Coulomb model uses the mechanical properties of materials, namely, the cohesion, the friction angle, Young modulus and Poisson ratio. In addition to these characteristics, this model uses porosity. The porosity injected in the model is the porosity of the studied rock equal to 0.011.

Table 1 – Mechanical properties of studied rocks

Rock property	Unit	Granite
Density	(kg/m3)	2658
Total porosity (nw)	(%)	1.1
Pore porosity (np/nw)	(%)	34.7
Crack porosity (nc/nw)	(%)	65.3
P-wave velocity	(m/s)	5902
Tensile strength	(MPa)	8.5
Compressive strength	(MPa)	196
Young modulus	(MPa)	22800
Poisson ratio		0.2
Cohesion	(MPa)	24.6
Friction angle		45°
Brittleness index		23

3.2 Geometry and mesh

In the following numerical simulations, the indentation problem is simplified to an axi-symmetry conditions, the size of the sample is equal to 8.5 by 10 cm². The position of the insert is located at the left end of the upper surface of the sample. In this simulation, a triangular mesh is used with 15914 elements and 8124 nodes.

3.3 Loading and porosity distribution

The inserts used by Souissi et al. (2015) in their experimental investigation were made from tungsten carbide. To reproduce numerically the progressive penetration of a spherical insert into the rock, an incremental displacement was applied on the insert rock contact surface located at the upper-left board of the half-sample. The numerical simulation is performed using a maximum imposed displacement of 2mm.The porosity is injected into the material in a random way (Trabelsi et al. 2023). The porosity varies between 0.1 and 0.15 (figure 1).

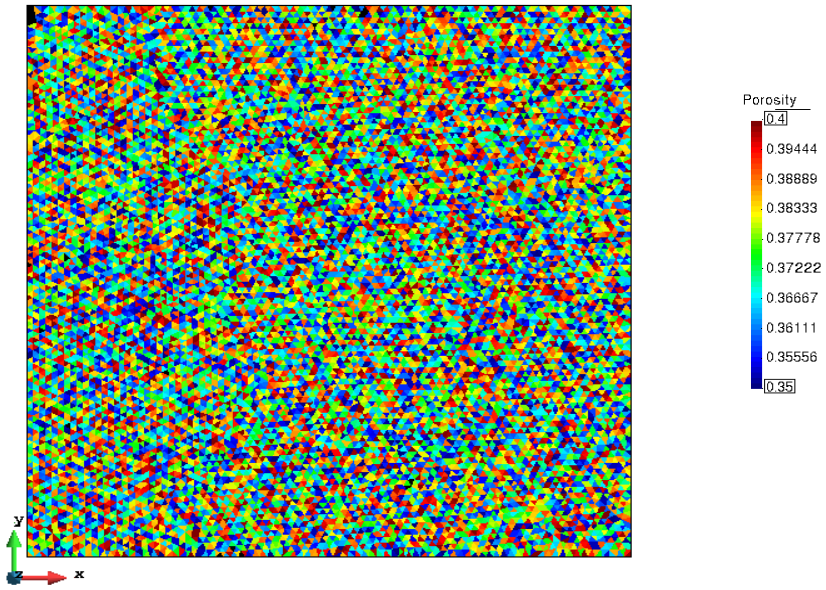


Fig. 1 Random distribution of porosity in the numerical sample

3.4 Boundary conditions

The loading is applied in the upper left corner of the numerical specimen. Displacements are prevented in the lower and the right sections. In the left section, only displacements along Y axis are allowed, this is due to the hypothesis of axi-symetry as showed in Figure 2.

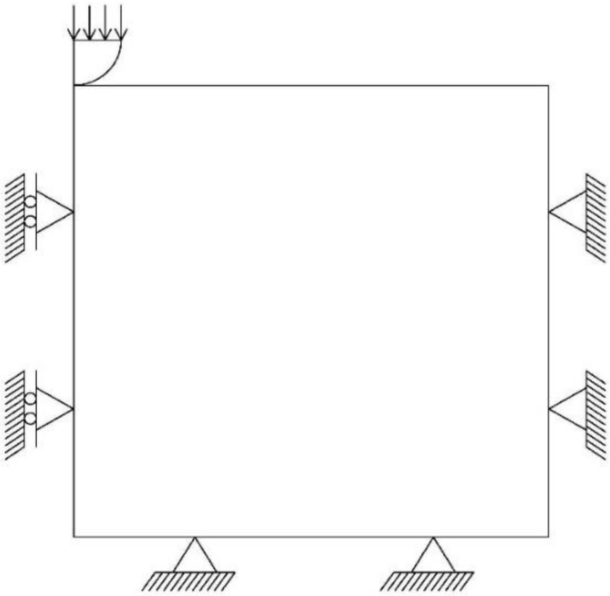
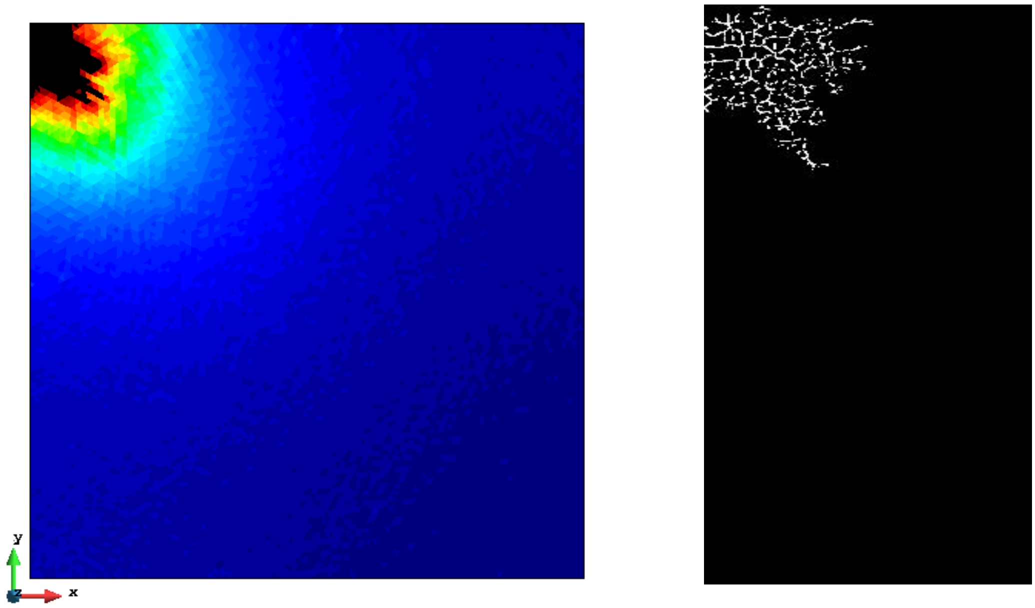


Fig 2. Boundary conditions layout

4 Numerical simulation results

4.1 Shape of cracks

The cracked zone found numerically using the modified Mohr Coulomb model is similar to the experimental damaged area under the indentation test. Figure 3 shows the numerical cracked zone and the experimental result of a granite sample subjected to an indentation test.



(a) (b)

Fig 3. Crack shape under indentation solicitation (a) numerical result, (b) experimental cracked zone

4.2 Crack evolution

When the indenter acts on the rock, a cracked zone, corresponding to the red colour in Figure 4 appears. As the stress intensity comes up with an increasing load, the cracked zone become larger until reaching the maximum imposed displacement.

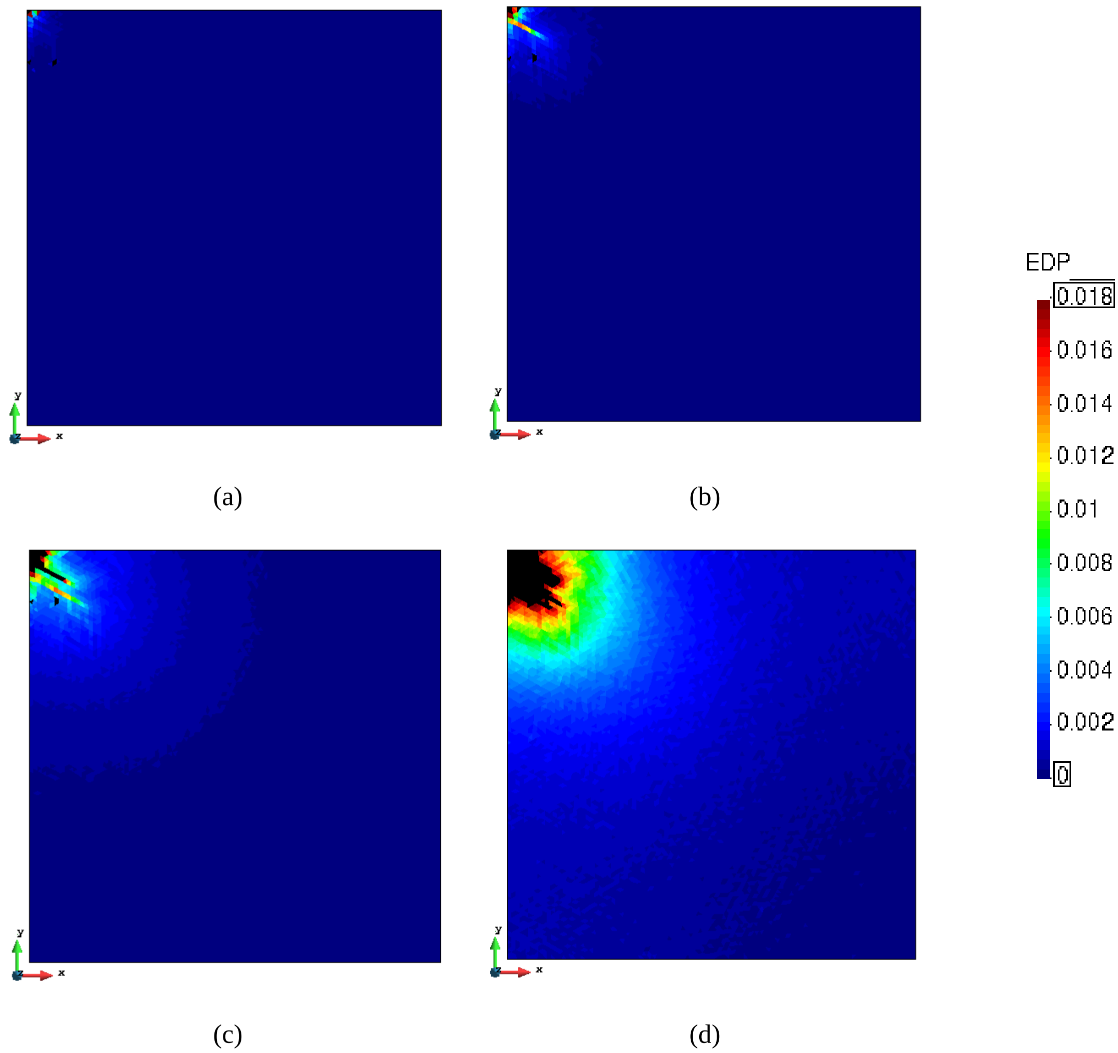


Fig 4. Cracks evolution (a) loading strat, (b,c) intermediary stages, (d) final stage

4.3 Radius of cracked zone

With increasing insert displacement, tensile stress increases under loading, and the extent of the cracked zone grows. Fig. 4 shows the evolution of the simulated cracked zone for granite. It is clear that these cracked zones have similar shapes in the experimental and the numerical specimen.

The radius of the cracked zone was evaluated numerically. Only black and red-coloured finite elements that are completely damaged were taken into account. Fig. 4 shows that this radius increases with increases in the maximum imposed displacement. This effect was also observed experimentally by Souissi et al. (2015). The numerical radii were compared with the experimental radii of the cracked zones, and very good agreement between the numerical and experimental results was found (Fig. 3). The numerical radius of the cracked zone is equal to 1.84 cm compared to 1.7 cm found for the experimental cracked zone. This result proves that the modified Mohr Coulmb model describes well the rock behaviour under indentation test, and that the introduction of porosity helps to model well the rock cracking under indentation.

4.4 Indentation curves

The force-displacement curve obtained from the numerical simulation is superposed with the experimental curve obtained from a previous study (Souissi et al. 2015) as shown in figure 5.

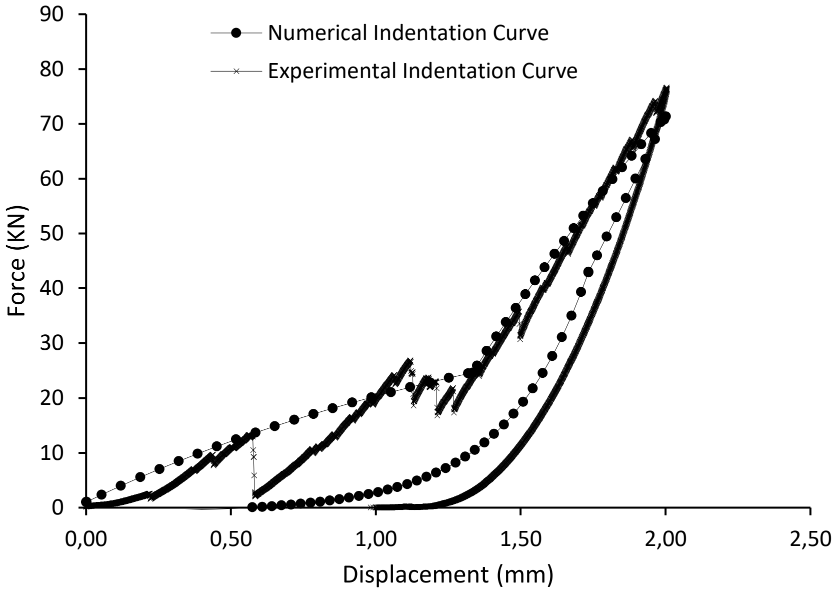


Fig 5. Numerical and experimental indentation curves

The comparison between experimental and numerical indentation curves highlighted that there is a similarity between the numerical model resulted curve and that reached by the experimental test.

5 Conclusion

Modified Mohr Coulomb model, normally used for soil, was used for the simulation of cracks in rock subjected to indentation conditions. A single indentation test, using a spherical insert, is modelled, and the radius of the cracked zone is estimated and then compared to the radius of a cracked zone estimated from a previous experimental study. A similarity of these two estimated radii is noticed. One can conclude that the Modified Mohr Coulomb model, involving porosity, describe well the behaviour of rocks under indentation test.

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