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Simulating hydro mechanical effects in rock deformation by combination of the discrete element method and the smoothed particle method

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ABSTRACT

The discrete element method (DEM) has been used successfully to simulate rock failure. However, when considering the deformation of fluid-saturated rock, the DEM lacks the contribution of the fluid pressure. The presence of a (pore)-fluid can affect the effective stress state, which might result in a change in some of the mechanical properties of the rock, e.g. strength and modulus. Additionally, saturated rock is more susceptible to strain rate effects.

An extension to DEM is presented in which the effective stress theory is embedded by coupling the DEM with a pore pressure diffusion process. This is achieved by interpolating the discrete properties of the DEM to a continuum by using a smoothed particle approach (SP). The model is able to predict the strengthening/weakening of a rock with respect to the amount of fluid drainage that has been allowed. To demonstrate the validity of the model, several simulations of tests under different loading conditions are conducted and the results are compared with experimental data from literature. The agreement between theory and experiment is very good.

1. Introduction

The presence of a pore-fluid can have a significant influence on various dynamic engineering problems, such as hydraulic fracturing[1,2] and cutting processes like drilling,[3–5] trenching, dredging[6,7] and offshore mining.[8,9] Due to its complex nature, the effect of the pore-fluid is often simplified by assuming fully drained/undrained behavior and assuming a constant effective stress during the process. However, both simplifications are only applicable when considering the extremes of these processes with respect to force and deformation rate (i.e. perfectly drained and perfectly undrained/impermeable).

The discrete element method (DEM) has been useful to model these kind of dynamic engineering problems, however, without taking pore-fluid into account. Several approaches have been developed to incorporate fluid pressure effects in rock. The first group are methods that are based on a discontinuum approach by modeling the flow of the pore fluid along the element contacts/bonds.[10–12] These methods are often used to model the hydraulic fracturing process, with typically mode-I (tensile) failures as the dominant failure phenomena. In case of large deformations, occurrence of new contacts and/or significant distortion of the contact network (i.e. mesh) of the fluid, it will be necessary to remesh the discretisation of the fluid phase. This is especially the case for problems concerning the transition from intact rock to moving fragments of rock (i.e. transition from intact rock to granular medium).

The second group are methods that apply an adaptive confining pressure boundary condition.[13,14] In such an approach, a confining stress is applied on a 'free' surface boundary. Various algorithms exist to determine which particles are part of the free surface and which are not. Although such an approach mimics some of the effects of an effective stress, it does not consider pores of the rock to be filled with a fluid. Thus such an approach inherently assumes that the pore pressure is constant and in equilibrium throughout the whole specimen.

In this research, the DEM is extended with fluid pressure effects. These fluid effects are based on a Smoothed Particle (SP) approach, which is a meshless Lagrangian particle based method used to solve continuum based problems. SP finds its origin in astrophysical problems,[15] nowadays it is used in many fields, e.g. hydrodynamics (SPH),[16] applied mechanics (SPAM).[17] Various researchers have used the combination of DEM and SP techniques in

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the field of rock mechanics. These can be distinguished into two groups.

The first group of methodologies are those in which DEM and SP are used to model the two phases fully separated, particles represent either solid or fluid (Lagrangian-Lagrangian model description). Such methods are used for problems like hydraulic fracturing,[18] rock blasting,[19] boudinage.[18] Besides, such a two phase description for fluid rock interactions, it is often used in modeling of multi-phase flows and/or fluid structure interactions as well, for example.[20–22].

The other group of methods are based on methods that treat the DEM and SP particles in a co-located fashion, meaning that the properties of both fluid and solid phases are based on the same particles and these properties are transported with the same particles as well. Thus far, the use of these kind of approaches is rather limited due to its limitations, transport of the two phases should be almost similar. However, it can be used to relate the discontinuous properties of DEM to a continuum field, e.g. heat, stress. A strongly simplified approach similar to SP that describes the stress state of DEM particles is used in SDEM (stress-based DEM).[23,24] In SDEM, the calculated stress is used as a failure criterion for the DEM. SDEM is too simplified in the sense of number of neighboring particles and the interpolation kernels that are used are insufficient to properly model a continuum. As a result, their application is limited to an interpolation scheme for DEM.

The objective of this paper is to present an approach that incorporates fluid pressure effects in the DEM, making it capable of dealing with shear failures and local varying pore pressures. This paper starts with an overview of the relevant phenomena to determine those effects that have the biggest impact on the rock mechanics. Then the setup of the numerical model is discussed and verified with benchmark tests. Furthermore, simulations are compared with a set of compression tests with varying strain rates on Kimmeridge Bay shale.[25]

2. Saturated rock mechanics

Pore fluids affect the mechanical properties of rocks by two classes of mechanisms[26]: (1) drainage mechanisms that control the effective stress of a rock, like compaction and dilation hardening, and (2) physico-chemical interactions between the fluid and solids affecting the mechanical properties of the rock skeleton. The two mechanisms can be hard to separate when comparing dry and saturated rock, because both are in principle capable of increasing or decreasing the strength of a rock. Although the hydro mechanical effects often operate on a different timescale compared to the physico-chemical effects, multiple experiments are needed to make a proper distinction between the two effects. In this study, only the group of drainage mechanisms are considered.

Drainage mechanisms control the effective stress in a rock. Pore pressures work as a counteracting effect on the normal stress in a rock, which is expressed by Terzaghi's law of effective stress.[27] When considering the compressive strength of a rock, the effective stress law is only valid below a critical strain rate, below which effective drainage of the sample is achieved.[28] A sample is considered to be effectively drained when the local pressure differences due deformation rate are significantly smaller than the compressive and/or tensile strength of the rock, i.e. $\Delta p \ll \sigma_c, \sigma_t$. However, at higher deformation rates, the local pressure differences can contribute to the strength of the rock, an example of such a phenomenon is dilation hardening with respect to compressive strength.[28] Another effect that might occur is compaction weakening. Which effect is more likely to occur depends on the microstructure of the rock. It is reasonable to assume that similar trends are valid for tensile strength (if it is tested at a sufficiently high hydrostatic pressure, to allow for a significant pressure difference to build up without having the fluid to cavitate). As a result, the observed material behavior can change with deformation rate and total hydrostatic pressure to which it is subjected.

Bulk compaction is related to the collapse of the rock matrix, which causes a reduction in pore volume. This reduction leads to an increase in pore pressure, which can lead to a decrease in effective stress, resulting in a reduction in compressive strength.[29] During dilation, the porosity increases due to the creation of new and the extension of existing microcracks. As a result, the pore pressure of an effectively undrained sample drops locally, resulting in an increase of the effective stress and thus an increase in compressive strength, which is often referred to as dilatancy hardening.[28] The effect of dilatancy hardening is associated with a critical strain rate $\dot{\epsilon}_{cr}$ and strongly depends on the hydraulic properties of a rock. At strain rates above $\dot{\epsilon}_{cr}$, the apparent strength of a rock increases more compared to that of a drained or dry sample.

Two mechanisms can limit the effect of dilatancy hardening, i.e. cavitation and grain failure.[3] When during dilation the pore pressure decreases to the vapor pressure of the pore fluid, the fluid will vaporize and as a result the pore pressure does not decrease anymore. In the case of grain failure, the contact stresses at the grain boundaries can exceed the strength of the grain. As a result, grains will fail, giving rise to a smoother surface and reducing the amount of dilation needed before grains can slide along each other and thus effectively a smaller drop in pressure in the dilative region. A schematic representation of the dilatancy hardening effect and its limits is shown in Fig. 1.

Rutter[30] performed experiments with varying strain rates and effective stresses on Solenhofen limestone saturated with water. Several trends are distinguished by Rutter, i.e. the ductility decreases (more significant strain softening) and the yield strength increases with increasing strain rates; both the yield strength and ductility increase with increasing confining stress.

Brace and Martin[28] showed that the law of effective stress does not always apply for low porosity (0.001–0.03) rock, for deformations above a critical strain rate, Brace and Martin measured an increase in strength beyond the failure criterion. They showed that the validity of the law of effective stress depends on the strain rate , the intrinsic permeability and the pore-fluid viscosity (note that it also depends on the fluid compressibility, but the compressibility of the fluids used by Brace and Martin were too similar to distinguish this effect). Something similar has been observed by Rutter.[30] Due to dilation hardening, the effective stress in the specimen at failure is higher than the initial effective stress of the experiment.

Swan et al.[25] observed a much greater effect of the increase of the compressive strength with increasing strain rates for saturated shale from Kimmeridge Bay, Dorset, UK They noticed an increase in both strength and strain to failure of the order of four and seven times respectively over three orders of increasing strain rates.

The hydro mechanical behavior of saturated rock is directly

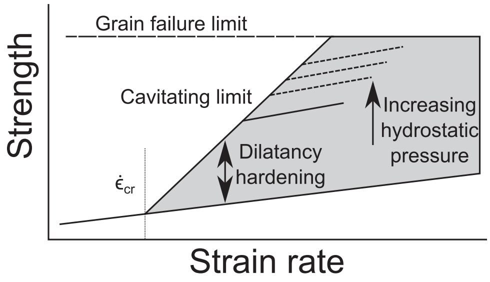

Fig. 1. Phenomenon of dilatancy hardening and its limitations, based on.[28]