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Anisotropic viscodamage–viscoplastic consistency constitutive model with a parabolic cap for rocks with brittle and ductile behaviour

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A B S T R A C T

This paper presents a new constitutive model for rocks that exhibit either brittle or ductile behaviour. The model is based on a combination of the viscoplastic consistency model in compression, and an anisotropic viscodamage consistency model in tension. The main novelty of the model is in the damage part formulated in the same manner as the viscoplastic consistency model by Wang. The model accounts for the damage-induced anisotropy by the corresponding evolution of damage compliance tensor. The Drucker–Prager yield function and the Modified Rankine criterion with a tension cut-off and a parabolic cap surface as a compression cut-off are used to indicate the stress states leading to strain softening/hardening and damage. A confining pressure dependent parabolic hardening-linear softening law in compression is calibrated with respect to the degradation index. Thereby, the model is able to capture the brittle-to-ductile transition exhibited by many rocks under high confining pressure. The hardening behaviour of rock under extremely high confined stress states is described by the viscoplastic cap model. The model performance is illustrated at the material point level with various uniaxial and triaxial tests. It is also shown finally that the viscodamage consistency model provides a localization limiter in the softening regime.

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1. Introduction

Rock material is an aggregate consisting of different minerals. Due to the geological formation processes of rocks, they contain initial microdefects, such as microcracks and microcavities or pores. The varying size and shape of the mineral grains, different material properties of these minerals as well as microfaults make rock a highly heterogeneous material. The heterogeneity and the existence of microcracks in rock materials are the major factors affecting the fracture process of rock under ultimate load. In addition to these microstructural factors, the external loading and its rate also affect the microscopic processes of fracture and, consequently, the corresponding fracture mode.

The experimental observations are used to define several typical fracture modes. In tension, the existing microcracks grow perpendicular to the direction of loading and new microcracks nucleate simultaneously. The response of the specimen can be either perfectly brittle or quasi-brittle, which depends on whether the propagation of new and existing microcracks is stable or unstable [1]. The failure mode is the transverse splitting mode with very small inelastic deformation. However, in unconfined compression, the strength of rock is about one order of magnitude higher than the one in tension. In the low confinement regime, grain-boundary sliding induced crack initiation, growth and coalescence will result in large inelastic deformation, macroscopic dilatancy and brittle faulting with the axial splitting failure mode. At intermediate confining pressure, grain-boundary microcracking becomes more distributed and, during strain-softening stage, localizes forming macroscopic shear bands. On still increasing confinement, the grain boundary sliding is suppressed by friction leading to disappearance of dilatancy effects and grain interior plasticity to accommodate the restricted external deformation. This brittle-to-ductile transition is exhibited at room temperatures and pressures accessible in the laboratory by compact carbonate rocks (e.g., marble and limestone). With these rocks, the shear stresses required to grain interior plasticity activation are relatively low [2]. Under extremely high confining pressures and hydrostatic loading, high porosity rocks (e.g., sandstone and limestone) exhibit micro mechanisms of pore collapse and grain crushing [2]. The deformation related to these mechanisms, called cataclastic flow, is characterized by inelastic deformations due to irreversible changes of the grain network geometry at the micro structural level [1]. Cataclastic flow results, as the grains are immobilized and the porosity is minimized rising the value of bulk modulus, which is macroscopically observed as a steep raise in the stress–strain curve [1].

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Finally, the effect of loading rate should be described in that higher loading rates result in higher material strengths. Moreover, a transition from the quasi-static loading rate to dynamic loading rates involves a transition from the single crack failure modes to multiple fragmentations.

A sufficiently detailed constitutive model for rock mechanics, providing the description of these complex phenomena, should have (at least) the following features: (i) thermodynamic consistency must be ensured, especially for models coupling plasticity and damage; (ii) model should capture damage induced anisotropy and rotation; (iii) localization problems related to classical strain softening models when implemented with the Finite Element Method should be addressed; and (iv) if dynamic loading conditions are to be included in the range of applications of the model, the loading rate sensitivity of rocks must be incorporated.

Many constitutive models based on viscoplasticity and/or damage mechanics has been developed to model the rock behaviour under various loading conditions (e.g., [2–22], with related works in [16,17,22] devoted to concrete models). Majority of these models are developed for quasi-static loading conditions while only [6,8,9,12,19] consider the time dependent (creep) behaviour [6,8,9] or strain rate effects of rock [12,22]. In addition, some of these models are pure damage models [13–15,18–20], being capable of accounting for the strength and stiffness degradation but not for inelastic deformations. In contrast, models in [3,4,9,11,21,22] are plain (visco)plasticity models being capable of accounting for the strength degradation via strain softening as well as inelastic strains but not for the stiffness degradation. The rest of the works cited here deal with the coupled (visco) plasticity–damage models that can account for all of these phenomena and are therefore superior. As for the damage formulation, the simplest choice is to use an isotropic damage concept to account for the strength and stiffness degradation in tension [5,7,8,10,12]. However, tensile loading in brittle-materials results in damage-induced anisotropy that cannot be described by a scalar damage model [23]. For this reason, anisotropic damage models are considered in [6,13–20]. Finally, most of the above mentioned studies concentrate only on brittle or ductile behaviour or rocks while works [3,4] consider only the ductile behaviour of soft rocks related to the brittle-to-ductile transition. It thus seems that there still is a need for a more versatile constitutive model that accounts for both brittle and ductile behaviour of rocks as well as loading rate sensitivity (crucial in dynamic analyses) and damage induced anisotropy.

Therefore, the starting point for the developments presented in this paper was the constitutive model for rocks with brittle and ductile behaviour, first presented by the first author in [12]. We have worked to eliminate some weak points of previous model [12], and provide further model extensions to accommodate various experimentally observed rock failure modes. In particular, the damage–viscoplastic consistency model with a parabolic cap model was developed specifically for modelling the rock fracture in dynamic bit-rock interaction that occurs in percussive drilling. The stress states leading to tensile damage, viscoplasticity in shear and compaction plasticity are identified by using Modified Rankine, Drucker–Prager, and a parabolic cap yield function, respectively.

The damage description of the original model [12] was based on the isotropic damage concept which, as mentioned above, cannot account for the damage induced anisotropy. The first enhancement thus concerns the development of an anisotropic damage model. For this end, we have followed the proposal first made in [16] and further advanced in [18,24–27] to introduce an anisotropic damage model in terms of compliance damage tensor. With further enhancement provided in this work, we can account for the strong strain rate sensitivity of rocks. The proposed model enhancement is formulated as a rate-dependent model in the spirit of viscoplastic consistency model by Wang et al. [28] but as a viscodamage model, with elastic strains.

The second model enhancement concerns the rock behaviour under low-confined compression, which is currently represented with a linear elastic–linear strain softening law neglecting the pre-peak nonlinearity observed in the experiments. This modification provides a new phenomenological confining pressure-dependent hardening law instead the linear softening law proposed in [12]. Our modified model uses the degradation index concept by Fang and Harrison [29] describing the post-peak degradation of strength and stiffness of rock under confined compression. The softening law of this kind, coupled with the cap hardening model, makes it possible for the model to capture the brittle-to-ductile transition. Namely, the brittle-to-ductile transition is ensured by activating the cap hardening model that describes the deformation behaviour of rock at confinement levels beyond the transition pressure.

The final model enhancement concerns the strain-rate sensitivity of the response. In particular, the cap model that was rate-independent earlier [12], is here extended to account for loading rate sensitivity. We show how such an extension can be formulated with the viscoplastic consistency approach as well.

The outline of this paper is as follows. First the general theory of viscoplastic and viscodamage consistency models is briefly presented. Particular model enhancements and the related components are then introduced and discussed. A special care is given to the important feature of brittle material pertaining to the unilateral nature of microcracks and the stress recovery on closing microcracks in cyclic loading. This effect is modelled here with the projector operator method [16]. Stress integration of the coupled model, facilitated by the compliance damage formulation and the consistency approach, is performed using the standard methods of computational plasticity (e.g., see [24]). The performance of the present model is demonstrated with typical constitutive uniaxial and triaxial tests by using a single element model. Finally, localization limiter properties of the viscodamage consistency model are studied numerically.

2. Theoretical formulation

Brief general description of the viscoplastic and viscodamage consistency models is given first, followed by the particular models developed in this paper. The phenomenological approach is chosen for specifying the hardening/softening laws. More detailed considerations of the plasticity coupled with compliance damage theory can be found in [24–27].

The fundamental kinematic assumption of the present compliance damage format is the additive decomposition of the strain tensor into [26]

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_{\mathrm{e}} + \boldsymbol{\varepsilon}_{\mathrm{vp}} + \boldsymbol{\varepsilon}_{\mathrm{vd}} \tag{1}$$

where $\boldsymbol{\varepsilon}_{\mathrm{e}}$, $\boldsymbol{\varepsilon}_{\mathrm{vp}}$, and $\boldsymbol{\varepsilon}_{\mathrm{vd}}$ are the elastic, viscoplastic and viscodamage parts of the total strain, respectively. The definitions of the two last strains are discussed subsequently.

This additive decomposition is enabled by the infinitesimal deformations assumption which we take valid for rock as a brittle material. It should be noted, however, that large inelastic deformations occur, for example, in highly confined compression of soft rocks. The extension to large deformation can be carried out by following the approach in [30] by using the principal axes and logarithmic strain measures, but this would require the more complex framework of manifolds.

2.1. Viscoplastic consistency model

The classical viscoplasticity formulation by Perzyna or Duvaut-Lions [24] do not utilize the consistency condition, i.e. the stresses

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